**University of Piraeus**

School of Information and Communication Technologies

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# Design, Development and Technology Acceptance Modeling of Accessibility Systems for People with Sensory Impairments with Applications on Autonomous Smartphone-based Navigation Systems for Blind People

Doctoral Dissertation

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**Doctoral Committee:**

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“There are no norms. All people are exceptions to a rule that doesn’t exist.”

— Fernando Pessoa

“The most exciting breakthroughs of the 21st century will not occur because of technology but because of an expanding concept of what it means to be human.”

- John Naisbitt

The views and conclusions contained in this document reflect the author and should not be interpreted as representing the official positions of University Piraeus.

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# Summary

This dissertation is part of the Human-Computer Interaction (HCI) field of studies concerning the challenges, the technological solutions developed to enable sensory disabled and marginalized groups of individuals and the effective training methodological approaches. The ultimate goal of this effort is to contribute towards the direction of reducing social exclusion and the stigma associated with disabled individuals.

In more detail, this effort focuses on enabling independent navigation in both outdoor and indoor spaces via assistive technology (AT) solutions that takes into consideration the special needs of the blind and visually impaired and considers the design of training sessions as an important factor for the success of any AT solution. Blind people face serious restrictions in their life due to their vision impairment resulting in both social and professional exclusion and a deteriorated quality of life. There are a lot of individuals worldwide suffering from eyesight deficiencies and a large amount is found in low to middle-income countries creating additional challenges for any solution. Taking all this into consideration the initiative for the MANTO project was created involving the design, implementation and validation of AT solutions for providing cost and functionally effective indoor and outdoor blind navigation applications.

The design phase involved the conduct of multiple interviews with the blind and visually impaired, where various categories of beliefs, attitudes and preferences emerged after a thorough analysis of the given input. Among the many categories, the most significant ones were selected to form the requirements concerning the functionality and interface provided by the two applications targeting outdoor and indoor navigation. The involvement of the blind and visually impaired individuals was critical to the applications' development cycle as dictated by the followed user-centered design approach. Taking into consideration the input of the requirements elicitation phase and the overall goals for cost and functional effectiveness, both applications were built on top of the Android platform utilizing low-end smartphone devices.

Regarding the case of outdoor space navigation, the application provides safe and highly precise blind pedestrian navigation without requiring the mandatory use of tactile ground surface indicators. The system employs voice instructions to continuously inform the user about the status and progress of the navigation and the various obstacles found along the navigational path. The Android application (BlindRouteVision) aggregates data from three different sources, an external high-precision GPS receiver tracking real-time pedestrian mobility, a custom-made external device consisting of an ultra-sonic sensor and a servo mechanism that resembles a sonar device in its functionality and, finally, a second external device installed on traffic lights for tracking their status in order to enable the passing of crossings near them. The user interacts with the system via an appropriately designed voice interface to enable fast and accurate interaction. Likewise, for the case of indoor space navigation, the application provides accurate and safe navigation in indoor spaces. Its basis lies in the combination of a state-of-the-art pedestrian dead reckoning (PDR) algorithm with surface tactile ground indicator guides, the gyroscope sensor found on smartphone devices, and last but not least, BLE technology radio beacons that are used to correct the accumulated error of the PDR method. The application provides its capabilities to users via a voice-command-based interface that is configurable to their preferences.

Both of these applications were validated in terms of Usability and User Experience (UX) by blind and visually impaired individuals. Usability employed a number of tasks to be performed by the blind participants relevant to the functionality of the outdoor (completion of a pedestrian navigation route, combining pedestrian navigation with public means of transport and passing marked crossings near traffic lights) and indoor (completion of thematic routes and location of Points of Interest (POIs)) application while UX was evaluated by means of standardized questionnaires (UEQ+) followed by a step of statistical analysis.

Furthermore, as the literature demonstrates, AT solutions are not widely accepted by blind and visually impaired individuals, a result which was also confirmed from the interactions with the blind and visually impaired. To address the issue of low acceptance rate and the subsequent abandonment of those solutions in a short period of time, we searched the literature to uncover the underlying causes. The effort revealed many factors of technological, financial and human nature contributing to this trend. Some of those factors can be addressed by the current technology and an improvement in assistive devices' interfaces while others are open research problems. Despite the current situation, during the interviews with the blind and visually impaired individuals, it became evident that training could play a significant role in improving the low acceptance rate and stopping the abandonment of AT solutions while being technologically and financially feasible as well as humanly approved. To explore the role of training, special training sessions were designed to demonstrate the features of the outdoor blind navigation application (BlindRouteVision). These sessions were incorporated in the context of the special Orientation and Mobility (O&M) courses where the blind learn fundamental skills for their independent mobility. A companion training application, functionally equivalent to the main application, was developed in order to facilitate and expedite the learning process. The training application itself was, also, evaluated from the perspective of Usability, UX and even further, with sentiment analysis conducted on the blind participants' responses via the use of Recursive Neural Network (RNN) deep learning models that are part of the CoreNLP framework. Overall, the training application was positively evaluated towards succeeding in its goal to facilitate the training sessions. To further validate the importance of training in improving Technology acceptance, we extended the Unified Theory of Acceptance and Use of Technology (UTAUT) to include training as one of the external factors that predict behavioral intention which according to UTAUT predicts, in turn, the actual usage of technology. The extended model was validated while evaluating the outdoor blind navigation application. Special questionnaires were used to evaluate the factors of the model followed by a thorough statistical analysis employing Explanatory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA) and Structural Equation Model (SEM). The analysis results showed a partial satisfaction of the model with the newly inserted training factor positively influencing the factor of behavioral intention.

Keywords: Assistive Technologies, Training, Special Education, Sensory disabilities, Blind and Visually Impaired, Deaf and Hard of Hearing, UTAUT, Usability, User Experience (UX), user-centered training, cognitive driven design, sentiment analysis, UEQ+, Outdoor and indoor navigation, smartphone, sensors

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# Chapter 1

## Introduction

There is a wide range of disabilities ranging from the Deaf and Hard of Hearing (DHH) to the Blind and Visually Impaired (BVI). Independent of the form of disability, all these individuals face similar issues of social and professional exclusion and reduced quality of life.

It is estimated that 295 million people worldwide have moderate to severe vision impairments, while 43 million are completely blind with the majority of them living in low to middle-income countries. As it can be seen from circumstances involving interactions with individuals suffering from any form of visual impairment, the challenges they face in their daily functioning, indoor and outdoor movement, social inclusion, communication, and work negatively affect the quality of their life and wellness. However, this is not only limited to individuals of the target group as it can also have an adverse impact on their immediate social circles like the family and the neighborhood as well. Further complicating these challenges was the advent of the COVID-19 pandemic as it posed new restrictions to the target group's day-to-day activities and, simultaneously, decelerated the development rate of innovative assistive technologies (ATs) (Senjam et al., 2021).

Hearing is considered the second most important of the senses as it plays a dominant role in the communication of humans, but also because it can help them perceive external space, thus completing and complementing the function of vision. Speech communication is the most significant barrier that affects the education, employment and acculturation of the Deaf and Hard of Hearing people with disabling hearing loss (DHH) [Pickett, 1986]. The most up-to-date statistics estimate the number of DHH to be 466 million worldwide [WHO, 2020], with a projected value of 900 million in 2050.

There is a broad consensus that assistive technology has the potential to reduce the effects of sensory disabilities. However, the current status of digital assistive solutions for both BVI and the DHH has not reached a satisfactory level, and the aforementioned barriers still remain [Gugenheimer et al., 2017].

Historically, blind navigation technologies were primarily focused on outdoor navigation as is evident both from existing research and commercial products (e.g., BlindSquare, Ariadne GPS, Lazarillo, InMoBs) (Ariadne GPS, n.d.; BlindSquare, n.d.; Lazarillo, 2022). This is due to the plethora of mature technologies such as GPS and other available solutions and infrastructure such as high-resolution maps and real-time telematics services for Public Means of Transport. On the other hand, the challenges for indoor spaces are greater and quite often it is the case that these types of ATs solutions face issues that are technically difficult or impossible to eliminate.

The latest literature on indoor space navigation proposes a number of solutions with the most common ones being based on approaches that utilize inertial odometry methods (Ren et al., 2021), pedestrian dead reckoning methods assisted by multiple-sensor fusion (Huang et al., 2019), indoor localization techniques utilizing computer vision and deep learning methods on camera-based input or signals readings from various sorts of beacons Koutris et al., 2022; Viset et al., 2022) as well as methods for reliably evaluating the adoptability of these solutions (Schyga et al., 2022). For the case of outdoor space navigation, the existing proposals employ various approaches including among others the utilization of the GPS infrastructure incorporating both the embedded sensor of the smartphones as well as external higher accuracy GPS receivers (attainable accuracy smaller than 1 meter) coupled with patent-pending novel routing algorithms (Theodorou et al., 2022a), the use of deep learning computing vision approaches for detecting obstacles in the user path, the directionality of cars as well as crosswalks near traffic lights (Chandna & Singhal, 2022; Das et al., 2021; Hsieh et al., 2021; Shelton & Ogunfunmi, 2020) and the use of smart traffic lights devices for guaranteeing the safe passage of crossings (Theodorou et al., 2022a). Finally, the proposed solutions offering both indoor and outdoor navigation combine the solutions described above into single systems (Anandan et al., 2020; Croce et al., 2019; Sipos et al., 2022).

Another observation as a result of thoroughly studying the literature was the realization that it is not evenly distributed among the two types of blind navigation. As a matter of fact, the skewness is different based on whether the authors discuss issues of technology or of training and adoption rate. In either case, a common challenge is the lack of acceptance of these Ats solutions by people with blindness and visual impairments as they cannot be incorporated easily into their daily activities.

Acceptance of mobile applications is a gradual process (Osman et al., 2003) and involves understanding the benefits offered by these applications before they are accepted and used systematically by the majority within a target group. In general, the development of smart applications does not consider the special requirements of people with disabilities, especially people with visual impairments. Even if the application is designed for use by individuals who are blind or visually impaired (see, for example, Csapo et al, 2015), it lacks features that would make it easier for them to learn the functionality of the application. The learning process depends entirely on the availability of an instructor and, in the case of an application that interacts with the environment, it requires the presence of the user at the place/site for which the application is designed. Navigation utilities for the blind are good examples where the process of familiarizing with the application depends on access to specific sites (see Meliones & Sampson (2018), among others). This problem directly affects the acceptance of technology by visually impaired people in relation to the use of smart applications.

Interestingly, however, little to no research has been conducted on the inherent peculiarities of the adoption of smart applications by blind or by visually impaired people. Further compounding the challenge of technology acceptance is the lack of proven design guidelines for minimizing the errors of users of those applications that inevitably will occur. The latter is a significant goal within the field of Human-Computer-Interaction (HCI) since its inception, however, major results have yet to be demonstrated.

Another underappreciated factor that could increase the adoption rate is of training. In that regard, the integration on smart devices of features including among others text-to-speech applications, the combination of audio with haptic channels opens a variety of new perspectives that address challenges pertaining not only to training purposes of users with impairments but also to their rehabilitation as well (Csapo, 2015).

The process of acceptance consists of multiple steps including the design of the application, the assessment of needs, desires and equipment as well as conducting special training courses, customization capabilities, and, finally, making it easy to incorporate it into the daily life of the user. Failure in any one of these areas can lead the users to have a negative proclivity against AT technology. Because so much is involved in the adoption process, assistive technology tools do not typically become the useful tools we hope them to be. For example, a crucial step in acceptance is the customization of the application to the special characteristics of the users as well as their participation in special training courses. The latter is highly dependent on the caregivers' training and time and in turn on the assistive technology specialists and the developers for training and support. The combination of novel AT technologies and the careful adjustment to the special needs of the users during training results in a more user-centered learning process. As the users familiarize themselves with the AT technology in a diverse set of scenarios and environments they acquire new skills, the re-quired cognitive load for performing their activities is lessened and, thus, it becomes naturally part of their everyday life allowing them to focus on other typical tasks.

## 1.1 Dissertation Structure

The dissertation consists of 12 chapters including the introduction itself. The rest of the chapters consist of:

- a chapter comprised of multiple surveys on 1) the current state-of-the-art on indoor and outdoor blind navigations applications systems based on smartphones, 2) the current state of acceptance of assistive technologies errors frequently made by BVIs and the reasons behind abandonment. Finally, the chapter presents a survey on the training concepts and methodologies employed for the blind and visually impaired as well as the role of virtual and augmented reality solutions in facilitating training.
- Ten chapters, each one presenting the results of the published research. The chapters are presented in a logical order as the exploration of the cognitive field progressed, which is almost identical to the time of their publication. The chapters are the following:

  **Chapter 3:** Developing apps for people with sensory disabilities and implications for technology acceptance models" - This chapter introduces the Technology Acceptance Models and the implications due to the requirements of sensory disabled individuals, both visual and hearing impairments, on developing smartphone applications. Specifically, it presents the development of two such initiatives. The first offers interactive indoor navigation for blind and visually impaired persons, while the second offers deaf people a user-friendly environment for text depiction of verbal speech, even when the articulation is defective, which is usually the case when the speaker is deaf. Despite the possible benefits of these apps, this does not necessarily translate to usage acceptance. As a result, this study aims to examine factors that may inhibit adoption, in order to obviate them as much as possible. Factors contributing to the acceptance of technology can be complex, such as 'perceived usefulness', 'self-efficacy' and 'social influence' and with the help of an exploratory study of this issue, qualitative evidence was accrued from the potential users. The chapter concludes by presenting recommendations for the development of a tentative initial modified Technology Acceptance Model (TAM) that considers the special circumstances around technology use by disability cohorts, to be tested as the research continues.

  **Chapter 4:** Human–Machine Requirements' Convergence for the Design of Assistive Navigation Software: The Case of Blind or Visually Impaired People" – The chapter discusses the desirability of autonomous navigation as a feature of "smart" devices or vehicles and the fact that software designed and developed for this purpose has become a hot research topic both in academia and industry. Furthermore, it recognizes that this trend is accompanied by a tendency to equip moving devices with artificial intelligence (AI) features. It is argued that as the capabilities of AI are being enhanced, convergence will occur among a significant subset of the requirements concerning assistive navigation software for the BVI and AI-equipped moving devices, respectively. The corresponding requirements which have been elicited through interviews with BVI people are also presented. A subset of these requirements, which exhibit direct or prospective convergence with the corresponding requirements of AI devices are outlined, with an emphasis on possible opportunities for interaction between the two research areas.

**Chapter 5:** User Requirements Analysis for the Development of Assistive Navigation Mobile Apps for Blind and Visually Impaired People" - The chapter presents an extensive qualitative analysis of the requirements for the development of two assistive navigation mobile apps targeting blind and visually impaired people (BVI). The analysis was based on interviews with BVIs and aimed to elicit not only their needs with respect to autonomous navigation but also their preferences on specific features of the apps under development which in the previous chapters was not performed. The elicited requirements were structured into four main categories, namely, requirements concerning the capabilities, functionality and usability of the apps, as well as compatibility requirements with respect to other apps and services. The main categories were then further divided into nine sub-categories. This classification, along with its content, aims to become a useful tool for researchers or developers who are involved in the development of digital services for BVI.

**Chapter 6:** Towards a Training Framework for Improved Assistive Mobile App Acceptance and Use Rates by Blind and Visually Impaired People" - The chapter starts by presenting the significant contribution towards increasing the adoption of digital assistive technologies by people with disabilities of mobile apps, which are either suitably adapted or specially designed for them. Throughout the design of two assistive navigation mobile apps for blind and visually impaired people (BVI), a set of everyday practices and psychological features of the BVIs with respect to the use of mobile technology was identified. Specifically, interviews with BVIs were held at the first stage of the design process. The analysis of the responses revealed that appropriate training of a BVI on how to use these apps plays a significant role in the anticipated app adoption and use rate. This was the point where the consideration of extending a Technology Acceptance model, which will be described in a subsequent chapter, was conceived. Furthermore, this study presented the everyday practices and psychological features of the BVIs, as they were inferred from the analysis of the interviews. It is argued that these psychological features and practices must be considered in the development of training practices concerning the use of the proposed technology. Towards this direction, a framework for the adequate training of BVIs on the use of assistive mobile apps is presented. Consideration of this framework during the development of assistive mobile apps for BVIs could contribute towards higher adoption rates.

**Chapter 7:** Gaining insight for the design, development, deployment and distribution of assistive navigation systems for blind and visually impaired people through a detailed user requirements elicitation" - The chapter presents the analysis of user needs, and requirements concerning the design and development of assistive navigation systems for blind and visually impaired people (BVIs). To this end, the elicited user needs and requirements from interviews with the BVIs are processed and classified into seven main categories extending the previous 4 categories of Chapter 6. Interestingly, one of the categories represents the requirements of the BVIs to be trained in utilizing mobile apps for assisting navigation. The need for the BVIs to be confident in their ability to safely use the apps revealed the requirement that training versions of the apps should be available. These versions need to simulate real-world conditions during the training process. The requirements elicitation and classification reported in this chapter aim to offer insight into the design, development, deployment and distribution of assistive navigation systems for the BVIs.

**Chapter 8:** Smart traffic lights for people with visual impairments:  A literature overview and a proposed implementation" - This chapter brings forth the initiatives taken by cities to improve the quality of life of the blind and visually impaired and, it emphasizes passing crossings near traffic lights. Specifically, cities have installed sound-emitting devices into traffic lights as well as sidewalks that assist the navigation of the BVI. Moreover, as most of the developed cities are always striving to move forward and achieve innovations concerning navigation for disabled individuals, smart traffic lights, capable of synchronizing in real-time according to traffic and individual mobility conditions, are already being installed around the world. This is in line with the adoption of the smart city concept, which involves a set of methodologies and indicators that regulate how cities perform regarding the promotion of citizens' quality of life. Another important aspect is the techno-economic dimension indicating the need for low-cost careful planning to produce cost-efficient solutions while balancing with important issues such as maintenance, power efficiency, and the means to coordinate numerous devices to facilitate operation in a timely and reliable manner. Taking all these into consideration, we present an overview of the existing solutions for the navigation of people who are blind and visually impaired accompanied by a requirement analysis performed on feedback received from interviews with members of the Lighthouse for the Blind of Greece both of which lead to the proposal of a new implementation that pushes the state of the art.

**Chapter 9:** An Extended Usability and UX Evaluation of a Mobile Application for the Navigation of Individuals with Blindness and Visual Impairments Outdoors—An Evaluation Framework Based on Training" - This chapter focuses on the extended Usability and User Experience (UX) evaluation of BlindRouteVision, an outdoor navigation smartphone application that tries to efficiently solve problems related to the pedestrian navigation of visually impaired people without the aid of guides. The proposed system consists of an Android application that interacts with an external high-accuracy GPS sensor tracking pedestrian mobility in real-time, a second external device specifically designed to be mounted on traffic lights for identifying traffic light status and an ultrasonic sensor for detecting near-field obstacles along the route of the blind. Moreover, during outdoor navigation, it can optionally incorporate the use of Public Means of Transport, as well as provide multiple other uses such as dialling a call and notifying the current location in case of an emergency. This chapter also presents findings from a Usability and UX standpoint of our proposed system conducted in the context of a pilot study, with 30 people having varying degrees of blindness. As part of this effort, we also received feedback for improving both the available functionality of our application and the process by which blind users learn the features of the application. The methodology involved standardized questionnaires and semi-structured interviews. The evaluation took place after the participants were exposed to the system's functionality via specialized user-centered training sessions organized around a training version of the application that involves route simulation. The results indicate an overall positive attitude from the users.

**Chapter 10:** An extended usability and UX evaluation of a mobile application for the navigation of individuals with blindness and visual impairments indoors: An evaluation approach combined with training sessions - This chapter starts by presenting the challenges of individuals with blindness and visual impairments during indoor navigation. Although many solutions exist, the acceptance of most of them is extremely poor due to their technical limitations and the complete lack of taking into consideration factors, such as usability and the perceived experience among others, which influence technology adoption. To alleviate this problem, we created BlindMuseumTourer, a state-of-the-art indoor navigation smartphone application that tracks and navigates the user inside the spaces of a museum. At the same time, it provides services for narration and description of the exhibits. The proposed system consists of an Android application that leverages the sensors found on smartphones and utilizes a novel pedestrian dead reckoning (PDR) mechanism that optionally takes input from the Bluetooth low energy (BLE) beacons specially mounted on the exhibits. This chapter presents the extended Usability and User Experience evaluation of BlindMuseumTourer and the findings carried out with 30 participants having varying degrees of blindness. Throughout this process, we received feedback for improving both the available functionality and the specialized user-centred training sessions in which blind users are first exposed to our application's functionality. The methodology of this evaluation employs standardized questionnaires and semi-structured interviews, and the results indicate an overall positive attitude from the users. In the future, we intend to extend the number and type of indoor spaces supported by our application.

**Chapter 11:** Challenges in Acceptance of Smartphone-based Assistive Technologies - Extending the UTAUT Model for People with Blindness and Visual Impairments – Despite the plethora of sensor-based assistive technology (AT) solutions, there is still no widespread acceptance and adoption by people who are blind and visually impaired. Many reasons prevent reducing abandonment levels with a prominent one being a lack of focus on the dimension of training, which according to indications from the collected data, is integral to the acceptance of ATs. To prove the importance of training, in this chapter we extend and validate a new version of the Unified Theory of Acceptance and Use of Technology (UTAUT) incorporating training as an external factor. Closed and open-ended questionnaires were given online and offline to 231 blind participants after conducting training sessions with an outdoor blind navigation application developed by our research team. To assess the UTAUT extension Exploratory Factor Analysis, Confirmatory Factor Analysis, and Structural Equation Model were employed to explore the relationships between the factors. A Usability and User Experience qualitative analysis supplemented the previous. We uncovered that no factor besides Performance Expectancy (Standardized regression weight = 0.264, p < 0,001) and Training (Standardized regression weight = 0.538, p < 0.001) significantly predict Behavioral Intention. Furthermore, the analysis demonstrated a significant interaction (p < 0.007) strengthening the positive relationship between Training and Behavioral Intention (Standardized regression weight = 0.142). The qualitative analysis showed an overall positive evaluation highlighting the application's usefulness and dependability. As a key takeaway, the results indicate that an application's adoption increases if blind individuals are properly trained and acquainted with the features in real-life scenarios and recognize the application's utility for their daily life. Furthermore, training plays an important role in Technology Acceptance and this can be leveraged to make solutions more appealing to blind people. Finally, this chapter concludes the methodology used in this doctoral dissertation and creates a new model upon which future research could be based on.

**Chapter 12:** Training blind and visually impaired individuals is an important but often neglected aspect of Assistive Technology solutions (ATs) that can benefit from systems utilizing multiple sensors and hardware devices. Training serves a dual purpose as it not only enables the target group to effectively utilize the ATs but, also, helps in improving their low acceptance rate. In this paper, we present the design, implementation and validation of a smartphone-based training application. It is a form of immersive system that enables users to learn the features of an outdoor blind pedestrian navigation application and, simultaneously, to help them develop long-term Orientation and Mobility (O&M) skills. The system consists of an Android application leveraging, as data sources, an external high-accuracy GPS sensor for real-time pedestrian mobility tracking, a second custom-made device attached to traffic lights for identifying their status and an ultra-sonic sensor for detecting near-field obstacles on the navigation path of the users. The training version running as an Android application employs route simulation with audio and haptic feedback is functionally equivalent to the main application and was used in the context of specially designed user-centered training sessions. A Usability and User Experience (UX) evaluation revealed the positive attitude of the users towards the training version as well as their satisfaction with the skills acquired during their training sessions (SUS = 69.1, UEQ+ = 1.53). Further confirming the positive attitude was the conduct of a Recursive Neural Network (RNN)-based sentiment analysis on user responses with a score of 3 on a scale from 0 to 4. Finally, we conclude with the lessons learned and the proposal of general design guidelines concerning the observed lack of accessibility and non-universal interfaces.

# Chapter 2

## Literature Review

In this chapter, we present the progress of the research for the last five years of the available solutions for both indoor and outdoor applications as it is depicted via the available surveys. Furthermore, we survey the literature for the reasons contributing to the low acceptance and adoption rates among people with blindness and visual impairments of those systems, and the training courses that help the users familiarize themselves with the provided functionality. We start with the technical review which is followed by the second part of issues around acceptance and training.

Our involvement with indoor and outdoor navigation for people with blindness and visual impairments started in the context of the MANTO project (in ancient Greek mythology, Manto was the daughter and blind escort of the famous blind seer Tiresias). Its aim was to design, implement and validate state-of-the-art navigation applications to resolve accessibility problems of individuals with low vision and/or total blindness during pedestrian navigation in outdoor and indoor spaces with the expectation to provide an unparalleled aid for individuals all over the world so that they can walk outdoors safely and experience self-guided tours in indoor spaces, including tours in museums. The result of this effort was two applications, BlinRouteVision and BlindMuseumTourer for outdoor and indoor navigation respectively.

BlindRouteVision is an application emitting critical information, via issuing voice instructions, for ensuring the well-being of the individual during outdoor navigation. It combines high precision tracking capabilities coupled with an obstacle detection system that helps in avoiding them. The system consists of two subsystems that are tightly integrated. These include a wearable device incorporating an external GPS receiver with high precision tracking pedestrian mobility in real-time, a second device with an ultrasound sensor mounted on a servo mechanism functioning similarly to sonar, an Android application that acts as the central component of the system and, finally, a custom-made voice interface to enable fast and accurate user interaction with the application. The system, also, offers the capability to optionally combine pedestrian navigation with Public Means of Transportation via the incorporation of available real-time telematics services along with guaranteeing the safe passing of crossings near traffic lights. The latter is achieved with the help of another external waterproof device designed by our research team that allows monitoring and transmitting with zero latency both the status of the traffic light and its remaining time until the next change occurs. A carefully designed set of voice instructions, customizable to user preferences, provides the required information to ensure the correct and safe navigation of the users, as well as to convey information about potential obstacles along their path.

BlindMuseumTourer is an Android application that enables individuals with blindness and visual impairments to autonomously navigate in indoor spaces with high accuracy and safety. It combines a newly proposed Pedestrian Dead Reckoning (PDR) algorithm with surface tactile ground indicator guides, the gyroscope sensor found on smartphone devices, and, optionally, BLE technology radio beacons that are used to correct the accumulated error of the PDR method. The capabilities of BlindMuseumTourer were evaluated inside the spaces of the Tactual Museum of Athens, one of the five tactual museums worldwide, organized around thematic tours including copies of famous artifacts from antiquity. The proposed PDR algorithm accurately tracks the user's position and the traveled distance minimizing as much as possible the associated error. The application provides a voice command-based interface to the users that, additionally, can be configured to match their preferences. In case of an emergency, BlindMuseumTourer can guide the users to designated places inside the museum as well as facilitate them to make emergency calls either to family members or public services. Finally, for the required internal space mappings, the proposed solution provides a companion web application that allows the employees of the Museum to create and modify the maps containing the configuration of the exhibition rooms. Based on the outcomes of this particular use case, in the future, we intend to evolve the application to enable navigation inside complex spaces including hospitals, shopping malls, universities and other public and private buildings.

Besides the technical evaluation of our proposed solutions, we also assessed issues relative to usability and user experience (UX). For the latter, the research team reviewed the various available methods and found that the most common ones for assessing users' interaction with the system are surveys, the think-aloud protocol, controlled environment testing, field experiments, remote usability testing and interviews. However, each of these approaches has disadvantages. According to Budrionis et al. (2022), the think-aloud protocol is inaccurate because it does not represent the environment in a natural way and the tasks are controlled while field experiments may also not be representative enough of the population. Furthermore, remote testing requires the use of additional tools for collecting data and interviews do not adequately address usability issues. Last but not least, a controlled environment testing setting imposes the risk of not incorporating factors that exist in the actual world that could potentially influence the user's experience.

The research team evaluated a few tasks during the O&M training sessions held in the vicinity of the BlindHouse of Greece for the case of outdoor navigation and inside the premises of the Tactual Museum of Athens for the case of indoor navigation. We employed surveys, interviews, semi-structured surveys, and field experiments as methods of assessment. After the completion of the evaluation of the pilot stage, users, all blind and visually impaired, were asked to evaluate their experience with the applications in combination with the complementary training process. It is our view that any solution targeting individuals who are blind and visually impaired requires extensive testing that involves their participation, is conducted in conditions that are as close as possible to realistic scenarios, and, finally, takes into consideration the resulting feedback for the further refinement of the proposed solutions. This is due to the fact that assistive solutions try to support a target group that is significantly different from average users.  Unfortunately, the majority of the available research conducts their test evaluations without the participation of the people in need of the applications and instead utilizes blindfolded sighted users. The downside to this approach, which is partially justified by the reluctance of people with blindness to participate in such efforts, is that a person without a visual disability cannot evaluate the solution appropriately, since the mental representations of the world and the relevant experience is completely different. Valipoor & de Antonio (2022) record that 27.5% of the reviewed literature utilizes blindfolded sighted users.  Furthermore, they note that the evaluation process should address two main aspects. One concern is the technical aspect and the validity assessment of the system while the other is the users-centric evaluation assessing the actual performance and usefulness of the solution. Despite the essential nature of the user evaluation as a complement to the technical evaluation, a noticeable number of works in the literature restrict themselves to only the latter neglecting, unfortunately, the former. As a matter of fact, Valipoor & de Antonio (2022), report that only 40,7% of the reviewed literature conducts both a technical and user evaluation while the remaining 59,3% conduct only a technical evaluation. The results from our evaluation indicate that due to the applications' removing limitations on pedestrian and indoor navigation, users have already reported positive effects in their lives. Specifically, in a short time, they became familiar with the application environment and reported that the training sessions greatly improved their proficiency with the device and the applications.

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For more technical details of our two proposed solutions, other related work available in the literature for each of the cases of indoor and outdoor navigation supporting individuals with blindness and visual impairments as well as the technical and usability/UX evaluation of our proposed solutions, the readers can refer to our published work (Theodorou et al., 2022a, Theodorou et al., 2022b).

## 2.1. Technical review

The main purpose of navigation assistive technologies is to provide support to individuals with visual impairments during independent mobility via augmenting their senses and providing contextual awareness of their surrounding environment. This is predominantly achieved via audio-haptic interfaces, nonetheless, the various modalities for providing navigation assistance need to constantly adapt to the preferences and behavior of the users that are changing along with the gained experience, preferences and necessity.

In the last decade, a multitude of approaches has been proposed in the research community trying to uncover the important features and provide the technical solutions to address the challenges that blind and visually impaired individuals have to face. For the acquired knowledge to remain manageable, various reviews have been conducted summarizing the most important results. In this section, our goal is to aggregate in one place and present in a comprehensive manner the most up-to-date reviews. The presentation is done in chronological order from the older to the most current one highlighting at the same time the progress made throughout the years.

Starting with Elmannai & Elleithy (2017), they present solutions meant to substitute vision dividing them into three subcategories that include Electronic Travel Aids (ETAs), Electronic Orientation Aids (EOAs) and Position Locator Devices (PLDs). According to them, ETAs gather information about the surrounding environment through sensor cameras, sonar, or laser scanners and transfer it to the user, EOAs provide directions to pedestrians in unfamiliar places, and, finally, PLDs via the utilization of GPS-based technologies determine the precise position of its holder. In order to shed some light on the missing features of the available solutions, the authors proceed to perform an evaluation by assigning a score produced by a normalization equation. The latter takes as input weights corresponding to basic features that assistive devices for blind persons should provide. These include the creation and emission of clear and concise information within seconds, consistent performance during day and night, support for mobility in outdoor and/or indoor spaces, and the detection of obstacles including both static and dynamic ones in an adequate range that guarantees the safety and well-being of the user.

Valipoor & de Antonio (2022) present a literature review of solutions with a primary focus on the scene understanding aspect, which includes object recognition and obstacle detection. Their attempt is driven by the need to make sense of the available deep learning and computer solutions as they have become highly effective, and, thus, provide guidance for researchers. The authors organized their review around three main categories: scene understanding, assistive services and evaluation. Each and every one is subsequently divided into the following subcategories: object recognition, obstacle and depth detection, algorithms, and hardware for the category of scene understanding, type of assistance and modality for the category of assistive services, and, finally, for the evaluation category, the technical and user-centered aspect. Finally, a key observation the authors make is about the lack of user testing leading to the abandonment of such devices (see next section).

Aileni et al. (2020) organize the literature review around assistive technologies for people with low vision acuity. Their main approach involves the utilization of the Internet of Mobility (IoM) and Internet of Mobile Things (IoMT) for the integration of these technologies into wearable and transportation systems.

Khan & Khusro (2021) conduct a literature review involving smartphone-based assistive solutions for individuals with blindness and visual impairments. Specifically, they highlighted the challenges of different kinds of solutions that are based on the utilization of sensors, sonars, and augmented reality approaches.

They primarily focus on the usability of the solutions and issues that involve inconsistencies related to interface elements, difficulties in entering and modifying text, incompatibilities due to devices, irrational order of items for blind users, and the like. Furthermore, in this review, the authors highlight the importance of user-centered design for the development of assistive solutions as in this approach the user is involved in the process of designing, developing, and evaluating the system, thus, satisfying the users' needs to the greatest degree possible.

Kuriakose et al. (2020) conduct a literature review and analysis covering multimodal navigation solutions aimed at people with visual impairments. Although several literature reviews have covered the issues of navigation for individuals who are blind or visually impaired in general, none has gone through the research synthesis of multimodal navigation systems. They mainly focus on the pros and cons of these solutions and their different modalities of tactile, visual, aural, and haptic feedback, as well as the overall benefits when compared with unimodal approaches. Finally, this review tries to present the challenges of designing and implementing such navigation systems and also tries to put forward recommendations for building effective multimodal navigation systems.

Kuriakose et al. (2022) contrary to other related attempts, systematically present the available solutions for blind navigation without limiting either to specific environments in which the proposed solution operates (indoor, outdoor) or the underlying technology utilized. The solutions are classified into (1) Visual imagery systems, (2) Non-visual data systems, (3) Map-based systems, (4) Systems with 3D Sound, and (5) Smartphone-based solutions. The goal of this review is to designate a set of design recommendations that can be considered for future solutions. These are 1) the appropriate choice of real-time object detection methods, 2) expediting and lowering the learning curve, 3) personal and private data management, 4) emitting in a succinct way the essential information in the right amount to guarantee safety, 5) portability, 6) usability, and, last but not least, 7) to avoid any social stigma.

El-taher et al. (2021) present a literature review on outdoor navigation systems for blind and visually impaired individuals ranging from 2015 to 2020. The authors classify the proposed solutions based on the three stages required for successful outdoor navigation, starting from the stage of Environment mapping, next being the Trip planning stage, and concluding with the Real-time navigation stage. According to the authors, the stage of Environment mapping gives the necessary location-specific information to support pedestrians with blindness and visual impairments in trip planning and real-time trip support by alerting them of the impending intersections, public transportation stations, and traffic lights. The second stage, Trip planning, leveraging the information from the previous stage, given a start location, selects the optimal route for the users' destination, guaranteeing at the same time safety. Finally, the stage of Real-time navigation provides the necessary information for raising environmental awareness, avoiding obstacles, and using public transportation.

The principal findings of this attempt recognize the significant amount of work being put forward over these years; however, there is still a long way before these solutions can be considered ready for real use. Specifically, the stage of Environment mapping requires annotations on the available maps signifying safety critical information such as the location of traffic lights, intersections, sidewalks, crosswalks, and public transportation. The standard GPS is not accurate enough for finding the locations of individuals who are blind and visually impaired as it does not yield the highly precise location accuracy required. Furthermore, the optimal route for the target group is not always about the shortest path as it needs to balance between the time to reach the destination and minimize the impending hazards (turns, traffic lights, and the like). They also notice that there is a shortage in the literature on combining outdoor pedestrian navigation with public transportation, tools for raising spatial awareness and traffic light recognition. Moreover, the authors call for a generalised obstacle avoidance system since the available but fragmented solutions are not practically usable. Likewise, there is no single application or device capable of providing all this functionality from a single point. Finally, the authors mention the lack of common terminology in the existing research literature.

Islam et al. (2019) propose a taxonomy of walking assistants based on the most significant contributing approaches. The authors classify the solutions into walking assistants utilizing (a) sensors, (b) computer vision, and (c) smartphones. The evaluation of the proposed solutions considers the features of capturing device types, types of feedback signal provided, the coverage area, the weight, and the cost. The rationale behind the choice of these features is based on the authors' conviction that these are key concerns for measuring the efficiency and reliability of walking assistants. Furthermore, they make the observation that no single framework can address the complete set of challenges blind and visually impaired individuals face, despite each framework offering a unique proposition. As a takeaway lesson, the authors provide an arrangement of fundamental rules that every assistive tool should adhere to in order to obtain better performance. These are 1) Simplicity, 2) Low cost, 3) Lightweight, 4) Reliability, and 5) Coverage area. Finally, a limitation of nearly all the proposed solutions is the lack of categorization of the detected obstacles in front of the users. Besides the latter, the authors recognize future research paths in resolving issues related to different roads, potholes on the road, the smoothness and the presence of liquid substances on the road surface and surface staircase situations.

Bhowmick & Hazarika (2017), conduct a survey to answer four major questions. These include the individual topics that constitute the field of research, the journals and conferences in which research in Assistive Technology is published, the rate of expansion of this research field, and whether the field operates as a coherent discipline or is just a set of disparate fields united into a coherent whole. The latter is the most interesting question as it reveals the major communities comprising the field of assistive technologies. By employing the log-likelihood ratio method between popular word pairs in AT for individuals with blindness and visual impairments, the authors quantified the existing connectedness. This attempt resulted in the creation of a co-occurrence graph depicting four distinct research communities. These include the community of multisensory research, accessible content processing and user interface design, mobility and research concerning accessible environments. Overall, the authors note that the field is a very coherent discipline despite the expansion of several sub-disciplines as is evident from the distinguishable names presented above.

The survey by Budrionis et al. (2022) presents an overview of Electronic Travel Aids (ETA) that employ smartphones for assisted orientation and navigation in indoor and outdoor spaces. The authors in conducting this review utilized the principles of the Prisma framework on a rather strict subset of the solutions that focus on people with blindness and exclude solutions that address the challenges of the visually impaired. The results of this attempt demonstrate the limited use of haptic interfaces, the limited use of state-of-the-art computer vision algorithms based on deep neural networks, and no evaluation of existing navigation commercial applications. Furthermore, they demonstrated a major mismatch between user needs and academic development when they contrasted their findings against a survey conducted with blind expert participants on problems related to navigation in indoor and outdoor environments. Specifically, the authors noted several limitations while evaluating the proposed solutions. When assessing computer vision-based solutions from a technical standpoint they noticed a lack of utilizing standard computer vision benchmark datasets and the utilization of relatively small datasets collected by the members of the research team, thus, making it impossible to compare the performance of the various solutions. Furthermore, they did not find any solutions thoroughly tested in a representative sample of blind users, which consequently leaves open unanswered questions about their effectiveness in the field. Complementary to the above, some of the authors of the proposed solutions neither perform validity and robustness testing nor elaborate on the details of the testing results. Unfortunately, it is common for tests to be conducted in test labs without the involvement of actual users.

Wang et al. (2022) conduct a survey of the available literature in an attempt to present a number of results exclusively on indoor travel aids for individuals who are blind and visually impaired from the perspective of spatial cognitive ability and navigation and analyze the current challenges as well as present the newer technological advancements in terms of software, hardware, architectural design, functional design, and commercial potential. Specifically, the selected research ranged from 2017 to 2020 and is representative in the sense that the proposed solutions are established in most respects and have the potential for commercial exploitation. The proposed solutions are evaluated relative to the aspects of availability, cost, function, accuracy, and commercial potential. Finally, the authors note that for the development of better navigation applications for the BVI in the future, researchers will need to broaden their understanding of spatial cognition theory and incorporate the most important results into their designs, pay more attention to the integration of perceptual interfaces for haptic, spatialized sound, or multimodal output, and be more engaged in the daily lives of the target group, understanding their real needs as well as providing special training frameworks in order to use the proposed systems better. The authors collectively organized all of the above under the principle of “human-centered, technology-assisted”.

Simoes et al. (2020), provide readers and researchers with a more recent version of what was proposed and the benefits and drawbacks of each approach to help guide reviews and discussions about these topics. Radio-based, inertial, sound-based, light-based, and computer-based systems were among the technologies grouped together to evaluate the available indoor positioning proposals. The evaluation examined the benefits and drawbacks of the grouped solutions in terms of accuracy and scalability. The authors also included various hybrid systems with an emphasis on the currently available solutions. Irrespective of the technical solution, they were analyzed from the perspective of utilizing mobile devices, particularly smartphones, since they are widely used and have the benefit of housing the majority of the sensors used in indoor positioning systems, thus, lowering the cost of these solutions for mass deployment. The authors observe that current solutions are more accurate and perform faster and new algorithmic arrangements have improved the quality of indoor positioning systems. However, the issue of indoor location positioning is still far from being resolved, and further study is necessary to achieve the level of precision required by specific user groups, such as those who are visually impaired. Finally, the authors conclude that a universal solution addressing the issue of an indoor positioning system that can be utilized indoors while maintaining standard behavior still has not found a satisfying answer. Quite commonly, fully accurate solutions are costly, or they do not operate in real-time, or cheaper proposals are very inaccurate.

## 2.2 Survey on acceptance, errors, and abandonment

The biggest issue the proposed assistive technologies face is the high rates of abandonment. One would consider that with the plethora of solutions existing in the space, the problem of abandonment would be solved. However, as research-based evidence demonstrates, this is not the case. Taking a closer look into the challenges the blind and visually impaired face when using such technologies reveals the errors that arise and, subsequently, the causes of abandonment. This section highlights the challenges, errors, and abandonment rates as they are reported in the literature and reaches the conclusion that the solution to increasing acceptance lies in the design of elaborate training courses centered around these devices.

### 2.2.1 Challenges

Independent navigation is challenging for blind people, particularly in unfamiliar environments, due to their reduced confidence and knowledge **(Giudice & Legge, 2008;** Williams et al., 2013). Assistive technologies in navigation provide additional support by guiding users (Fallah et al., 2013; Katz et al., 2012; Loomis et al., 1998; Petrie et al., 1997), increasing their knowledge of the surroundings (BlindSquare, n.d; Blum et al., 2011; Kacorri et al., 2016) or both (Ahmetovic et al., 2019; Ahmetovic et al., 2016; Sato et al., 2019). Despite the existence of the available solutions, many of them being commercial, there are still open issues and due to various technical limitations, accurate solutions are still not widely available (Guerreiro et al., 2017).

When individuals with blindness and visual impairments try an AT solution for the first time, mostly via a smartphone device with no or few supporting peripheral devices, it can result in a daunting experience (Rodriguez et al., 2015). This can be due to the induced fear the target group feels as they are constantly concerned about whether they can leverage the given functionality, the lurking danger of physically hurting themselves, or the disappointment when they realize that their expectations cannot be met. Even if users are confident enough and choose to face their fears when utilizing assistive technologies, these solutions have to work hard to convince about their effectiveness as it is commonly accepted among the communities of the target group that smartphones as a technology medium are not designed for them (Manduchi & Kurniawan, 2010).

In order to help individuals to make the usage of assistive technologies (ATs) easier for them, a number of challenges that hinder smartphone adoption need to be addressed. These can be the result of either environmental conditions or specific design choices. One of the environmental challenges affecting the adoption of smartphone devices is the case of situational impairments. They have been shown to degrade the performance of a user while using a smartphone device. The study by Kane et al. (2009), identified with the help of various participants several such factors that negatively affected their ability to use their smartphone devices. Specifically, using the smartphone device while walking presented challenges to some participants as it both reduced their motor control over their situational awareness and made it impossible to listen to sounds in the environment. Further compounding the challenge of using smartphone devices while walking is the case when other tasks are involved where situational awareness can be degraded even more.  This is backed up by previous research that shows performance degradation from using a smartphone device during these kinds of circumstances, demonstrating simultaneously these effects may be more adverse for people with visual impairments. This suggests that it may not be possible to use smartphone devices without reducing situational awareness (Albouys-Perrois et al., 2018). Other challenges related to the design decisions made for smartphone-based applications include the following: 1) gestures-related issues, 2) a lack of consistency in the applications as there is no single path to a feature, 3) different interfaces per application leading to confusion, 4) non-accessible-friendly features for non-visual users and 5) issues related to learning to use the talkback service by novices. This list is by no means exhaustive.

Besides the above limitations that affect all types of smartphone applications for people that are blind and visually impaired, the set of applications that we focus on, namely, outdoor and indoor navigation applications have their own set of unique challenges. Contrasting those two, we can further identify that the indoor case is even more limited by a unique set of technical barriers. This is due to indoor navigation applications relying on infrastructural interventions that increase the cost of the solution. As a consequence of the latter, many of the current state-of-the-art approaches are based on computer vision technologies because it allows circumventing many of the drawbacks of other approaches. Nonetheless, there is little to no knowledge of how unexpected faulty conditions affect user experience, and these systems, as is commonly the case, are not free of them. Besides the previously mentioned, since smartphone-based solutions prevail, another limitation concerns the required computational intensity and its effects on battery consumption, thus imposing new challenges regarding effectiveness and usability.

In order to address the challenges and deficiencies despite the selected technological approach, resources are required to aid the adoption process. However, our research team discovered that there is a scarcity of those relevant resources available further compounding a difficult problem that is both time-consuming and difficult to undertake. Currently, it is expected from the users to be persistent and willing to ask for aid. Especially the latter is impossible to eliminate no matter how well-designed a solution is as has been demonstrated by all of these years of research. Furthermore, even with the progress made where many challenges have been identified, there are several still overlooked or underexplored

(Rodriguez et al., 2020). Below we provide a comprehensive list of open challenges that future research needs to address to achieve better smartphone-based accessibility:

- **Learning and exploring** - Challenges related to learning and performing movements on touchscreens have not yet been overcome, despite the effort put into that area. It remains difficult for individuals with blindness and visual impairments to discover and learn based on any given description, leaving them only with their support network for substantive assistance.
- **Adapting mental models** - New releases of the widely available operating systems and of applications usually bring new changes to the existing interfaces, without any accompanying relevant descriptions in an accessible format, thus forcing users to adapt their daily routines to the new conditions every time a redesign of user experience occurs.
- **Accessibility of applications** - Although there is a great number of efforts targeting accessibility aspects of smartphone applications, the results are fragmented without providing a common frame of reference or any sort of actionable advice.
- **Forced interfaces** - The choice of a touchscreen interface does not seem to be the most appropriate one for blind users. Instead, a redesign of smartphones for the target group having more physical buttons could be a step in the right direction.
- **Ubiquitous accessibility information** - Individuals with blindness and visual impairments require access to a centrally available repository of information relative to accessibility issues for applications and devices, to facilitate the adaptation of the users' mental model caused by the ongoing non-standard interface changes introduced in each re-iteration. Users might be able to make meaningful choices with the help of a dedicated accessibility rating and other statistics.
- **Enabling sharing and peer support** - Many individuals find no support for their cases as it is either inaccessible or incompatible with their device configuration. Rodriguez et al. (2017) identified the shortcomings of the current communication methods that include asking questions to other people and/or searching online as both being time-consuming and removing the user from the context of the problem often providing no results. To address and achieve effective communication in an accessible manner, the right understanding and tools are required.

## 2.2.2 Errors

Balata et al. (2015), identified a set of commonly occurring errors during outdoor navigation. Specifically, these concern reorientation at a corner, crossing from corner to corner, travelling along, reorienting around and crossing from a building, finding a landmark, absence of contextual awareness on the behalf of the user, temporary changes in the environment, landmark confusion, veering off the navigational path. Despite these errors from Balata et al. (2015), which occur in the context of a sighted person giving live instructions to an individual who is blind or visually impaired, these are the exact same situations that a smartphone-based system will have to address. In fact, addressing these errors is far more difficult for a smartphone-based system, as a human, being a dynamic system, can easily help the individual with blindness and visual impairments to find their way in relation to the static yet versatile representation of the same information of smartphone-based applications.

Similarly, indoor blind navigation is not free of errors. Abdolrahmani et al. (2016), identify applications with three types of errors based on computer vision. These concerns indoor space feature misidentification, false negatives and false positives detection as well as social/environmental settings where these errors manifest.

Theodorou et al. (2022a), showed a set of recurring errors during the evaluation of an indoor navigation system. Specifically, this system is a smartphone application employing an innovative PDR algorithm able to utilize BLE beacons for even better minimization of the localization error. The identified errors include collision with the museum exhibits, veering off the navigational path, over-turning, and issues related to the instructions emitted by the application.

Alkhanifer & Ludi (2015), identified another common error that indoor space navigation solutions must resolve. This involves the factors that could potentially cause disorientation to individuals with blindness and visual impairments in indoor spaces. Specifically, the factors are categorized into those caused by the environment, the lack of available information and processes that concurrently take place around the individuals. Each factor is then further analyzed into a number of constituent parts. Environmental factors are broken down into physical barriers obstructing individuals from receiving auditory cues from the surroundings that could potentially be used to orient themselves. Another environmental factor concerns large, open spaces having fewer points of reference which make it harder for the target group to find their way during indoor traveling and inconsistent building layouts that quite often leave the target group in confusion. Last but not least, various configurations of indoor lighting setups can introduce challenges to individuals who have a limited perception of light. The second category of Information factors in turn concerns the lack of available information for an indoor space both in the form of braille signs, which the majority of the target group is familiar with and in the absence of any human assistance. Finally, process factors are those that can affect the orientation process due to human interference as well as noise and traffic levels. Individuals with blindness and visual impairments are susceptible to being disoriented in situations where they can be surrounded by multiple sources of noise, like pedestrian and car traffic, obstructing them from being able to perceive the environment and important auditory cues.

A step toward ameliorating the situation is to study user behavior related to the context of the problematic scenarios mentioned above. Mixing better localization accuracy (Guerreiro et al., 2018) and interfaces compatible with the strategies learned in O&M training (Wiener et al., 2010), new navigational assistance standards (see Pérez et al., 2017) and knowledge about the behaviors, preferences, and coping mechanisms of the target group during navigation (e.g., Abdolrahmani et al., 2017; Nicolau et al., 2009; Williams et al., 2013) can be leveraged to develop effective navigation systems with better error rate (Sato et al., 2017). While the causes of errors may be due to an occasional decrease in localization accuracy, they can also be the result of problematic situations where specific/unexpected user behavior or coping mechanisms interfere with the system interface.

### 2.2.3 Abandonment

A survey conducted by Phillips and Zhao (1993) involving 227 individuals with disabilities showed that 30% of assistive devices are completely abandoned. In order to comprehend the reasons behind AT abandonment, they identified four predictors, namely, effectiveness, affordability, operability, and dependability. Moreover, they also noted that another significant factor is the gradual shift in user priorities and demands over time. For instance, changes in the eye conditions of individuals with blindness and visual impairments, such as macular degeneration, which is quite common, could result in a major shift in user needs (Petrie et al., 2018). Other highlighted causes for abandonment include dismissing user feedback, difficulty in acquiring devices, and poor device performance. Likewise, Kintsch & DePaula (2002), developed a framework for the identification of attributes that lead to AT abandonment. They observed that device abandonment is closely linked to the individual's tolerance for frustration and also to the sensitivity to failure. Moreover, they found that another factor closely related is the degree to which the learning experience was errorless. Last but not least, Verza et al. (2006), suggest that reasons contributing to a decreased engagement with assistive technologies include the lack of considering the users' opinions in the development process, inefficient solutions and insufficient user training.

Besides the accuracy of the technological solutions for indoor blind navigation, Abdolrahmani et al. (2016), discovered that acceptance of a device is impacted by the error type, the building feature for which the error is made, and the broader social/environmental setting. Specifically, they recognized a set of three factors that should be taken into account when considering the parameters affecting the technology adoption rate (Abdolrahmani et al., 2016). These concern, firstly, indoor space feature misidentification and the involved risk to the user as a wrongly identified set of stairs/escalators is more forgivable than making a mistake in identifying the restroom gender sign, secondly, the types of errors classified as false negatives and false positives with the former being more acceptable to the users than the latter and thirdly, the broader social/environmental settings where these errors manifest with the ones occurring in professional settings being less acceptable that in densely populated settings. The general impact of the social environment on whether assistive devices are accepted (Shihonara, 2010; Shinohara & Tenenberg, 2007; Shinohara & Tenenberg, 2009) has also been demonstrated in previous research where drawing unnecessarily the attention to the user's impairment can negatively impact adoption (Shinohara & Wobbrock, 2011). As a result, various design initiatives for socially acceptable assistive devices have emerged (Shinohara & Wobbrock, 2011; Shinohara & Wobbrock, 2016).

Lee et al. (2020), found in their study that the perception of technological solutions depends on whether the users have direct or indirect experience with them and highlights that the former positively affects in a significant way the opinion of the users. Given the higher cost of conducting on-site user studies, they propose a mix of both on-site and remote user studies in order to better capture user opinion, thus, recommending a way that can potentially lead to a better adoption rate. However, Valipoor & de Antonio **(2022)** make the observation that the majority of user studies are performed by blindfolded sighted individuals instead of real blind or visually impaired ones. Therefore, this has the unfortunate consequence of evaluating the applications with a subject group where significant differences exist in the employed mental representations and as stated leads to a lower adoption rate.

Although a large portion of the research studies the reasons why users are reluctant to adopt assistive technologies, little has been done to explore the disregarded aspect of non-volitional causes contributing to abandonment. The high learning curve is an impediment to the adoption of new assistive technologies as the chance of failure is higher and people who are blind and visually impaired do not want to maintain the idea that they are somewhat less capable (Shinohara & Wobbrock, 2011). Furthermore, the research by Wessels et al. (2004) demonstrates that the time of acquiring the disability plays a significant role in whether an individual will use assistive technologies with the abandonment rates being higher among those who acquired the disability later in life, but acceptance rates being higher among those who accept their disability (Pape et al., 2002). Finally, reasons for the non-use of assistive technologies can be the result of excessive costs, lack of knowledge about advances in accessibility, or no interest in assistive technologies. Other reasons include the lack of personal access to assistive technologies, having no time or resources to learn how to use such technologies, technical knowledge deficiencies, or even satisfaction with current devices (Brady et al., 2016).

## 2.3. Training

From the above, it is evident that despite the existence of a plethora of different solutions and approaches addressing a wide range of technical challenges, all of them suffer from low adoption rates at best. This observation highlights the fact that purely addressing technical challenges is not enough when developing solutions for individuals who are blind and visually impaired. Since the ultimate goal is to effectively facilitate the lives of the target group, there is little sense in continuing to conduct research in the same way. We claim that a major component, often neglected, contributing to the low adoption rate is the lack of sufficient training but it is by no means the only cause. Our insistence on the latter is solely based on our conviction that training can produce the most promising results. Given that the widespread use of smartphone devices is not the ideal interface for the blind and visually impaired, training, preferably starting from a young age, will play a substantial role in reaching a compromising, yet realistic, solution to the problem of achieving the desired higher adoption rates.

For people to navigate the existing environment and understand what it has to offer, they utilize different navigational strategies that are based on having the appropriate knowledge. The former differentiates the strategies between allocentric that encode the location of the target as coordinates on a two-dimensional plane relative to the location of other objects, egocentric that encodes the coordinates of the target changes continuously relative to the axis of the target itself and beacon allow navigation from one object or place to another object or place without requiring from the target to have a representation of the space. The latter is organized and conceptualized into what is known as cognitive maps. Despite the existence of several different definitions (Kitchin, 1994), it is commonly used as an umbrella term for all mental representations (Hersh, 2020). Frequently, it refers to performing high-level spatial processing based on an all-encompassing representation of the environment with the goal to allow efficient navigation between places.

People who are blind and visually impaired also utilize cognitive maps and research reports that both the target group and sighted people have similar abilities to construct spatial mental models (Noordzij et al., 2006) and possess equal or higher localization capabilities (Afonso-Jaco & Katz, 2022). Localization, however, depends on the interpretation of auditory spatial cues having varying results and usefulness. As a result, it was considered that vision is an integral component of spatial cognition and perception and, therefore, its absence would substantially degrade the ability to form accurate spatial representations. However, from the performance of certain spatial tasks, it has been shown that visual experience is not a requirement for spatial mapping mechanisms (Giudice et al. 2011; Giudice et al. 2009). The argument for this case is that the differences in spatial abilities are not a result of vision loss but a consequence of lacking appropriate training skills, and access to critical navigational information as well as a result of an overprotective culture. Instead of considering visual loss as being a special condition affecting the blind and visually impaired, a more appropriate way to frame the problem would be to consider it as a different state of performing spatial tasks utilizing degraded visual or no visual information at all (Giudice, 2018). Furthermore, the research reports that these spatial models are detailed and accurate for at least some blind people (Jacobson, 1998), but the creation of cognitive maps for the target group depends on different types and amounts of information about the environment than sighted individuals require and usually takes more time when the method of construction is not based on locomotion (Afonso-Jaco & Katz, 2022). Another aspect emerging from these studies is that people with blindness prefer egocentric (based on body coordinates) over allocentric (based on exterior coordinates) frames of reference when elaborating mental representation of space over survey representations (Corazzini et al. 2010). The research of Thinus-Blanc & Gaunet (1997) has shown early blind individuals have at least the same or even better perceptual abilities than sighted individuals when the frame of reference is egocentric, but their perceptual abilities are significantly degraded when an allocentric frame of reference is required (Voss, 2016). Furthermore, it demonstrated that if an individual in the target group had any early visual experience, it would result in a better understanding of the external spatial coordinate system (Afonso-Jaco & Katz, 2022).

Central to the creation of cognitive maps is spatial learning. Specifically, the latter is the process where individuals acquire and integrate information about the environment into their cognitive maps, by establishing and refining knowledge about points of interest in the environment and their spatial relationships, such as navigational routes knowledge and configurational knowledge of landmarks and other POIs (Banovic et al., 2013). Existing research shows that likewise to sighted people, individuals with blindness and visual impairments utilize sequential route-based instructions when building mental representations of the environment (Thinus-Blanc & Gaunet, 1997; Millar, 1994). This process can be aided via the use of sensory substitution assistive solutions to support the independent spatial learning of individuals who are visually impaired. However, the creation of cognitive maps for the target group is difficult in comparison to those created by sighted people, as vision provides larger amounts and more precise information over other modalities based on non-visual information. Furthermore, another difficulty for the particular target group lies in their limited or absence of the ability to concurrently access both the constructed model and the information about the routes and the pertinent POIs (Thinus-Blanc & Gaunet, 1997; Bradley & Dunlop, 2005).

### 2.3.1 O&M skills

Overcoming the challenges already described in this and previous sections necessitates not only the use of assistive technologies but also the creation of an effective training method where these devices, in combination with the strategies the existing training methods employ, become a building block in the effort to construct the essential cognitive representations guaranteeing secure and independent navigation in the real world (Kayukawa et al., 2020). Therefore, navigation assistive technologies need to complement O&M skills. Orientation and mobility (O&M) are fundamental components of the spatial cognitive theory for individuals with blindness and visual impairments as it provides the support to efficiently and safely navigate and prove their worth mainly in familiar and unfamiliar environments (Long & Guidice, 2010). Orientation is defined as the state of the people of this target group having the capacity to understand their current location and find the correct path toward their intended travel destination. Specifically, it pertains to people's preferences involving information such as whether they want to visit a small room in close proximity or somewhere in a more distant location such as a shopping mall. Mobility, on the other hand, is defined as the state of the users having the capacity to move safely and efficiently from one place to another. Specifically, it frequently involves the use of public transportation and crossing streets among others guaranteeing safety (Kuriakose et al., 2022).

### 2.3.2 Factors to consider when developing training courses for the blind

Training individuals with blindness and visual impairments to use assistive technology is a costly and time-consuming process. Age, educational level, type and degree of impairment, and possible comorbidities are some of the factors that affect training. There are four types of information participants can learn about the environment and five factors that affect the type and amount of information required. The former classifies information into high-level information, safety, navigation and places including activities of interest as well, while the latter classifies the factors that affect the former into changes regarding the environment, user proficiency, navigation aids, frequency of visits and environmental familiarity (Banovic et al., 2013).

A suitable strategy for learning about the environment with systems that employ aural interfaces is the use of pull and push-based information. In the case of the former, the user actively requests information from the system in response to cues from the environment such as smells and changes in the physical layout of the environment or when in need to reorient themselves. However, an issue with this kind of information is that these cues are quite rare (Banovic et al., 2013). The latter case concerns information that the system emits to the user in response to an event and it is especially helpful in safe and content-rich environments. This information can be leveraged in the learning process for teaching the individual about new places and activities happening in the surrounding environment. In order to avoid creating new problems by masking critical audio events, push-based information needs to be regulated by the user of the system regarding the amount and frequency of the provided information.

Another factor to consider when developing courses is the adoption of a perspective that is less technology-driven. For a short period, some researchers asserted that people with disabilities should adapt to the assistive technology (i.e., training with the help of assistive technology specialists or caregivers), instead of the technology being adapted to the users (Kintsch & DePaula, 2002). However, this has poor results when it comes to adopting the solutions (Kane et al., 2009; Oliveira & Martins, 2011). Furthermore, likewise to many researchers, they have started to emphasize the user-centered perspective for developing simple, easily accessible, and user-friendly assistive technology (Abascal & Nicolle, 2005; Persad et al., 2007; Plos et al., 2012; Sutcliffe et al., 2003; Wobbrock et al., 2011), the same user-centered approach needs to be adopted for the design of assistive technology centric training courses. The fundamental concept of the user-centered perspective is to fully understand the users' needs; from this understanding, users are enabled to have satisfactory experiences with assistive technology.

Moreover, as has been shown by Rodriguez et al. (2017) it is important to conduct the training sessions in collaborative and not in private settings. Specifically, Rodriguez et al. (2017) revealed a frequent need for other people's assistance, despite the level of comfort with technology. It is worth highlighting that people benefit from explanations given to the person next to them; this knowledge was "contagious", spreading from one person to another, creating a collaborative learning experience. Naturally, there is a tendency for inexperienced users to organize around a sort of technology specialist. This person, quite often, is tech-savvy and motivated to explore and learn new technologies.

The exposure to similar doubts alongside the pace at which people were able to learn together revealed both an opportunity and a need to enlarge the support networks beyond their current reach. Currently, users are limited to relying on others for help, or searching online for answers, which is cumbersome, takes the user out of the context where the problem arose, relies on the user being able to describe his issue, and often will not produce any result. According to Rodriguez et al. (2017) people favor hands-on practice over listening to instructions from others, thus, preferring a more active style of learning. Helpful to the endeavor of training are sighted people and although they are seen as helpful resources, the majority of them are unaware of the difficulties faced by users utilizing screen readers. They often understand the processes required to complete a task but are unable to use accessibility services to complete those actions. That's why they should be trained to navigate and utilize the applications by themselves.

Finally, another factor that should be taken into consideration is to leverage the use of proprioceptive and kinesthetic cues as well to perform activities and help them stay oriented when in absence of methods for in familiar contexts and in the absence of visual, auditory, or tactile input (Job et al., 2022). Proprioception is the use of signals received from receptors in the muscles, tendons, joints and skin to perceive the position of the body in the environment. It has been shown that proprioceptive information is important in the performance of spatial tasks.

## 2.3.3 Virtual and Audio-Augmented Simulation Environments

### 2.3.3.1 Virtual reality in O&M training courses

People with blindness and visual impairments still rely on canes and other traditional navigational aids that are not helpful for developing orientation skills for larger scales or for route planning. Besides exposing the target group to the real world for acquiring spatial knowledge, there is the alternative of utilizing other sources like language, maps, or simulation via virtual environments. A common approach employed for the latter, in order to increase the target group's spatial knowledge (Connors et al., 2014; Picinali et al., 2014) is navigation through egocentric exploration via the use of 3D audio. The idea of a virtual environment that allows experiencing unfamiliar regions through actual walking while remaining in a safe, regulated setting has been proposed as a solution to the issue of acquiring O&M skills. Since the complexity of this virtual environment can be dynamically modified, it can be used to provide training scenarios of varying complexity ranging from simple to realistic settings (Kunz et al., 2018).

The first work highlights the success of integrating a virtual environment application into O&M training sessions for improving the O&M skills of individuals with blindness and visual impairments is (Lahav, 2015). The findings of this research demonstrate that the targeted group improved in performing orientation tasks in real space. Furthermore, the strengths of the proposed tool that utilizes virtual environments are threefold: a training simulator for O&M, a diagnostic tool for O&M specialists to track participants’ spatial behavior, and a technique for advanced exploration of unfamiliar spaces.

Guerreiro et al. (2020), studied the effect of using virtual navigation on building route knowledge and to what extent this acquired knowledge can be transferred to the real world. They found that during virtual navigation users were able to accelerate the learning process of short routes and gradually improve their knowledge of both short and long routes. Afterwards the users were able to transfer the acquired knowledge from virtual navigation to the real world and successfully complete unassisted navigation tasks.

An example of a system utilizing virtual route navigation is SpaceSense (Yatani et al., 2012). It allows users to navigate from a simulated location to a selected POI via emitting sequential turn-by-turn instructions. A special vibrotactile sensor mounted on the back of the phone provides feedback regarding the direction of and distance to the destination.

Yoshikazu Seki (Seki, 2015; Seki & Sato, 2011) developed an acoustic virtual reality auditory orientation system based on HRFT simulation to enable more efficient O&M training courses. The system allows the blind individual to walk through the virtual training environment safely by listening to various sounds and perceiving them three-dimensionally via headphones. In particular, the system supports four types of sounds including walls, roads, landmarks, and various other sound sources such as vehicles, stores, ambient noise and the like. It can reproduce simultaneously six sound sources and four ambient noises from every possible direction. The evaluation of the system revealed benefits for the blind and visually impaired. These are summarized as follows: 1) virtual training is more effective than actual training for walking while listening to ambient noises, 2) because virtual training is less dangerous than real training, it can lessen the stress that new learners feel, 3) both actual training and virtual training are equally effective in enhancing walking mechanics, and 4) virtual training is just as successful at reducing walking anxiety as traditional training. However, the main limitation of this system is its high cost.

Lindsay & Lamptey (2019) reviewed the best practices, most useful techniques and successful elements of 25 years' worth of training programs for young people with disabilities on safe and effective pedestrian mobility and public transportation. The work highlights that virtual and augmented reality, apps and personal digital assistants, and multimedia can be leveraged to improve skills in navigation, route learning and public transit. Specifically, interventions using virtual or augmented reality showed improved route learning, landmark recognition, and navigation skills while multimedia interventions showed improvements in navigational skills, pedestrian, and bus travel. According to the authors, even better results for traveling interventions can be achieved when the above are combined with the promising format of apps and personal digital assistants as research indicates the suitability of this format is able to improve route learning, wayfinding, and navigation abilities among normally developing youngsters more than paper maps can (Hergan & Umek, 2017). Lastly, an added benefit of apps and virtual travel training is that it takes less time and effort than adult supervision, which is necessary to train kids.

Lahav (2022), investigates how virtual environments affect individuals who are blind and visually impaired in exploring, creating cognitive maps, and carrying out activities requiring spatial orientation in real situations. The findings of the study demonstrated that multisensorial VR systems impact the same or even better spatial abilities of the individual when compared with exploring space in the real world. However, it does take some time before the user is able to quickly transfer spatial knowledge from the virtual environment to the real world. These findings emphasize the need for such an orienting tool, particularly when it is impossible to independently explore a new environment. Analogous outcomes were discovered in other VR orientation system studies (Bowman & Liu, 2017; Evett et al., 2009; Gonzalez-Mora et al., 2006; Guerreiro et al., 2020; Lahav, 2014; Lahav et al., 2015; Lahav et al., 2018; Max & Gonzalez, 1997; Merabet & Sánchez, 2016; Ohuchi et al., 2006; Seki & Ito, 2003; Seki & Sato, 2011; Torres-Gil et al., 2010). In the previously mentioned studies, participants could explore new environments on their own.

#### 2.3.3.2 Audio-based Virtual Reality Video Games

A rising in popularity approach concerns the use of user-centered audio-based computer games utilizing virtual reality. The argument for the adoption of this type lies in the fact that the remaining senses and especially hearing, see performance improvements, thus, constituting this approach as a foundational technique to efficiently rehabilitate and train individuals with blindness and the visually impaired for mobility, orientation and navigation skills.

The use of audio-based video games with virtual-reality-based environments forms a reliable training modality that helps blind people build solid spatial representation skills and cognitive maps as it motivates them to collect, process and transfer the acquired information from the virtual to the real world in an accessible and entertaining way (Balan et al., 2015). In doing so, they provide an engaging and interactive interface emitting continuously contextually oriented sound information with the aim to support a sensory thrilling experience for building cognitive spatial maps and improving orientation and mobility skills. Usually, the method followed in this type of games assigns to elements of the virtualized environment appropriate audio signals in order to differentiate their distinguishing features and create an immersive experience that promotes situational awareness. The latter is achieved via the use of directional cues that utilize different dimensions of sound (amplitude, pitch) to codify the current position of objects and the various spatial relationships (distance, elevation). This results in enriching the amount of information conveyed through sound and simultaneously enhances the 3D auditory perception.

Among the available methods in game-based learning, Merabet et al. (2009), demonstrate that the ludic-based approach is more efficient than other alternatives in learning to navigate in unfamiliar settings and transferring knowledge into the real world. Further contributing to this is the evidence provided by the literature that proves the effectiveness of immersive simulators in enhancing contextual learning for the development of mobility and orientation skills.

Both games and other forms of training employed in O&M sessions combine the knowledge of O&M specialists and present information to the students/users about landmarks and cues as reference points to locate specific targets. Landmarks play an important role in navigation as they can function as easily memorable decision points (Goldschmidt, 2018), and spatial learning around landmarks activates the hippocampal cortex which is known to be associated with spatial memory enabling navigation (Wang, 2022). After all, research shows that individuals with blindness and visual impairment as a consequence of the neuroplasticity process involved in the brain have improved brain regions responsible that affect decision-making activities besides having better navigational performance (Balan et al., 2015).

Audio-based games besides providing an excellent opportunity for supporting the training process can be leveraged in research of higher-level cognitive processes as virtual audio 3D rendering allows to flexibly reconstruct complex scenarios that would be difficult to orchestrate in the real world (Afonso-Jaco & Katz, 2022; Katz & Picinali, 2011).

Another advantage of understanding the overall framework of O&M is that it contributes to the design of more innovative travel aids for this target group of people that effectively enhance mobility, thus, highlighting the feedback loop between O&M training sessions and assistive technologies.

Although the combination of assistive technologies in the context of special O&M training courses can help for providing in situ support for route navigation and spatial learning, a feature that many individuals who are blind and visually impaired commonly request, it brings considerations regarding the burden of having to carry more things potential obstructing their senses. A concern that needs to be addressed is to find a way to minimally disrupt the target group’s hand interaction and comply with the current coping mechanisms in order to facilitate learning through sensing and touching **(Banovic et al., 2013)**.

### 2.3.3.3. Conclusion of training

Critical to the success of any O&M training process despite the use of innovative assistive technology solutions is the presence of well-educated O&M specialized instructors and of caregivers of individuals with blindness and visual impairment. Their task is to attend to the unexpressed desires of people who are blind and visually impaired in order to help them acquire orientation and mobility skills. Moreover, the instructor must always be aware of the fact that the available tools of every individual are determined by the surrounding social context. In that way, users can feel reassured and safe that they will develop the necessary orientation and mobility skills to cope with unanticipated events (e.g. low battery and the like) (Theodorou & Meliones, 2020a; Branham et al., 2017; Kane et al., 2009; Williams et al., 2014; Williams et al., 2013). Another area to pay close attention to is that both individuals who are blind and visually impaired and the entire community that supports O&M for the target group are unfamiliar with the plethora of available systems, their capabilities, and subsequently their usage in O&M sessions. As noted by Senjam et al. (2021), there is a need for guidelines for caregivers and other related professionals in recommending the correct assistive technology solution. This shortcoming was observed from our own experience when our research team created a custom-made training tool for individuals with blindness and visual impairments in order to become familiar with our proposed application in simulated conditions and scenarios, avoiding external hazards and guaranteeing their safety. Thus, future efforts should also aim at disseminating the results in more accessible mediums (forums and chat rooms) to the communities of blind and visually impaired and O&M instructors.

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# Chapter 3 (Content partially published in #1)

## Developing apps for people with sensory disabilities, and implications for technology acceptance models.

### 3.1 Introduction

The advance of 'smart' devices has been one of the defining characteristics of the 21st century, along with equally smart 'apps' that help people to carry out a wide variety of tasks. It is surprising, therefore, that little or no research appears to have been undertaken on the particular circumstances inherent in the take up of technology by people with disabilities. These include usability problems, where the devices or apps are not designed or have not been adapted for people who have particular needs, the extent and type of support offered (possibly of greater relevance to people with learning disabilities), and their differing needs.

This research focuses on the design and user acceptance of apps for people with significant hearing or visual impairments. On the basis of international statistics, blind people around the world amount to 36 million [1]. The largest proportion lives in poor and developing countries. Most of the blind population are young and at productive age. It follows that there is a demand for technological solutions aimed at improving the accessibility, self-service and autonomous living of the blind, contributing catalytically to social inclusion, promoting the educational and cultural level, independence in social and professional life, and upgrading the quality of life of the blind. In this context, large populations of blind are looking for autonomous navigation systems and therefore it is estimated that the proposed innovative application of autonomous safe outdoor blind navigation with excellent guidance accuracy will be readily adopted by blind people.

Turning to deaf and hearing-impaired people, it is estimated that around 466 million people worldwide have disabling hearing loss [2]. The largest proportion of them lives in poor and developing countries. Hearing is one of the five senses and is considered the second most important of the senses as it not only plays a dominant role in the communication of humans or animals but also helps one perceive external space, thus completing and complementing the function of sight. Therefore, the spoken word, which is the most important means of communication between people, depends directly on hearing. The loss or inadequacy of this sense creates a serious impact on our relations with our fellow human beings. People with deafness or hearing loss also face other serious difficulties in their everyday life involving the handling of simple actions such as using the phone, watching TV, and listening to the alarm or the horn of a car. Many times, they give the impression that they are slow in perception and understanding, with the result that they are subject to derogatory comments. Moreover, it has been claimed that deafness is the loneliest handicap of all.

Without adequate accessibility measures (signing for deaf people, or audio description for those with visual impairments) people with disabilities must overcome barriers such as:

(a) reduced exposure to new information, such as from TV news/radio broadcasts,
(b) reduced ability to participate in social networks, and
(c) difficulties using technology.

On the other hand, when it is suitably designed and configured, technology can be powerful, significantly improve access to information via various channels and provide access to culture and independence in social and professional life. In fact, it has the power to greatly facilitate social inclusion and the quality of life generally.

In this article, we provide recommendations for the appropriate adaptation of the Technology Acceptance Model [3] to the case where the user is sensory deprived. These recommendations are derived, in part, from a qualitative analysis of interviews which have been held with blind and visually impaired people.

## 3.2. The technology acceptance model

The TAM is a model that aims to explain why and how people would choose to use a particular technology. TAM was based on the Theory of Justification and was introduced by Fred Davis (1989). It is specifically designed to model the acceptance of systems and technologies by users. Davis's goal was to explain and predict the determinants of acceptance of these technologies that lead to an understanding of user behaviour across a wide range of computer technologies.

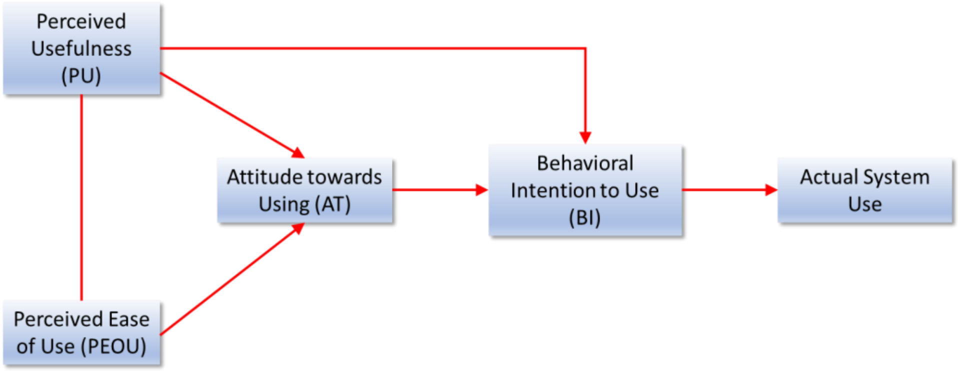

***Figure 3.1*** *Perceived usefulness and ease of use as determinants of actual system use: the first TAM [3]*

The basic TAM included and tested two constructs, Perceived Ease of Use and Perceived Usefulness. Perceived Ease of Use is defined as the degree to which a person believes that using a particular system will require no effort, while Perceived Usefulness is the degree to which a person believes that using a particular system will increase her performance at work [3]. Research to date has demonstrated the validity of this model, which is now widely accepted [4]. However, the first TAM did not include any social factors that play an important role in a person's attitude. For this reason, Venkatesh and Davis [5] proposed the second Technology Acceptance Model (TAM2), a modified model to offset the previous defect.

During the last decade, various models of technology adoption have also emphasized features that have an impact on the adoption of technology by people with disabilities. However, the negative social and psychological characteristics that impede the adoption of such technologies have not been studied by academic research.

### 3.2.1. TAM for people with disabilities

TAM explores technology acceptance factors but doesn't address the consequences of disabilities, such as those of visually impaired, blind or deaf people. For example, in the original (Figure 3.1) and updated (Figure 3.2) TAMs there is little regard paid to the influence of those who may act as 'gatekeepers' to the technology. Only in the updated model [6] is the influence of outsiders considered, but not in this regard (only a general 'social influence').

Our research focuses on the understanding of how blind or deaf people will accept and absorb the technological knowledge in order to take advantage of the very substantial potential benefits that may accrue in terms of independent living (self-navigation) and inclusivity (e.g., being able to better communicate with people who are not deaf). In particular, we aim to examine possible negative social and psychological features that may prevent technology adoption by these groups of people. Within this framework, we consider the influence and importance of adequate training for people with disabilities.

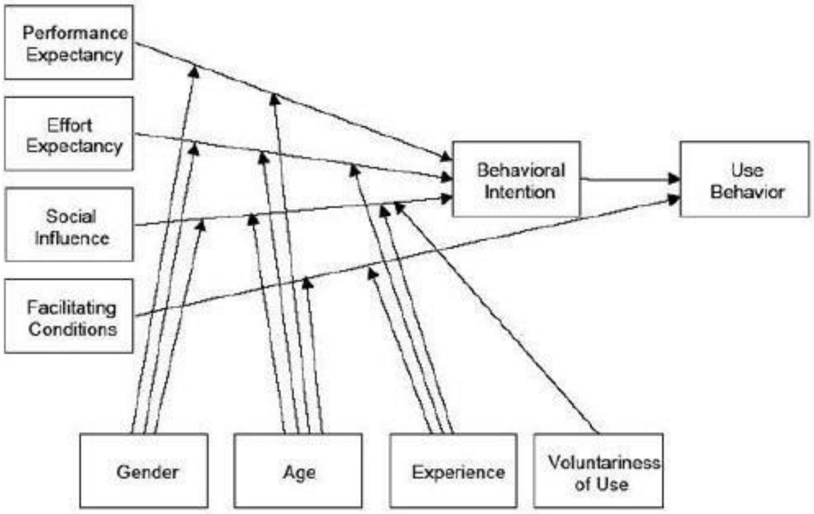

***Figure 3.2*** *Unified theory of acceptance and use of technology [6]*

## 3.3 Type of support facilitating usage

As later TAMs suggest [6], acceptance of technology by the target users themselves may be influenced by the social environment. In a major study, Eckhardt, Laumer and Weitzel [7] found that the adoption of Information Technology in the workplace was significantly influenced by 'referents' such as colleagues and line managers. However, TAM has not, to date, considered the influence of close family members, friends, or even teachers and trainers, who may facilitate access to technology by the individual. Although people with physical impairments may not be disabled in terms of their critical thinking or intelligence, nevertheless, their impairment may mean that the role of these 'significant others' assumes greater importance than might otherwise be the case. A blind person, for example, may require a greater degree of training in order to be able to use an 'app' (which itself may need to be reconfigured).

The research reported here can be also viewed as the first part of an exploratory study of this issue, because it accrues qualitative evidence from the potential users, to explore the factors which influence TAM-elicited issues such as 'perceived usefulness', 'self-efficacy' and, of course, the role of 'social influence' in general. Opinions are sought to elicit the reactions of the target users in order to (a) help identify the unique circumstances and situations of the target population and (b) help tailor training methods designed to obviate usability problems, enhance potential users' views, both on the usefulness of the apps and on their own self-efficacy (the latter referring to the abilities they perceive themselves as having in order to use the technology).

## 3.4 The apps

A series of assistive apps for people with disabilities is being developed by our research team. Two examples are described in this research; one app aims to help blind and visually impaired people to travel safely, and the other to help deaf and hearing-impaired people communicate.

Blind RouteVision is being designed to facilitate the pedestrian navigation of blind people outdoors. It will have GPS functionality and utilise the Google Maps service for navigating, but with additional voice prompts and an ultrasound sensor for real-time recognition and avoidance of obstructions along its path. It will also contain

(a) a simple keyboard for the interaction of blind people, to enable them to select routes and other available functions,
(b) application synchronisation with traffic lights and weather information, and (c) (c) the utilisation of information telematics of the Athens Organisation of Civil Transport (OASA) for routes and urban transport stops.

The second app offers deaf people a user-friendly environment for automated text depiction of the user's verbal speech. Speech recognition is a mature technology which specifically refers to translating spoken language into text. All modern OS platforms include speech-to-text tools. However, these do not necessarily work for the hearing impaired. Indeed, they are not designed to do so. Special requirements have to be considered when offering a specialised real-time speech-to-text transcription device addressing the hearing impaired. This is because the articulation of deaf people is often idiosyncratic, with a wide variation of pronunciation styles and unusual intonation. The SeeSpeech application is designed to take these into account when processing the speech and rendering it to text, to still give an accurate translation of the speech (see [8] for a first and simple implementation).

SeeSpeech will also implement an interface for a simple dialogue with a deaf or hearing-impaired person in different languages, doing so by integrating two Application Program Interfaces for transforming speech to text. Another key feature of the application is the ability to register sound from an external Bluetooth microphone. This makes SeeSpeech a very competitive application in the arena of similar scope applications.

## 3.5 Method: elicitation of user requirements

During the development of the apps, qualitative research is carried out in the form of user needs and requirements analysis. For reasons of economy, we focus on how we have been undertaking this analysis with respect to the requirements of the blind and visually impaired people. For the precise identification of the problems and preferences, as well as the specific characteristics of this particular cohort, the requirement analysis was conducted based on interviews with members of this community. Next, we present a synopsis of preliminary interviews.

### 3.5.1 Interviews with blind and visually impaired people

The interviews were undertaken with a small but highly knowledgeable and articulate sample of three experts: These were (a) the Head of the famous Greek institute 'Lighthouse of the blind' (male) who is blind, (b) a teacher (male), also blind, of the Braille system for reading and writing who also teaches blind people how to use new technologies such as smartphones and (c) a visually impaired museum guide (female) for blind people.

Questions concerned both those which placed the Blind RouteVision app into the context of people's general use of digital technology and those related more specifically to the future functionality of the app. Later interviews will be undertaken after the trial of the app, seeking feedback from users and their views on how the following iteration of it. The interviews outlined below were undertaken before interviewees were shown a prototype of the app itself. This was so they would not be influenced by its functionality or appearance. As the interviewees were experts in the field and had considerable experience in being and working with others in the same situation, the questions did not only relate to them as individuals but to their knowledge of other people's experiences. Later, when a large number of users will be involved, the focus will be more on themselves.

Contextual questions concerned:

- Familiarity with pre-existing apps and software (e.g. Google maps for navigation with voice prompts) and whether they are easy to use.
- Use of particular hardware/devices.
- Use of headsets, experiences of how ambient sounds are rendered, and the type of the headset (a preference for Bluetooth or cable).
- Questions relating to the development of the app included:
- How a keyboard should be configured.
- How sounds should be used to signify obstacles (e.g., continuous sound increasing frequency and interrupted sound).
- Optimum navigational menu options.
- Preferences regarding the synchronisation of the app with traffic lights (the developers recommend that it be centralised through the traffic management system, so it does not require each traffic light to be equipped with an audio signal).

## 3.6. Results from the analysis of the interviews

Each interview was recorded, and the answers were compared, classified into categories and analyzed. The results of the analysis identified the following main issues with respect to apps' ease of use and usability by blind and visually impaired people, classified into the following requirements:

(a) application requirements (detection of obstacles, navigation, adaptability and change possibilities, notification of a person of confidence about the position of the BVI),
(b) functionality requirements of applications and devices (maintain external stimuli separate, complete and seamless voice and sound interaction between the BVI and the app, enhanced positioning accuracy),
(c) usability requirements (user-friendly device and application features, simple handling and voice function),
(d) requirements concerning the learning process (these are many and varied, and include the physical environments – places where all aspects of the apps may be tested, and safely – and also methods and materials with regard to teaching and promoting the app) and

(e) compatibility requirements and parallel operation of project applications with other applications and screen readers.

## 3.7 Discussion

The acceptance of mobile services is a gradual process [9] which involves understanding the benefits offered by these services before their acceptance and systematic use by the majority within a target group. In general, the development of smart apps does not take into account the particular requirements of people with special needs, especially of the BVI [10]. Even in the case that an app is specially designed for sensory-deprived people, there is no such extension of the TAM, which is adapted to their needs and requirements with respect to assistive mobile apps.

In this study, a first step is made towards filling this gap in the literature. The main interest, however, in the results of this study is not theoretical. By means of our qualitative analysis, we showed that people with sensory disabilities are more demanding with respect to the design of assistive apps. Moreover, the classification of user needs and requirements, presented in Section 6, forms a framework for the appropriate adaptation of the TAM so that it can meet the specific needs of sensory-deprived people. The next section provides recommendations with respect to the design of a TAM which will be adapted to people with sensory disabilities.

## 3.8 Recommendations

The findings reported in the previous sections highlight the importance of understanding the special needs and requirements of people with sensory disabilities. Specifically, it was identified that factors such as the interaction of the app with the environment and the location where the app will be used may increase the difficulty of acceptance of the corresponding technology by its potential users. It was also identified that details concerning specific features of user interfaces are much more important to sensory-disabled people. These features must be designed considering the elicited requirements of the app target group.

A TAM which aims to be applied to people with sensory disabilities must be adapted to the following two factors:

(a) the increased sensitivity of these groups of people to particular needs related to their disabilities and
(b) the corresponding psychological patterns which stem from the insecurity caused by the disability.

The interviews with the blind and visually impaired people provided support for the significance of these two factors. A good example of the first factor is the requirement of the BVI that sounds of the surrounding environment must not be covered by the sounds generated by the app. As far as the second factor is concerned, it is interesting that the BVI felt reluctant to try learning the assistive navigation app for the first time in an environment not familiar to them, although a big part of the functionalities of the app concerns unknown environments.

Furthermore, the interviews revealed that people with sensory disabilities probably feel much more attached and dependent on assistive apps that they are already using. This fact was highlighted by the emphasis all the interviewees gave on how the assistive app will be compatible with other services or apps they are often using (such as screen readers). This remark implies that the TAM for people with sensory disabilities must consider the assistive apps and services which are already used by the target groups.

## 3.9 Conclusion

In this article, we described the results of user requirements analysis concerning assistive apps for people with sensory disabilities. Specifically, it described how the process of development of two innovative apps for people with visual and hearing impairments involves the identification of these groups' particularities with respect to technology acceptance, and consequently, the corresponding adaptation of educational and training methods. Therefore, the implementation of these apps will be undertaken with a view to enhancing their acceptance, according to an enhanced TAM that takes into account the specific circumstances of people with disabilities. This approach focuses on the social value of the tools, achieved by adopting empathy and real interest for the users and those who support them. In this way, one can see the apps through users' own criteria for usability, usefulness and understanding of how attitudes towards technology are shaped.

It is hoped that the further development of the apps described above, considering user needs and wishes, will enhance technology acceptance of the 'end users' (the people with disabilities). Their contributions – and indeed their attitudes and whole approach to using the apps specifically, and digital technology generally – will inform in more detail how the TAM should be applied to the particular group in order to formulate a best practice for the acceptance of the relevant technologies. The research in this area has yet to be undertaken – full-scale tests of usability and practicability are to be carried out, and appropriate feedback is accrued to inform the extent to which the technology is being accepted. In addition, no previous research has been carried out to investigate the acceptance of 'Assistive Technology' by supporters, such as, for example, teachers in schools or more generally in other support structures for visually impaired or hearing-impaired people. This will be captured in a modified TAM which should inform anyone attempting to improve the lives of people with disabilities, through the use of technology.

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# Chapter 4 (Content partially published in #2)

## Human–Machine Requirements’ Convergence for the Design of Assistive Navigation Software: The Case of Blind or Visually Impaired People

**Keywords** Autonomous navigation, Artificial intelligence, Blind and visually impaired people, Assistive navigation software, Requirements analysis

## 4.1 Introduction

Autonomous navigation has been a difficult problem for traditional vision and robotic techniques, mainly due to the noise and variability associated with real-world scenes. Autonomous navigation systems based on traditional image processing and pattern recognition techniques often perform well under certain conditions but have difficulties with others. Part of the difficulty stems from the fact that the processing carried out by these systems remains fixed in a variety of driving situations [1].

Autonomous navigation of a unit, being either a human, a robot or a vehicle relies on processing sensor and dynamic map data to derive guidance information. As far as non-human units are concerned, the necessity of employment of artificial intelligence.

(AI) was early enough identified (see [2] or [3], among others) due to the complexity of these operations and the high safety and accuracy requirements (see also [4, 5] for a recent review and survey of contemporary practices on the impact of AI on autonomous vehicle safety).

More than thirty years after Treder [3], the rate of deployment of efficient AI-equipped units which are capable of autonomous navigation is still slow. However, the benefits from the use of such devices have attracted the attention of many of the biggest technology companies worldwide during the last decade (see e.g. Amazon prime air [6], Uber’s self-driving car technology [7], Tesla autopilot [8], Google, Apple, etc.), boosting the privately funded research on this topic. This research has already led to the production of cars, unmanned aerial vehicles (UAVs) and robots equipped with features that enable restricted forms of autonomous or semiautonomous navigation.

Although the funds directed to research concerning autonomous navigation are continuously increasing, the complexity of the task along with the reasonably high safety and efficiency requirements reveals that the current status of AI and system control technology is still not adequate for the commercial deployment of units capable of multi-purpose autonomous navigation. A look, however, towards the near future, should not ignore already existing technologies that are yet to be deployed (such as 5G), which will enhance significantly critical requirements of autonomous navigation, such as interconnectivity, positioning accuracy and obstacle detection. At the same time, the capabilities of AI are expected to be continuously improving, along with the available data for applications of deep learning procedures.

Autonomous Navigation Technologies, however, do not concern only artificial units, such as cars, UAVs, field robots, etc. It is also a very significant issue for certain groups of people, such as the blind and visually impaired (BVI). In particular, this is a case where human intelligence is obliged to overcome the barrier caused by the impairment of the most significant human sensory ability concerning autonomous navigation, namely, the vision.

Navigation is the acquisition and use of spatial knowledge in order to determine a movement through a physical or virtual environment, along with the movement itself. This is a fundamental aspect of our cognitive range of perception [9]. The purpose of the navigation system is to provide users with the required and/or helpful data to reach the destination point and to monitor their position in previously modelled maps [10]. This task becomes very difficult or impossible without assistance from either sighted people, guide dogs, or technology solutions. Consequently, the ability of the BVI to use public spaces, including urban areas, transport systems and public buildings is reduced [11], except reliable, usable, safe and cost-effective technological solutions are discovered for both outdoor and indoor guidance needs.

## 4.2 Related Work

Given the advances in the fields of mobile technologies, software and communications during the last two decades, there is an increasing demand for technological solutions aiming to assist the BVI towards autonomous navigation. The adoption and use of such solutions would improve accessibility, self-service and autonomous living, upgrading significantly the quality of life of the BVI. Various assistive mobile apps that aim to contribute to the autonomous navigation of the BVI are already available. Apps that offer improved GPS functionality, such as Loadstone GPS [12], Mobile Geo [13] and Seeing Eye GPS [14] offer enhanced positioning accuracy in order to assist the BVI during pedestrian navigation, while apps such as BlindSquare [15] inform the BVI about points of interest during outdoor navigation.

Academic research has also been focusing on the requirements and the development of systems that assist autonomous navigation of the BVI in outdoor environments (see, e.g., [16–18], in interior spaces [19–23], etc.) or in both [24]. None of the corresponding solutions, however, is widely adopted by the BVI according to Giudice and Legge [25], and the demand for autonomous navigation systems specially designed for the BVI is increasing. This is also verified by the discussions during the interviews concerning our research with the BVI. Part of the explanation may be due to a disconnection between engineering factors and a system's perceptual and practical usefulness, which means that a product may be theoretically effective but may not work in reality for the intended consumer who adopts this navigational technology [25].

BVIs now can use general navigation applications through accessibility functions, but the acceptance of mobile and location-based services is a gradual process [26]. It involves understanding the benefits offered by these services before their acceptance, and systematic use by the majority within a target group. In general, the development of smart apps does not take into account the particular requirements of people with special needs, especially of the BVI [27]. Even in the case that the app is designed especially for the BVI (see Csapo et al. [28], for a survey of assistive mobile apps for blind users), several features that facilitate the BVI to learn how to use the app are missing.

Assistive navigation apps for blind people are good examples where the familiarization process with the app depends on access to specific locations (see Meliones and Sampson [23], among others). This problem directly affects the rate of technology acceptance of the BVI concerning smart app use. Interestingly, however, little or no research appears to have been undertaken on the inherent particularities in the take-up of assistive navigation software by the BVI.

A necessary step in the development process of autonomous navigation software is that of the elicitation and analysis of the requirements of the potential users (where, in the broader sense, the user may be an AI unit). We aim to draw parallels between the requirements of sensory-deprived human intelligence (the BVI) and AI-equipped autonomous units with respect to autonomous navigation. This is achieved using data collected from interviews with members of the BVI community. Specifically, the answers of the BVI are classified into four main, characteristic requirements categories which are further divided into eight sub-categories (a part of the final requirements of the whole project). Then, for every elicited requirement of the BVI, it is examined whether the consideration of a corresponding requirement for an AI-equipped unit is reasonable. This procedure also allows us to identify requirements that correspond to the "human nature" of the BVI, with respect to the current status of AI robots or autonomous vehicles. Finally, the possibility of convergence of requirements that stem from human and artificial intelligence is examined.

The rest of this chapter is organized as follows: Next section describes the structure of the interviews, as well as the characteristics of the BVI participants. The same section presents the classification of the requirements, as it was derived by an analysis of the answers of the BVI. The third section presents the analysis of the elicited requirements with a particular focus on the requirements that seem compatible with the current status of mobile AI units. The section also includes a discussion about the possibilities of convergence between AI and human requirements in the cases where AI evolves towards a human-like intelligence or not. The last section concludes the chapter.

## 4.3 Methodology

### 4.3.1 Interviews with BVI People and Requirements Classification

A user needs and requirements analysis has been conducted during the initial phase of the development of two assistive mobile apps for autonomous navigation of the BVI by our research team. These assistive apps are being developed within a project entitled "MANTO" (funded by the Greek RTDI State Aid Action RESEARCH-CREATE INNOVATE of the National Operational Programme Competitiveness, Entrepreneurship and Innovation 2014–2020 in the framework of the T1RCI-00593 contract). The first mobile app (Blind RouteVision) aims to assist the BVI during outdoor pedestrian navigation. The app's design includes enhanced GPS functionality and interconnectivity with other apps that may be useful during navigation, such as the corresponding service of Google Maps. The app is a part of an assistive navigation system which includes ultrasound sensors for real-time recognition and avoidance of obstacles along the BVI's path, synchronization with traffic lights and weather information, and utilization of information telematics of the Athens Mass Transit System (AMTS) for routes and urban transport stops. The initial version of the Blind RouteVision system is presented in [23]. The smartphone application and its supportive external components consist of the aforementioned system for outdoor interactive autonomous navigation for BVI (see Fig. 4.1).

*Figure 4.1. Blind RouteVision outdoor navigation—advanced field navigation sensor*

The second mobile app concerns autonomous blind navigation in indoor spaces. Since GPS is not reliable for indoor positioning, the app is supported by a highly accurate indoor location determination subsystem which includes accessibility mapping of indoor spaces with overlays of the positions of points of interest (POIs) (see Fig. 4.2). Moreover, Bluetooth beacons are used as proximity sensors and location indicators. The app will inform the BVI about his/her relative position of POIs and will use dynamic issuing of voice navigation instructions towards POIs considering the current position of the BVI. Blind IndoorGuide inherits the features of the Blind MuseumTourer system, a system for indoor interactive autonomous navigation for blind and visually impaired persons and groups (e.g., pupils), which has primarily addressed blind or visually impaired (BVI) accessibility and self-guided tours in museums, as they are presented in [23]. Blind IndoorGuide aims to extend the functionality of the Blind MuseumTourer beyond the case of museums. The conceptualization of the Blind IndoorGuide is discussed in [23].

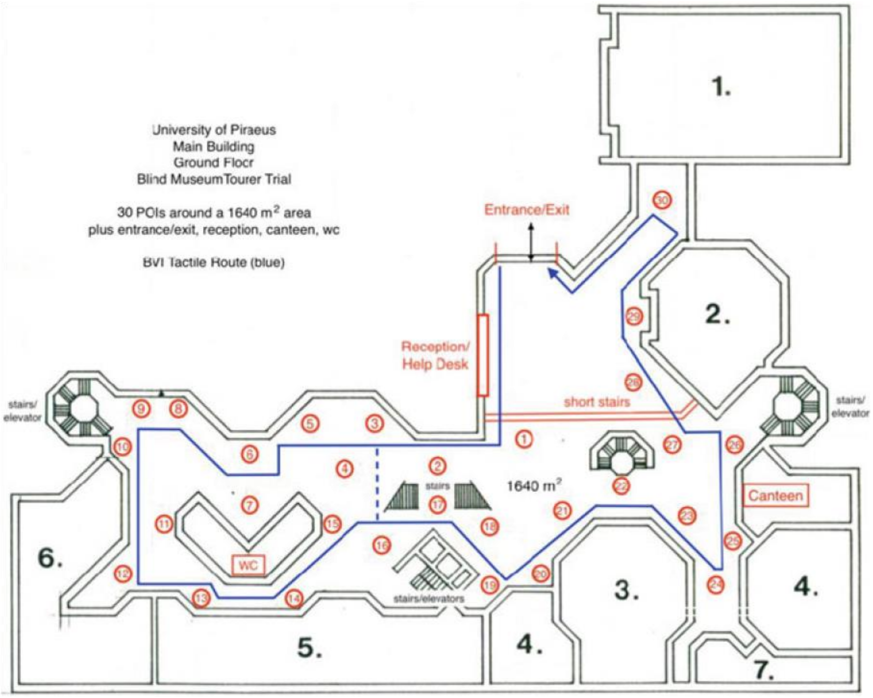

*Figure 4.2. Blind MuseumTourer indoor navigation and guidance system preliminary*

### 4.3.2 Description of the Participants

In this section, we present the setup of the interviews with the BVI, which were conducted to determine the user needs and requirements for indoor and outdoor navigation assistive mobile apps, but also psychological characteristics and practices (preferences, habits, facts) that are related to their impaired vision (see also[29]). The interviews were conducted at the premises of the Lighthouse for the Blind of Greece, which is the main non-profit organization for education and assistance of the BVI in Athens. Thirteen male and female members of the BVI community participated in semi-structured interviews. Their vision problems ranged from severely impaired vision to complete blindness, according to self-report. Each interview lasted at least 45min. The descriptive characteristics of the interviewees are presented in Table 4.1.

The number of participants not only appeared to be in line with the literature on qualitative research (Guest et al. [30], and Adu et al. [31], including that concerning people with visual impairments, Wolffe and Candela [32], Kane et. al. [33] and Guerreiro et. al. [34], among others) but also proved, in practice, adequate because data saturation appeared to be already reached before the last interview.

Now we turn to the methodology for deriving the classification of the BVI and the creation and analysis of the requirements. We validated this classification by

Table 4.1 Characteristics of the BVI who participated in the interviews

| | Gender | Age | Degree of vision loss | Cause of vision loss | Digital sophistication |
|---|---|---|---|---|---|
| P1 | Male | 55 | Complete | By birth | High |

| | | | | | |
|---|---|---|---|---|---|
| P2 | Female | 35 | Severe | By birth | Average |
| P3 | Male | 36 | Complete | Diabetes | High |
| P4 | Male | 40 | Almost complete (95%) | By birth | Low |
| P5 | Male | 40 | Almost complete (95%) | By birth | Low |
| P6 | Female | 55 | Complete | Retinopathy (23 years old) | Low |
| P7 | Male | 40 | Almost complete (90–95%) | By birth | Low |
| P8 | Male | 40 | Complete | Cancer (7 years old) | Low |
| P9 | Male | 35 | Almost complete (>95%) | Benign tumor (15 years old) | Low |
| P10 | Male | 60 | Complete | By birth | High |
| P11 | Male | 30 | Complete | By birth | High |
| P12 | Male | 40 | Complete | By birth | High |
| P13 | Male | 38 | Almost complete (90–95%) | craniocerebral injuries at 23 | High |

conducting a pilot study with two BVI interviewees who were specialized and experienced in the field, with whom we created the questions and the thematic axes, a large part of which are listed in Table 4.2. The whole classification and its subcategories are listed and fully described in [35]. We identified a subset of these requirements, to which the corresponding requirements of AI devices may converge, as the

Table 4.2 Classification of the requirements of the BVI for assistive navigation apps

| | | |
|---|---|---|
| 1. | Requirements concerning usefulness and capabilities | a. Obstacle detection |
| | | b. Navigation |
| 2. | Functionality requirements | a. Navigation |
| | | b. Navigation |
| | | c. Navigation |
| 3. | Usability requirements | a. Characteristics/features of apps and devices |
| | | b. Device handling |
| 4. | Compatibility and parallel operation with other apps | a. Compatibility and parallel operation with other apps |

capabilities of the devices increase. Indicative quotations from some of the 13 participants are provided close to the following requirements classification. Additionally, the questions asked during the interview are given in supplementary material.

### 4.3.3 Requirements Classification

Next, we present the subjects which were discussed during the interviews with the BVI. First, the participant introduced herself or himself. During this part of the interview, BVI people were asked about characteristics such as age, degree of vision loss, cause of vision loss and age at which this occurred. They were also asked whether they were employed and, if this was the case, to describe their job. They were also asked about how familiar they feel with digital apps. Then, the section of the interviews included a presentation of the features and capabilities of the apps as they were initially conceptualized by our research team. Finally, a discussion followed, which included specific questions concerning the BVI's indoor and outdoor navigation habits. During this section of the interview, the BVI were asked specific questions about their preferences and requirements that would ideally lead them to adopt and efficiently use the apps. These questions concerned requirements about the usefulness and capabilities, functionality and usability of the apps. They also had suggestions concerning the compatibility of the apps with other apps and services they had already been using.

The initial design of the interviews, along with the feedback from the answers and suggestions of the interviewees led us to a classification of the subjects of interest with respect to the design and development of assistive mobile apps for the BVI. The interviews with the BVI were recorded on paper. Their answers, suggestions and comments were then classified into four main categories, namely, requirements concerning the usefulness and capabilities of the apps, functionality requirements, usability requirements and requirements concerning the compatibility and parallel operation of the apps with other apps and services. These categories were further divided into subcategories as presented in Table 4.2.

The first category includes the requirements concerning the usefulness and capabilities of an assistive navigation mobile app from the BVI perspective. The structure of the interviews allowed the interviewees to focus on the issues that they find more important. Specifically, we observed that the main subjects of interest in BVI people can be classified into two subcategories: (a) Obstacle detection, and (b) navigation. The second category includes the functionality requirements, as the BVI perceive them. Again, we identified three sub-categories: (a) requirements concerning the treatment of external stimuli, (b) requirements about the way sound (or voice) could be used to facilitate the interaction between the BVI and the smartphone (or the app) and (c) requirements about the accuracy of tracking and the devices that could be used to improve it. The third category concerns the usability requirements of the apps and interconnected devices. Apart from the first sub-category which concerns the characteristics or features that a BVI requires from the assistive navigation apps and devices, it is of special interest to identify the optimal way of handling the smartphone (the apps) and interconnected devices. Finally, the BVI showed particular interest in the way the assistive apps will seamlessly collaborate with the usual apps a BVI uses, for example, screen readers and web mapping services.

The left column of the classification presented in Table 4.2 is abstract enough to be adapted in a framework of an AI requirements analysis concerning autonomous navigation software. It can be observed however that subcategories 2.a, 2.b, 3.a and 3.b of the fine classification (second column) are significantly related to human– machine features for the case of the BVI. Part of the analysis of the requirements of the BVI in the following section focuses on the identification of which of them may be compatible with possible requirements of AI-equipped autonomous moving devices.

## 4.4 Analysis of the Elicited Requirements

This section presents in detail the elicited requirements of the BVI concerning assistive mobile navigation apps. It also identifies possible links and differences between these requirements and the ones of AI-equipped autonomous moving devices. Finally, it concludes with a discussion concerning the possible human–machine requirements convergence under the prism of two main directions of the evolution of AI in the near future.

### 4.4.1 Elicited Requirements of the BVI

An important qualitative advantage of a designer of navigation software for the BVI with respect to the corresponding one for autonomous vehicles or moving devices is the possibility of conducting interviews with the BVI. The material collected from these interviews can be classified as remarks, preferences and suggestions of the BVI that are related to their human substance (including psychological characteristics and ambitions) and to those that are mainly related to the specific task of autonomous navigation. This subsection mainly focuses on the latter class of requirements which exhibit direct or prospective convergence with the corresponding requirements of AI devices.

#### 4.4.1.1Requirements Concerning Usefulness and Capabilities

In this subsection, the requirements concerning the usefulness and capabilities of assistive navigation applications and devices are presented, as they were elicited from the interviews. These requirements have been classified into two sub-categories.
These are the following: (a) object/obstacle detection, (b) navigation.

a. Object/Obstacle Detection

- The software should be capable of simultaneously processing sensor signals concerning multiple obstacles and reporting them appropriately. (P3: "It should be possible to simultaneously detect multiple obstacles and report them appropriately, guiding the BVI to manoeuvre with precision.", P8: "It is a problem to have obstacles at a different height at the same time, so there should be the adequate ability to identify multiple obstacles and to properly inform the BVI user").
- Sensors should be able to detect obstacles at different heights. These obstacles may not be ground-based like signs sticking out from buildings. The sensor data should be capable of providing height information, and the software should be able to interpret this information in specific directions. (P3: "The sonar should be able to detect obstacles that are relatively high and not only ground-based in front of the BVI, such as low balconies, awnings, signs, etc.", P1: "The sonar should be capable of scanning both horizontally and vertically").

b. Navigation

- The software should be capable of identifying traffic lights and interpreting their status. (P3: "The app should be able to identify the traffic lights on the streets, as well as their status").
- The software should be able to identify possible threats to the unit even when traffic lights do not allow motion. In other words, the stream of data from the sensors should be continuously processed and the correctness of the units' path and speed should be continuously validated. Safety is a prior requirement and its maintenance should not be threatened at every point of the route. (P1: "When the app notifies the BVI about the status of a traffic light, it should be able to identify the danger that may arise from a driver who does not follow the signal of the traffic light.", P1: "It must be possible to identify the danger at traffic lights even when the application has correctly stated that the blind person should proceed.", P7: "The maintenance of the software should be frequent, while adequate control systems should report any malfunction in real-time.", P11: "In order that such a system functions properly, regular maintenance of the communication systems must be provided. Moreover, appropriate control and information systems or processes should be used to promptly identify any hardware malfunction").
- The software should be swift at detecting a wrong route and correcting or adjusting it accordingly. (P2: "The app should be possible to detect a wrong route and to correct or adjust the route in case of deviation from the selected path").
- It is desirable that the software could manage multiple destinations or stops and continuously optimize the route. (P3: "It is desirable to be able to add multiple destinations or stops along a route").

#### 4.4.1.2 Functionality Requirements

This subsection presents the elicited requirements concerning the functionality of mobile assistive navigation apps. These requirements have been classified into three sub-categories. The first (sub-category a) concerns how the apps and the peripheral devices should react to external sounds, while the second (sub-category b) includes requirements concerning the interaction of the BVI with the device through voice commands and directions, as well as through other types of sounds. Finally, the third (sub-category c) corresponds to requirements concerning the accuracy of tracking and positioning of the navigation system (app and auxiliary devices), as well as functional requirements of the auxiliary devices.

a. External Stimuli

   - The software must be able to deal with noisy data from the sensors. As far as the BVI are concerned, this also include the case where external sounds interfere with the voice interaction with the mobile app. (P1, P3: "The ambient sounds should not be covered by the sounds produced by the app because the BVI always use their hearing in order to perceive the surrounding space. Therefore, the use of a headset that covers both ears is excluded from the implementation of the assistive navigation system. One ear should be able to hear the sounds of the surroundings").
   - Only important cell phone information should be reported phonetically in order not to cover or suppress the ambient sounds. It seems difficult to claim that for an AI moving unit a similar requirement holds. (P1: "Only important cell phone information should be reported phonetically, and ambient sounds should not be depreciated or covered").

b. Sound (or Voice) BVI-Smartphone (or App) Interaction

   This sub-category corresponds to requirements that are related to the human nature of the BVI, and mainly to the fact that they substitute their vision with hearing during their interaction with the apps.

- The app should offer voice menus of the key destination options. These options must be able to include combined pedestrian navigation and the use of other means of transport. (P1: “Voice guidance is preferable to audio”, P1: “Combine pedestrian route and public transport (voice reporting of basic options).”, P4: “The app should provide voice reporting of key route identification options that may combine pedestrian navigation and Mass Public Transit (MPT) use”).
- The app must provide an audio signal for the traffic lights. (P1: “It is necessary to have an audio signal on the traffic lights (the blind should not be left without audio information)”).

c. Tracking and positioning accuracy and auxiliary devices

- GPS and sonar amplifiers should be discreet and not too obvious. Of course, the geometry of a machine allows easier incorporation of such amplifiers. (P1: “It takes a great deal of precision in positioning. When it comes to using a GPS precision amplifier, this should be discreet and not too obvious. There is a general problem with GPS accuracy”).
- Positioning accuracy must be high (at least at the centimetre level). (P1, P6: “Positioning accuracy should be as high as possible”).
- Any sonar or GPS device must refresh the information it provides at high frequency because some BVIs can move at a fast pace (the same would also be the case for AI-equipped units). (P1: “About sonar for obstacle detection: Some of the BVI move very fast, especially the elderly. Ideally, the frequency of refreshing information transmitted by the sonar should be at least once every 1 s”).

#### 4.4.1.3 Usability Requirements

This subsection presents the elicited requirements concerning the usability of mobile assistive navigation apps. These requirements have been classified into two subcategories. The first (sub-category a) refers to the special characteristics and features of the apps and the peripheral devices that the BVI would wish to have, while the second (sub-category b) concerns device handling requirements.

a. Characteristics/features of apps and devices

As in subcategory 2(b), some usability requirements of the BVI are not compatible with the navigation software requirements of a machine.

- The BVI showed a preference for simple, easy-to-learn keyboards or pads. (P1: “The user interface on the touch screen must operate with clear and simple gestures. Keyboards are also useful”).
- Because cables are often entangled, BVIs prefer to use Bluetooth headphones. (P1, P3: “Bluetooth headphones have the advantage that they do not have cables which may become entangled. On the other hand, they are more easily lost and they require to be changed often”).

b. Device Handling

- The software should be easily integrated or interconnected with the user. Concerning the BVI, this corresponds to their ability to set the destination on their own. As far as an AI machine is concerned, this would imply seamless communication and connectivity with the navigation software.

- Concerning outdoor navigation, it would be desirable that the software provides an editable list of "favourite" destinations. (P7, P12: "As far as outdoor navigation is concerned, it would be ideal for the app to include a list of 'favourites' (or preferred) destinations to be edited by the BVI").
- The BVI should have the ability to dictate the destination address. The ability of phonetical exchange of commands and information between AI-equipped machines is currently a very interesting research topic. (P1: "The BVI should be able to set the destination on their own (the independence of the blind is very important). It is preferable for the blind to be able to dictate the destination address on the device and to have voice navigation in the search menu").

#### 4.4.1.4 Compatibility and Parallel Operation with Other Apps

This subsection presents the elicited requirements concerning the compatibility and parallel operation of the assistive navigation mobile apps with other apps or services.

a. In general, the software should be able to run in parallel with other applications (such as screen readers, in the case of the BVI). (P2, P3: "Allow other applications (e.g., screen reader) to run in parallel with the navigation application").
b. It would be useful if the software could interconnect/collaborate with an application that describes images. (P4: "It would be very useful if the navigation apps could cooperate with image recognition apps that describe images, such as Google Lens").

## 4.5 Discussion

Within our initial project, a detailed analysis of the BVI needs and requirements with respect to the design and development of assisting navigation systems is conducted. For this purpose, seven main categories are identified for the classification of the user needs and requirements which are elicited from extensive interviews with the BVI. To the best of our knowledge, this is the first time that the needs and requirements of the BVI are presented in such a complete and structured way that outlines a useful framework for the development of assistive navigation systems. This framework aims to provide insights concerning features and approaches that will potentially increase the use rates of navigation systems, along with the benefits offered to them. A very interesting example of such an approach, with emphasis on integrated multipurpose assistive navigation systems, is the combination of organized training offered to the BVI with a training version of the corresponding navigation app. We also identified that even the BVI who have good abilities in using mobile apps would prefer to test the navigation system in a controlled environment before trying it in conditions likely to be found in the outside world.

The previous subsection presented a part of the elicited requirements from interviews with members of the BVI community. These requirements were classified into main categories and subcategories. For the purpose of the present study, which is to link requirements gathered from BVI individuals for wayfinding activities to those required by an AI system such as those found within autonomous vehicles, the description of the requirements was abstract enough. This was intended to highlight, when this was possible, the similarities with reasonable requirements for the navigation software of autonomous AI-equipped units. The variety of such units, however, does not support the view of "one size fits all", because these may include humanoid robots, autonomous vehicles, UAVs, or even lawnmower machines, vacuum cleaners etc.

There exists always an argument supporting the view that these machines do not actually need to possess AI capabilities when they operate in fully controlled, or remotely identified (or perceived) environments, because in this case, the machines would just need to be remotely controlled or operated (by a human or, possibly, by a remote AI). On the other hand, however, current trends support autonomous (or semi-autonomous) operations, and consequently, a requirement for autonomous (or, semi-autonomous) AI. The latter case (that concerns AI-equipped units) is the one that mainly is related to the analysis of this study.

Concerning current trends in the development of AIs for autonomous machines, two directions may be identified. The first corresponds to the effort to imitate human intelligence. Structurally, this does not only depend on how well we understand and are able to simulate the human brain, but also on how the AI is confined physically by the geometry of the unit it resides, and by the sensors that imitate human vision and hearing (although smell, taste provide information to a human, the main senses concerning communication and learning are the first two). In the case of a strict imitation of human geometry and sensory abilities, the elicited requirements of the BVI may directly correspond to the sub-modules of the AI that will have to deal with signals from the visual and sound sensory systems of the robot.

The second direction corresponds to AIs that aim to exploit every available degree of freedom in order to accelerate and enhance their learning ability, speed and efficiency. Even in this case, the appropriate treatment of sensor data will be central to autonomous navigation.

In both, the cases described above, the requirements from the interviews of the BVI concerning necessary information about the route, or safety, can be considered as variables with respect to whether the user of the software is a human or not. On the other hand, requirements concerning user interfaces mostly depend on human nature and the particular characteristics of the BVI. This, however, does not preclude the case where a humanoid robot in the future will use an interface designed to facilitate the interaction between an assistive navigation app and a BVI.

## 4.6 Conclusion

The purpose of this study was to examine whether requirements which are elicited in the initial phase of the design of assisting navigation apps for the BVI are comparable with reasonable requirements concerning navigation software that could be possibly used by AI-equipped units.

The case of the BVI, as far as the design of navigation software is concerned, is particularly interesting because of two main facts: The first concerns their general requirement that visual information, along with data from other sensors has to be interpreted to specific directions. This may be thought of as an analogue of the necessary treatment of the data from the visual sensory system of any machine before specific directions are derived. The second fact concerns the availability and the ability to conduct interviews with the BVI within the framework of user requirements analysis. Unfortunately, for the time being, it is not possible to conduct interviews with AI-equipped autonomous units for this purpose. This fact makes the elicited requirements of the BVI a valuable source of information concerning the design of not only standalone software but also of specific modules that will aim to treat sensor data in order to provide efficient and accurate navigation directions to autonomous units. Conclusively, it is important to investigate the human–machine requirements convergence for the design of assistive navigation software because this research could benefit from getting implications for designing AI-equipped autonomous units and the reverse.

## Appendix A

QUESTIONNAIRE/QUESTIONS TO DISCUSS.

We are developing two systems that aim to assist blind people to navigate.

**The first system concerns outdoor navigation and autonomous and safe pedestrian travel to predetermined destinations**.

1. *Description*: The app is intended to be used by Android smartphones.

   Questions:

   - Are there any comparative advantages of the iPhone over the Android smartphones? If so, what are they?
   - Do you know smartphones specially designed for blind people (for example SmartVision 2)? What is the preferred operating system by blind people?
   - Do they opt for Apple iPhone? Will it be easy to switch to Android smartphones or to get a second smartphone that will use Android?

2. *Description*: Our system utilizes Google maps for voice-guided navigation.

   Question:

   - Are the voice capabilities of smartphones used by blind people and to what extent? Do you find Google Maps easy and functional to use?

3. *Description*: There will be used headphones that do not isolate both eardrums. We recommend the use of bone-conduction headphones, or of a single ear headphone so that the ambient sounds are not dampened.

   Question:

   - Do BVI people use headsets connected to their smartphones? Is it easy for a blind person to simultaneously recognize sounds from different sound sources by each ear? Do you find this specification reasonable? Do you have anything else to recommend? What kind of handset do you prefer, Bluetooth or wired?

4. *Description*: A simple keypad will be used for the blind person to easily interact with the application, to select routes and other available functions.

   Question:

   - Do you think the keypad should have any specifications regarding its functionality, ease of use and usability? (That is, how good and easy it is to use).

5. *Description*: The app will use voice commands to inform the BVI of obstacles in the direction of their movement.

   Question:

   - Questions: How do you think obstacles should be reported and what instructions would be given to them along their route? Increasing continuous sound, interrupted sound, or vibration with increasing frequency as the obstacle approaches? Simultaneous or only voice reporting? How do you think the warning about the obstacle will be more user-friendly or practical?

6. *Description*: There will be a configuration activity that allows the user to create an extensive list of destinations to be selected from the keyboard.

   Question:

   - Do you find this easy for the BVI? Are there any examples of navigation in the options menu? Are options menus widely used? (e.g., smartphone Smartvision has an audio description function for the menu)

7. *Description*: It will be possible to synchronize the application with traffic lights. We recommend that the system will be implemented centrally through the traffic management system so that the BVI does not depend on whether or not each traffic light is equipped with a sound broadcasting system.

   Questions:

   - Do you have any suggestions concerning these features?
   - Is it sufficient that the mobile phone can produce a sound similar to that of traffic lights equipped with sound broadcast features for blind people? Do you have any suggestions for improvements?

8. *Description*: Weather information will be provided so that the blind person can dress appropriately for the pedestrian route.

   Question:

   - How do you keep up to date with the current weather?

9. *Description*: The app will send notifications to selected persons about the current position of the BVI in case of need

   Question:

   - Who should be informed about this relative, police, or ambulance)? In the case of automatic activation, is there the nearest person who can receive a message? (It is logical that if no one answers the phone, there will be a hierarchy of options that will be called automatically). Note that the SmartVision 2 commercial smartphone has an SOS button that can send GPS coordinates (SmartVision 2, 2019).

10. *Description*: The app will use real-time information from the OASA telematics system for routes and stops for the development of complex routes that may include urban transport, etc.

    Question:

    - How does a BVI now choose the means of transport?

11. *Description:* The app will be connected to an external wearable subsystem, which could be fitted to e.g., a hat to ensure clearer reception of the GPS receiver and a sonar.

    Questions:

    - Is there an original to evaluate the ease of use?] Do you think a wearable device can easily be adopted by a BVI? What could be the type of wearable device that should be used/worn by the BVI to improve GPS accuracy (eg vest, hat, or embedded in a cane)?

12. *Description:* The application will be able to extract semantic information (along the way) which will be communicated to the BVI.

    Question:

    What do you think are the objects of interest that a BVI would want to identify along the way (toilets, pedestrians, obstructed vehicles, shops/species identification)? — list completion.

The second application is a blind navigation system in public interior spaces with a pilot application to provide autonomous tours of museums.

1. *Description*: It is designed for Android smartphones

   Questions:

   – The question serves both versions of apps (indoor and outdoor).

2. *Description*: It will use voice guidance.

   Questions:

   - The question serves both versions of apps (indoor and outdoor).

3. *Description*: Guidance will be provided along the tour route.

   Question:

   - Which one of the following is preferred by a BVI? Voice guidance (speech), audio or a combination of both?

4. *Description*: The app will provide audio information about the exhibits the BVI has approached. It will also notify the user about whether it is allowed to touch the exhibit.

   Questions:

   - Do you have any suggestions for additional specifications?
   - The app will have the ability to give accurate voice guidance at any time on how to access the help desk, the exit, the WC or the restaurant. Are there any other similar points of interest?

5. *Description*: Ability to request assistance from the Museum staff at any time.

   Question:

   - The question serves both versions of apps (indoor and outdoor).

6. *Description*: Emergency call option.

   Question:

- The question serves both versions of apps (indoor and outdoor).

7. *Description*: Design and implementation of an appropriate simple user interface on the touch screen of the smartphone.

   Question:

   - How do you propose to split the screen of the smartphone so that the blind can choose commands?

8. *Description*: Screen reading will support special reading functionality for the BVI.

   Question:

   - What is applicable today?

9. *Description*: The app will be used at the Tactual Museum - Lighthouse for the Blind of Greece, and after the completion of the project at the National Archaeological Museum and the Acropolis Museum.

   Question:

   - Is there another indoor destination you would like to visit?

10. *Description*: The implementation of a training version of the applications and the development of educational and training methods and strategies will be of high importance.

    Questions:

    - Do you find what those apps have to offer appealing?
    - Will we be able to have the BVI's massive participation in training on these apps, on the use of equipment, and by what means?
    - How long is a BVI going to spend on training in these applications?
    - What is the process and training that will allow the BVI to gain the confidence to navigate on his/her own?

    Questions:

    - Do you believe that a training version of the apps, which could be easily parametrized and applied by a sighted trainer to your routes or locations, would increase the rate of acceptance and involvement of the apps?
    - Do you think this could successfully replace the need for training in real conditions (for example, in a museum)?

    Questions:

    - Now that the main features of the assistive navigation apps have been described to you, do you believe that the presence of a sighted escort along your trip (outdoors or indoors) is still necessary, given that you have learned how to use the apps? To what extent can these apps support the autonomous navigation of a BVI person?

11. *Description*: The operation of navigation aids for BVI depends on external systems (such as beacons, signal recognition, NFC sensors, etc.) whose space must be equipped to support the operation of

the application. In essence, these external systems determine how the application interacts with the environment. It cannot, therefore, be learned in places that are not equipped with such systems.

Questions:

- Would you be reluctant to use the app for the first time during your visit to the museum? What do you think about it?

Questions:

- Does learning the app detract from the main goal of the visitor, to enjoy and learn from the exhibits?
- Does this happen also when navigating to an external destination which becomes complicated by learning the corresponding auxiliary application utility?

Questions:

- Do you think an educational version of each application would be beneficial which could be tried with the help of an instructor, in familiar places first, before being used in conditions likely to be found in the outside world?

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# Chapter 5 (Content partially published in #3)

## User Requirements Analysis for the Development of Assistive Navigation Mobile Apps for Blind and Visually Impaired People

**Keywords:** Accessibility, assistive mobile apps, blind and visually impaired people, user requirements analysis.

## 5.1 Introduction

The introduction of the iPhone in 2007 determined the direction that the design and the capabilities of "smart" mobile devices would follow in the subsequent years. Since then, the mobile phone market has been flooded by an increasing number of slim and light devices, the "smartphones", equipped with touchscreens that almost cover their larger surface, and at least two cameras. Apart from their external features, these devices are nowadays equipped with strong micro-processors, able to run operating systems which allow access to the web and other devices, including satellites. Most importantly, however, these operating systems allow access to a continuously expanding universe of mobile applications ('apps').

The ability of mobile apps to operate as a medium of socialization, to offer entertainment or access to education, and to assist people to carry out a wide variety of tasks, has placed the smartphone as one of the most useful and often used devices. The design of most of these apps, however, does not consider the case where the user is a BVI. Specifically, the majority of mobile apps require the user to visually observe how the app responds to her gestures and how the app interacts with the environment (when interaction features exist, such as the use of a camera, or other sensors of the smartphone, etc.), while their output includes visual content. It is, therefore, implied that in most cases, the benefits which stem from the use of mobile apps are not directly accessible to a BVI. In order to reduce this accessibility gap, the BVI use specially designed apps that act as interfaces, as, for example, screen readers, speech-to-text and text-to-speech apps, as well as virtual agents that can listen to natural language and enable human-computer or human-smartphone interaction, such as Apple's Siri or Microsoft's Cortana.

Quite recently, it is observed an increasing interest in the development of mobile apps that aim to assist BVIs in everyday activities which include interaction with the environment. Navigation in the interior or exterior spaces is a good example where a BVI encounters significant difficulties because of her inability to visually perceive the environment. This has a strong negative impact on the ability of the BVI to use public spaces, including urban areas, transport systems, and public buildings [1]. To design policies that reduce this type of accessibility gap, one must consider that the number of BVIs at the global level is approximately 285 million [2]. Therefore, any attempt to address the accessibility gaps caused by severe vision loss should consider methods that can be massively adopted. The design, implementation and distribution of mobile assistive apps might be one of these methods. Our research team at the University of Piraeus, Greece, is implementing two mobile apps that aim to assist the BVIs in autonomous navigation. Specifically, the first app is being designed to facilitate the pedestrian navigation of blind people outdoors, while the second app aims to facilitate the navigation of a BVI in interior spaces of interest, as, for example, in tactile museums, stations of the underground railway, hospitals, shopping malls, etc.

The design of assistive navigation apps must consider the particular needs and requirements of the BVI user. The identification of these particularities relies on the efficient implementation of the threefold 'user needs analysis', 'requirements elicitation' and 'engagement maximization'. It is also important that the apps ensure the safety and well-being of the users [3].

Needs analysis aims to reveal the goals, aspirations or needs of the users. On the other hand, user requirements elicitation concerns the identification of the requirements of a system from potential users (see [4] as an example of user requirements analysis in mobile services). On the other hand, because assistive navigation apps for BVI are voluntary use systems, the degree of user's engagement with them directly depends on the perceived quality of experience and benefit of usage [5], and the existence of competitive alternatives [6]. User engagement can be also considered as an assessment of the response of the BVI to the assistive app. Specifically, it should combine user's interest, focus and enjoyment that "encompasses self-direction, interaction, emotion, and choice naturally motivated by stimulating activities/actions" (see [7] and [8], among others).

During the first steps of development of our mobile apps, interviews were conducted with BVIs, aiming to identify in detail needs and requirements of the potential users with respect to autonomous navigation. The elicited information from the responses of the interviewees has been structured into four main categories, namely, requirements concerning the capabilities, functionality and ease of use of the apps, as well as compatibility requirements with respect to other apps and services. The main categories were then further divided into nine sub-categories. We present this classification along the results of the analysis of the responses of the BVI. The classification along with these results aims to become a useful tool for the researcher or the developer who is involved in the development of digital services for BVI.

The following section (Section II) presents the setup of the interviews and the categories into which the responses of the BVI were classified. The results of the analysis of the responses are presented in Section III. Section IV concludes the chapter.

## 5.2 Interviews with BVIs

In this section we present the setup of the interviews with the BVIs, which were conducted to determine the user-side needs and requirements for indoor and outdoor navigation assistive mobile apps. The interviews were conducted as part of the requirements analysis for the assistive apps which are being developed in the framework of the research project "MANTO Blind Escort Apps", undertaken by our research team at the University of Piraeus.

The overall discussion during the interviews was aiming to elicit user characteristics and needs, as well as recommendations concerning specific functions (and the corresponding modules) of the apps under development. A proper consideration of these characteristics and recommendations during the design of the apps is expected to enhance both interest and engagement of the future users.

### 5.2.1 Characteristics of the Participants in the Interviews

The interviews were held at the premises of the Lighthouse for the Blind of Greece, the main non-profit organization for education and assistance of BVIs in Athens, Greece. Eleven male and female BVIs, with vision problems ranging from complete blindness to severely impaired vision participated in interviews with Ms. Theodorou. The duration of each interview was at least 45 minutes.

### 5.2.2 Classification of the Subjects Discussed during the Interviews

Next, we present the subjects which were discussed during the interviews with the BVIs. The discussion of each subject was separated into two sections. The first concerned the presentation of possible related to the subject features that were initially considered during the conceptualization of the apps. The second section concerned the discussion on the subject and the recording of the answers of the interviewee. Specifically, the interviewee was asked about how he perceived the efficiency of the initial app design. Then he was urged to propose features for the app, which he believes that are either necessary or that would significantly enhance the functionality of the app with respect to the specific subject. The discussion of each subject included references to general characteristics of the BVIs, as for example, those concerning psychological factors, or particular needs in their everyday activities.

The initial design of the interviews, along with the feedback from the answers and suggestions of the interviewees, led us to a specific classification of the subjects of interest with respect to the design and development of assistive mobile apps for the BVI. This classification is summarized in Table 5.1.

Table 5.1 Requirement classification for the development of assistive mobile apps for BVI

| | |
|---|---|
| 1) Requirements concerning usefulness and capabilities | a) Obstacle detection<br>b) Navigation<br>c) Additional characteristics |
| 2) Functionality requirements | a) External stimuli<br>b) Sound (or voice) BVI-smartphone (or app) interaction<br>c) Tracking accuracy and the devices that aim to improve it. |
| 3) Usability Requirements | a) Characteristics/features of apps and devices.<br>b) Device handling |
| 4) Compatibility and parallel operation with other apps | a) Compatibility and parallel operation with other apps |

The first category includes the requirements concerning the usefulness and capabilities of an assistive navigation mobile app from the BVI perspective. The structure of the interviews allowed the interviewees to focus on the issues that they find more important. Specifically, we observed that the main subjects of interest of the BVIs can be classified in three subcategories: a) Obstacle detection, b) navigation, and c) additional characteristics (including general but significant requirements).

The second category includes the functionality requirements, as the BVI perceive them. Again, we identified three sub-categories: a) requirements concerning the treatment of external stimuli, b) requirements about the way sound (or voice) could be used to facilitate the interaction between the BVI and the smartphone (or the app), and c) requirements about the accuracy of tracking and the devices that could be used to improve it.

The third category concerns the usability requirements of the apps and the interconnected devices. Apart from the first sub-category which concerns the characteristics or features that a BVI requires from the assistive navigation apps and devices, it is of special interest to identify the optimal way of handling the smartphone (the apps) and the interconnected devices.

Finally, the BVIs showed particular interest in the way the assistive apps will seamlessly collaborate with the usual apps a BVI uses, as for example, screen readers and web mapping services. Next section will present the findings of the interviews with respect to this classification.

## 5.3 BVI requirements for assistive navigation mobile apps

The previous section presented a structure for the classification of user needs and requirements, as it was derived by an examination of recorded interviews of the BVIs. In this section we present the findings of the interviews, properly classified in this framework.

### 5.3.1 Requirements Concerning Usefulness and Capabilities

When we were initially introducing to the BVIs the purpose and aims of the apps it was important for us to understand their perspective with respect to what they would require from an assistive navigation app to offer them for it would be most useful to them. We identified the following needs and requirements:

1. Object Detection
    (i) The app should be capable to simultaneously detect multiple obstacles and report them appropriately (for example, guiding the BVI to maneuvers with good precision.
    (ii) Any sonar device should be able to detect obstacles that are relatively high, such as low balconies, awnings, signs, etc., and not only ground-based in front of the BVI.
2. Navigation
    (i) The app should be capable to assist the BVI throughout routes that combine both pedestrian and navigation and navigation by any other means of transport.

    (iii) The app should be capable to detect a wrong route and to correct or adjust it accordingly.
    (iv) It is desirable that the app could manage multiple destinations or stops along a route.
    (v) The app should provide real-time information on public transport (e.g., connection to bus telematics services).
3. Additional Characteristics or Features of the Apps
    (i) It is important to be able to notify a trusted person or the police about the BVI's position.
    (ii) When visiting interior spaces, such as museums, it is important that the BVI is able to request assistance by from the staff through the app.

### 5.3.2 Functionality Requirements

Going through the details of the possible implementation of the apps, the BVIs had the opportunity to express their point of view with respect to apps’ features related with their functionality.

1. External Stimuli
    (i) It is very important that sounds from the environment are not covered by the sounds of the apps. All the BVIs believe that such a case would put the BVI user in great danger. This remark excludes the use of headsets that cover both ears. One ear should be able to hear the sounds of the surrounding environment

(ii) Only important cellphone information should be reported phonetically in order not to cover or suppress the ambient sounds.

2. Sound (or Voice) BVI-Smartphone (or App) Interaction

(i) The app should offer voice menus of the key destination options. These options must be able to combined pedestrian navigation and use of other means of transport. (iii) The app must provide audio signal for the traffic lights.

3. Tracking Accuracy and the Devices that Aim to Improve

(i) GPS and sonar amplifiers should be discreet and not too obvious.
(ii) Positioning accuracy must be high (at least at the centimetre level).
(iii) Any sonar or GPS device must refresh the information it provides at high frequency because some BVIs can move at a fast pace.

### 5.3.3 Usability Requirements

Apart from the capabilities and functionalities of the apps and the interconnected devices, the BVIs showed particular interest on specific features and modules of the assistive navigation system with respect to the ease of use of the apps.

1. Device and Application Features

(i) The BVIs would prefer that the smartphones would be equipped with simple, easy-to-learn keyboards or pads. The apps should respond to clear and simple gestures on the touchscreen.
(ii) They prefer to use Bluetooth headphones because cables are often entangled.
(iii) They require smart and fast access to the service of assistance call (possibly through a specific gesture on the touchscreen, or a devoted key combination on a keyboard).

2. Device Handling

(i) The BVIs should be able to set the destination on their own (the autonomy and independence of the BVIs is very important).
(ii) As far as outdoor navigation is concerned, it would be desirable that the app provides a list of "favorite" destinations that the BVI can edit.
(iii) The BVI should have the ability to dictate the destination address on the device.

### 5.3.4 Compatibility and Parallel Operation with Other Apps

(i) The apps should be accessible to screen readers.
(ii) In case that the navigation app requires de-activation of the screen reader, the screen reader should be automatically re-activated when the app goes into the background.
(iii) In general, however, other applications (including the screen reader) should be able to run in parallel with the navigation apps.
(iv) It would be useful that the apps could interconnect/ collaborate with an application that describes images.

## 5.4 Conclusion

We highlighted the fact that the design of assistive navigation apps for BVI people is a very important step in the process of offering functional and easy to use solutions for the problem of location accessibility of the BVIs. To optimize the benefits of these apps we proceeded in interviews with BVIs, aiming to elicit not only their needs and requirements with respect to blind navigation, but also their preferences with respect to special features of the corresponding apps.

The analysis of the responses of the BVIs, who participated in the interviews, yielded a classification of their requirements and needs into four categories that include nine subcategories. This classification may be used as a guide for the development of assistive apps for BVIs.

As far as the assistive navigation mobile apps, the analysis of the interviews helped us identify specific needs and preferences of the BVIs. For example, that the apps should be capable to simultaneously detect multiple obstacles, to manage multiple destinations and stops, to notify persons of trust or an ambulance in case of need. Moreover, we learned how important is for the BVIs that the apps do not cover sounds of the environment, as well as the capability to produce an audio signal for the state and proximity of traffic lights. Another example of interesting, elicited preference of the BVIs concerns the amplifiers of the GPS signal, which should be discrete, and if possible, not visible, while a practical issue concerned the preference of the BVIs to Bluetooth headphones because it is difficult to them to untangle cables. These interesting and significant observations, along with the rest described in Section III, will be central to the design of our two assistive navigation mobile apps. They may also be useful to any researcher or developer who aims to offer effective digital accessibility solutions to BVI.

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# Chapter 6 (Content Partially Published in #4)

## Towards a Training Framework for Improved Assistive Mobile App Acceptance and Use Rates by Blind and Visually Impaired People

**Keywords:** assistive mobile apps; blind and visually impaired people; qualitative analysis; training framework

## 6.1. Introduction

“Smart” devices, and particularly smartphones, have characterized the massive adoption of digital technologies during the last two decades. Along these devices, an extensive universe of smart digital applications (apps) has emerged. Surprisingly, however, little or no research appears to have been focusing on the particular characteristics and circumstances that drive the take-up of technology by people with disabilities, which stem from the differing needs of these groups, as well as from significant usability problems. These problems mainly arise from the fact that both devices and apps may not be designed or adapted for use by people with disabilities. On the other hand, even in the case that an app (or a version of the app) is equipped with accessibility features, these mainly concern basic functions, while the design of these features usually takes for granted the ability or the will of the disabled person to use them properly.

According to international statistics, the number of blind people and people with severe vision problems is approximately 36 million [1] and 285 million [2] worldwide, respectively. Their majority lives in poor and developing countries, while most of them are young and in productive age. Their demand for improved accessibility, self-service, and autonomous living has been identified by digital app developers and researchers who are providing an increasing number of solutions that contribute catalytically to social inclusion, promote the educational and cultural level, independence in social and professional life, and consequently upgrade the quality of life of blind and visually impaired people (BVI).

Assistive mobile apps aim to play a significant role in the autonomous navigation of BVIs. Apps such as Loadstone GPS [3], Mobile Geo [4], and Seeing Eye GPS [5] use GPS positioning to assist the BVI during pedestrian navigation. Other apps, such as BlindSquare [6], provide information concerning points of interest during outdoor navigation. Academic research has been focusing on the requirements and the development of systems that assist outdoor navigation [7–10], indoor navigation systems ([11–16] among others), or both [17] for the BVI. In this context, there is significant and increasing demand for autonomous navigation systems especially designed for BVIs.

Our research team at the University of Piraeus, Greece, is developing two assistive systems for the autonomous navigation of blind and visually impaired people. These systems are mainly based on two corresponding mobile apps. The first app is being designed to facilitate the pedestrian navigation of blind people outdoors. The second app aims to facilitate navigation of a BVI in interior spaces of interest, as, for example, in tactile museums, stations of the underground railway, hospitals, etc.

At the first steps of development of the two assistive apps, interviews were conducted with BVIs aiming to identify in detail needs and requirements of the potential users with respect to autonomous navigation.

During the interviews, the main goals and features of the apps were described. The responses of the participants to a wide set of questions revealed that appropriate training of a BVI on how to use these apps plays a significant role on the anticipated app adoption and use rate.

On the other hand, user engagement is also related to multiple psychological constructs, as, for example, interest, focus, and enjoyment [18,19]. It also depends on the perceived quality of experience and benefit of usage [20]. Interestingly, during the interviews a set of particular practices (including stated preferences, habits, etc.) and psychological features of the BVIs with respect to the use of mobile technology were also identified. We argue that these psychological features and practices must be considered in the development of optimal training practices concerning the use of the proposed technology. Based on this argument, we introduce a framework for the adequate training of BVIs on the use of assistive mobile apps.

The next section presents the materials used and the methods followed in our research. Specifically, it provides a brief introduction of the two assistive navigation mobile apps for BVIs, which are developed by our research team, followed by a description of how and with whom the interviews were conducted. In Section 3, the results of the interviews are presented, followed by an analysis of their implications on the training methods that aim to maximize the adoption of mobile apps by BVIs. Section 4 concludes the chapter.

## 6.2 Materials and Methods

At the University of Piraeus, two assistive navigation apps for BVIs are being developed. The first app aims to help the BVI to travel safely, while the second will guide the BVI in interior spaces of interest (accessible or tactile museums, hospitals, shopping malls, etc.).

Specifically, *Blind RouteVision* is being designed to facilitate the pedestrian navigation of BVIs outdoors. It has an enhanced GPS functionality and connects with the Google Maps service for navigating, enriched with additional voice prompts. Its design accommodates an ultrasound sensor for real-time recognition and avoidance of obstacles along the BVI’s path. Additional features of *Blind RouteVision* include:

(a) A simple keyboard for the interaction of blind people to enable them to select routes and other available functions,

(b) application synchronization with traffic lights and weather information, and

(c) the utilization of information telematics of the Athens Organization of Civil Transport (OASA) for routes and urban transport stops.

The initial version of the *Blind RouteVision* system is presented in the third section of [15].

*Blind IndoorGuide* is an application for the autonomous blind navigation in indoor spaces available in both Android and iOS. It is supported by a highly accurate indoor location determination subsystem, including accessibility mapping of indoor spaces with overlays of the positions of points of interest (POIs), Bluetooth beacons as proximity sensors and location indicators, as well as unobtrusive assistive tactile indications on the floor according to international standards for BVIs. It will inform the BVI about POIs and will allow selection of POIs and the dynamic issuing of voice navigation instructions towards POIs considering the current position of the BVI. *Blind IndoorGuide* inherits the features of the *Blind MuseumTourer* system, as they are presented in [15]. It aims to extend the functionality of the

*Blind MuseumTourer* beyond the case of museums. The conceptualization of the *Blind IndoorGuide* is discussed in [15]. In the context of the development process of the two assistive navigation mobile apps, an extensive qualitative analysis of the requirements of potential users has been conducted. The analysis was based on interviews with BVIs and aimed to elicit their needs with respect to autonomous navigation but also psychological characteristics and practices that are related to their impaired vision.

### 6.2.1 Interviews with BVIs

The interviews were conducted at the premises of the Lighthouse for the Blind of Greece, the main non-profit organization for education and assistance of BVIs in Athens, Greece. Eleven male and female BVIs with vision problems ranging from complete blindness to severely impaired vision participated in interviews with Ms. Theodorou. Each interview lasted at least 45 min. Table 6.1 presents descriptive characteristics of the interviewees.

Table 6.1 Characteristics of the participants in the interviews.

| | **Gender** | **Age** | **Degree of Vision Loss** | **Cause of Vision Loss** | **Digital Sophistication** |
|---|---|---|---|---|---|
| P1 | Male | 55 | Complete | By birth | High |
| P2 | Female | 35 | Severe | By birth | Average |
| P3 | Male | 36 | Complete | Diabetes | High |
| P4 | Male | 40 | Almost complete (95%) | By birth | Low |
| P5 | Male | 40 | Almost complete (95%) | By birth | Low |
| P6 | Female | 55 | Complete | Retinopathy (23 years old) | Low |
| P7 | Male | 40 | Almost complete (90–95%) | By birth | Low |
| P8 | Male | 40 | Complete | Cancer (7 years old) | Low |
| P9 | Male | 35 | Almost complete (>95%) | Benign tumor (15 years old) | Low |
| P10 | Male | 60 | Complete | By birth | High |
| P11 | Male | 30 | Complete | By birth | High |

The interviews started with an introduction of the participant, where the BVI was asked about characteristics such as age, degree of vision loss, cause of vision loss and the age at which this occurred, job description and status, familiarity with digital apps, etc. Then, the features and capabilities that were initially considered during the conceptualization of the apps were presented to the BVI. After the description of the characteristics of the apps, a discussion followed concerning the BVI's travelling habits. Along with characteristics which were directly relevant to blind navigation, the BVI was encouraged to state preferences, doubts, and general needs and habits. In other words, the discussion included references to general characteristics of the BVIs. For example, those concerning psychological factors or particular needs in their everyday activities.

The answers, suggestions and comments of the interviewees were recorded and classified into categories that affect the design and development of assistive mobile apps for the BVIs. Interestingly, it was identified that psychological factors and everyday practices, particular to the BVIs, underlie their preferences and perceived needs significantly. The results of the analysis of the interviews are presented in the next section.

## 6.3 Results and Discussion

Two important aims of the assistive navigation mobile apps are to enhance the sense and the degree of autonomy and independence of the BVIs. This enhancement will be achieved not only in practice (i.e., when the apps will be used in real world conditions), but even before the first use of the apps, during their introduction to the BVI community and during the learning procedure of the apps.

The first step in the derivation of appropriate approaches concerning the design and implementation of the apps, as well as the way they will be introduced to the BVI community, involves the identification and understanding of particular characteristics of the potential users. These characteristics can be classified as everyday practices and psychological features of the BVIs. In contrast to previous studies which focus on the user interface design and specific features of mobile assistive apps [10], the present study focuses on the set of psychological features and everyday practices of the BVIs as they were elicited from the interviews. These features and practices of the BVI are presented in this section. Moreover, when the primary interview data allow it, we present possible links between evidence and theoretical (or qualitative) characteristics by relating these features to corresponding practices of the BVIs. We note that these connections are not derived from an extensive quantitative analysis (which would usually incorporate proxies of the psychological properties), but rather depicts possible relationships for which further study may be required. On the other hand, the focus of our investigation is not to conduct such a quantitative study, but to use the elicited psychological features and practices of the BVIs within a specific educational framework for the adoption of assistive mobile apps.

### 6.3.1. Particular Characteristics of the BVI

The characteristics of the BVI were elicited from an analysis of the recordings of the interviews. First, we present psychological features of the BVIs, with links (when possible) to everyday practices.

#### 6.3.1.1 Psychological Features

(1) BVIs need to be organized in order to feel secure. They are afraid of being lost and not being able to find the items they need. *Possible Related Evidence or Common Practices of the BVI:*

   a. They map in their mind any space or object they perceive.
   b. This mapping also includes dimensions that correspond to other senses. For example, they memorize and relate sounds and smells to specific points or places of their route.

(2) The fear of being lost intensifies for the BVI when they visit an unfamiliar place. *Possible Related Evidence or Common Practices of the BVI:*

   a. To avoid getting panicked, the BVIs are often advised to only visit alone places they are familiar with.
   b. Otherwise, they prefer using a taxi the first time they go to a destination.

(3) BVIs are reluctant (or they feel insecure) to use or trust someone offering a service which is not supported by a well specified and understood system. *Possible Related Evidence or Common Practices of the BVI:*

a. They do not trust taxis which are not connected to central reservation/call systems. In other words, they don't pick a taxi randomly from the road. They always call a taxi by phone or the internet because this assures them that it will be a real one.

(4) Social inclusion is a very important need of the BVI. They often feel different, even ashamed, when they have to use the white cane (e.g., right after getting off the bus). *Possible Related Evidence or Common Practices of the BVI:*

a. They feel that they are not as capable as other people.
b. The idea of getting noticed by others is unpleasant to them.

(5) The BVIs learn not to be spontaneous when the move. They have learned to be systematic and not to leave emotions or sudden thoughts interrupt their concentration to their travel. They rarely are relaxed when they travel.

a. The BVI do not answer phone calls or, generally, use a smartphone while walking. In order to use their smartphones they first have to stop walking.

(6) In fact, often BVIs (especially those who were born blind) are afraid of the idea of having (or gaining) their vision. This would dramatically change their way of living, while they would have to confront with the true shapes and colors of objects, animals, and persons (as most importantly with their appearance).

(7) The image that a BVI creates for something or someone is usually better than the real one.

(8) BVIs that have some minimal vision often place their smartphones near their faces as if they can see, despite the voice functionalities of the apps they intend to use. This possibly implies that they do not easily surrender to the idea that their vision is obsolete.

(9) The mentality of a BVI that once had functional vision is often much worst that this of a BVI by birth (or one that does not remember how it was to be able to see) ceteris paribus.

(10) BVIs are conservative and fear to change their way of living. As this could be a consequence of adopting a new technology, they usually are not eager do so.

(11) Another reason which makes them reluctant to use new technologies is the lack of confidence in their abilities. In other words, they fear that they will not be able to properly use new technologies, or even that they will cause problems in their attempts to use them (for example, blocking a cell phone).

Next, the everyday or usual practices of the BVI are presented. It must be noted that the interview data mainly referred to navigation practices, because the main subject of the interviews concerned the assistive navigation mobile apps which are being developed at the University of Piraeus.

#### 6.3.1.2 BVI Practices (Preferences, Habits, Facts, etc.)

(1) In general, taxis are the most preferable means of transport for a BVI.

(2) The younger BVI use the internet for choosing a means of transport while the older ones prefer to be accompanied.

(3) Most of the BVIs choose (and prefer) to have someone to escort them.

(4) They use 'smart stops' when they take a route they already know.

(5) They ask the bus driver where to get off the bus.

(6) They use hearing to perceive when cars are moving or if a car is coming toward their direction.

(7) If they are confused by the narrow streets, they recall odors they have retained from previous times.

(8) They recall particular details along the track to their destination.

(9) When they follow a track for the first time, they memorize characteristics of their route (step counting, direction, sounds, and odors).

(10) They also often ask people that they meet on their way.

(11) When they get off the bus, they rely on hearing, smell, and touch, and count steps in order to move on the sidewalk.

(12) They always follow the special tactile paving on the sidewalk to avoid permanent obstacles.

(13) If they make a mistake (step counting, loss of direction, etc.) and feel lost, they try to return back to the sidewalk and start again from the beginning.

(14) BVIs are often employed in professions that require particular ability to identify by touch (for example as physiotherapists).

(15) They learn mostly by word of mouth that an application is good and useful (e.g., e-radio, google translate, and OASA telematics).

(16) They lose their smartphones more often than a sighted person does.

(17) Blind people are also familiar with having a wearable device. They believe it is a good solution to attach such device on the cane or to develop a cane with such additional functionality.

Both everyday practices and psychological features of BVI can be used to set directions for the specification of a training framework for improved assistive mobile app acceptance and use rates by the BVI. This framework will be adapted suitably in order to reduce the effects of BVI specific inhibitors or to enhance the effects of BVI specific enablers or facilitators, respectively, which concern the adoption of assistive mobile apps. These directions are presented in the following subsection.

### 6.3.2 Discussion—Towards a Training Framework for the BVI

The term "training of BVI" most often corresponds to the method followed within an educational framework and goal with aim to overcome the consequences of visual impairment. As early as the 1960s [21] and 1970s ([22–29], among many others), information and communications technology has proven to be capable of providing very useful tools that significantly have been facilitating the educational process of the BVI.

Another trend concerning the training of people with visual impairment has been focusing on enhancing their ability to use signals from their other senses, as well as their spatial perception through them. The latter is very significant not only concerning the autonomous navigation of a BVI, but also with respect to the accuracy of motion, for example, as it is required for handwriting [30]. Another approach that consists a good example of such a training for BVI is that through audio-based computer games [31–33], the games provide virtual environments in which the BVI exercise their ability to process audio signals in order to perceive the (virtual) surrounding space.

The introduction, however, of mobile devices and the development of pattern recognition apps, screen readers and artificial intelligence-based virtual assistants or other assistive apps specially designed for the BVI, outline a trend towards the substitution of the need for enhancement of the functional senses of the BVI by the requirement that a BVI can easily adopt and use assistive apps.

Apart from other factors such as perceived usability and usefulness of these apps, their adoption and use rate is directly related to the perceived by the BVI degree of difficulty to learn how to use them. However, as new apps aim to carry out more complex tasks, their complexity increases. The results presented in the previous subsection imply that this complexity may create a barrier concerning the adoption of the complex assistive apps by a BVI. Specifically, the analysis of the interviews reveals that the mentality, fears, and concerns of an average BVI do not coincide with those of an average sighted person. Because vision is the most important of the senses concerning the observation of the environment, the BVIs are afraid that they would be easily lost or that they would easily lose their portable property (such as mobile phones). However, these are not the only fears that a BVI must encounter. For example, because they use their imagination in order to produce images of objects and people they cannot see, they are afraid of what they would see if somehow their vision was recovered.

The analysis also revealed that the attachment of a BVI to specific practices offers the feeling of security. The need for this feeling seems to be greater for a BVI than for an average person, and this seems to be reasonable when one considers that the consequences of a negative non-anticipated event would be probably significantly enhanced by the inability of visual perception.

The answers of the BVI to questions about autonomous navigation and the use of new technological solutions implied that although they seem to be willing to hear or learn about new assistive technologies, they are reluctant to adopt solutions or services of a certain degree of complexity. The BVI seem to be more conservative and in fact, do not have the confidence in their abilities to meet the requirements that more complex applications impose. They have adapted to a way of life that requires form them not to be spontaneous but rather more self-controlled than the average person. In order to overcome difficulties caused by their inexistent or reduced sense of vision, the BVI learn to be systematic and methodic. However, these characteristics do not suppress the expressions of their need for social inclusion and autonomy.

A training framework for the use of mobile assistive apps by the BVI aims to optimize the adoption and use rates of the apps considering the findings of this analysis. Such a BVI oriented framework seems to be a significant factor for the adoption of complex assistive apps. It is important to note that by the term “framework”, the preparation of the training is also considered. In other words, it also involves actions that aim to convince the BVI to participate in the training. Given the findings mentioned in the previous paragraphs, the following procedure is proposed (accompanied, of course, by standard non-BVI specific approaches for technology adoption):

First, any contributions of the assistive mobile apps with respect to social inclusion and autonomy of the BVI should be highlighted since the initial communication of the apps' aims. Secondly, the aims of the apps and the initial description of their main features should be followed by an analytic description of the "safeguards" that will reassure the BVI about the controllability of the consequences of any unanticipated event that will be related to the use of the app. These "safeguards" would correspond to specific features and modules of the app, the design, and functionality of which should be implemented after a thorough identification of the BVI's fears and needs concerning the app related activities. The purpose of these features or modules would maintain and ensure the sense of safety for the BVI user during the use of the app's services. A third issue, which is related to the conservatism of the BVI, concerns the necessity that the BVI becomes familiar with the idea of using the app autonomously. The BVI would have to change everyday practices which possibly work at a satisfactory degree. The effort of the people who will introduce the apps to the BVI should concentrate on making this transition a pleasant experience.

It must be noted that a pleasant experience is not synonymous with an effortless experience. In fact, learning how to use mobile apps (such as navigation apps) which involves interaction with the environment or other appliances usually requires effort from the BVI user. In such a case, as mentioned above, the existence of an option that the BVI could be trained on how to use the app may play a significant role in whether the app will be adopted or not. Based on the previous analysis, a training framework for the BVI would optimally be adapted to the particularities of people with visual impairment. Specifically, it is proposed that the following directions are followed:

(a) Training in familiar environments: the BVI employ their functional senses to perceive the environment. In case that the training takes place in an unfamiliar environment, mental resources of the BVI will be assigned to this function.

(b) Tasks to be learned must be easily feasible and understandable: in case that the BVI must be trained to perform more complex tasks, these tasks will be divided into a series of smaller tasks, each of them not requiring much effort from the BVI. The aim of this process is to prevent the BVI from questioning their abilities to successfully complete the tasks.

(c) Adaptation of the tasks to the systematic way that a BVI acts: the BVI have adopted a very methodological way of doing things in order to compensate (or be protected) from the implications of their visual impairment. The learning and exercise of these systematic practices by a BVI can be clearly considered as training and applications of algorithmic thinking, respectively. This observation provides a clear perspective concerning the approach that must be optimally followed when the apps are introduced to people of this group. Specifically, this observation leads to the following suggestions:

   a. The tasks on which the BVI will be trained must require sequential smaller actions.
   These actions should be analytically presented to the BVI.

   b. Before teaching the BVI about each task, exactly one goal must be described. This suggestion stems from the fact that the BVI find perplexed any multidimensional grid of actions. In other words, the description of multiple options within a task should be avoided when this is possible. This is in line also with the first suggestion about the sequential structure of the tasks to be taught.

The three above suggestions along with a proposed pre-training approach described at the beginning of this subsection outline the direction that would be followed in order to derive a training framework that would aim to maximize the adoption and use rates of assistive mobile apps by the BVI.

## 6.4. Conclusion

Along with the ambition of digital technologies to assist blind and visually impaired people overcome the barriers caused by their vision impairment, the complexity of the tasks that assistive mobile apps aim to perform has been continuously increasing. In this study, the need for training of the BVI on how to use mobile assistive apps was first highlighted. Specifically, an analysis of BVI interview responses revealed that they have particular characteristics (practices and psychological features) which are related to their inability to visually perceive people, objects, images, as well as their position in the surrounding environment.

Second, the particular everyday practices and psychological features of the BVI, as elicited by the interviews, were presented. In some cases, possible links between psychological features and specific practices were suggested.

Third, based on these characteristics, a framework was proposed for the training of BVI on how to use assistive mobile apps. This framework is naturally divided into two sections. The first concerns the way the apps (goals, benefits, and features) are presented to the BVI in order to enhance motivation and decrease the causes of negative attitudes towards the adoption and use of these apps. The second section corresponds to simple suggestions concerning the training method that the BVI should follow.

It must be noted that the proposed framework is far from complete, as the continuous tendency for the development of assistive apps that correspond to more complex tasks will naturally reveal additional requirements or needs of the BVI. This implies that this framework must be continuously enriched and adapted towards the main ideal goal of optimal adoption and use rates of assistive mobile apps.

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# Chapter 7 (Content Partially published in #5)

## Gaining insight for the design, development, deployment and distribution of assistive navigation systems for blind and visually impaired people through a detailed user requirements elicitation

### Abstract

**Keywords** Blind and visually impaired people, assistive navigation system, requirements' elicitation, mobile app

## 7.1 Introduction

The twenty-first century has been characterized by the advance of smart devices, along with the development and extensive use of smart "apps" aiming to assist people to carry out a wide variety of tasks. The typical learning procedure on how these apps are used involves the reading of the basic instructions by the potential user, but most often is explorative through gestures on the touch screen, involving calls to a "help menu" or, more generally, a graphical user interface (GUI) when required [1]. The user's vision plays a significant role in this exploration, not only because the user directly observes how the app responds to the gestures, but also by observation on how the app interacts with the environment (when the interaction features exist, such as the use of a camera, or other sensors of the smartphone, etc.). It is, therefore, directly implied that the procedure of learning how to use a smart app is fundamentally different and more complex when the user is blind or visually impaired (BVI).

According to the World Health Organization [2], at least 285 million people globally have severe vision problems, of which 36 million are blind [3]. Furthermore, taking into account that the majority (82%) of people with visual impairment are over the age of 50 years [4], their experience with smart technology should be included throughout the design phase. The inability to visually observe the environment significantly affects the ability to use public spaces, including urban areas, transport systems and public buildings [5]. In particular, vision problems affect every activity of daily life, including mobility, orientation, education, employment and social interaction. Despite these limitations, BVI persons generally develop special abilities through other senses to partially offset the implications of vision loss [6–8]. For example, people with visual impairments sometimes develop a sense of space through sound (echolocation), a skill that involves the detection of objects and their distance through active sound generation [9]. Similarly, blind people tend to develop a very sensitive touch that allows them to read using Braille [10]. Other researchers introduce the use of vibration output or speech as input to assist BVIs [11, 12].

The acceptance of mobile services is a gradual process [13]. It involves understanding the benefits offered by these services before their acceptance and systematic use by the majority within a target group. In general, the development of smart apps does not take into account the particular requirements of people with special needs, and especially of BVI [14]. Even in the case that the app is designed especially for the BVI (see Csapo et al. [15], for a survey of assistive mobile apps for blind users), several features that facilitate the BVI to learn how to use the app are missing. Consequently, the learning procedure of the BVI relies on the availability of an instructor and, in the case of an app that interacts with the environment, the presence of the BVI at a location for which the app is designed. Assistive navigation apps for blind people are good examples where the familiarization process with the app depends on access to specific locations (see Meliones and Sampson [16], among others). This problem directly affects the rate of technology acceptance of BVI concerning smart app use. Interestingly, however, little or no research appears to have been undertaken on the inherent particularities in the take up of smart apps by the BVIs.

During our endeavor to explore this field in our previous work [17], we presented the development of training practices concerning the use of navigation applications based on the everyday practices and psychological features of the BVIs. Specifically, everyday practices (preferences, habits, facts) and psychological characteristics of the BVIs were identified and recorded from the interviews of 11 participants aiming to create an adequate framework for the development of training practices concerning the use of the proposed implementations. In this work, we proceed with adding questions and enriching the analysis of requirements and add more participants in the interviews to comply with works in the relevant literature using samples of similar sizes (see Sect. 3.1).

Furthermore, in this work, we have started running the interviews in the initial development phase of the assistive applications. Contrary to the former work [17], in which we presented only the plans of the proposed system to the interviewees, at this point we have demonstrated the preliminary design (beta version) of the two under development implementations.

Next, we proceed with the implementation phase which is an ongoing work with iterations. More specifically, various working versions of the envisaged applications are delivered to pilot users resulting in consecutive evaluations and suggestions for improvements. In this phase, a comparative study between the elicited requirements and the proposed technology that is under development follows.

The identification of the particularities of the BVI concerning assistive navigation apps relies on the threefold “user needs analysis,” “requirements elicitation” and “engagement maximization.” It is important that these apps not only augment user capabilities but also ensure the safety and wellbeing of the BVI [15]. User needs analysis and requirements elicitation are two fundamental stages within the user requirements analysis, along with information gathering, envisioning and evaluation [18]. Needs analysis focuses on the goals, aspirations or needs of the users. User needs can be elicited through various methods, e.g., task analysis, user surveys, focus groups or interviews. On the other hand, user requirements’ elicitation, which is the process of seeking, uncovering, acquiring and elaborating requirements for computer-based systems [19], aims to discover and elucidate the requirements of a system from potential users (see Brown et al. [20], as an example of implementation of user requirements analysis in mobile services). Another example is the proposed micro-navigation system and the requirements classification that was included in Guerrero et al. [21].

Given the fact that assistive navigation apps for BVI are voluntary use systems, the degree of user’s engagement with them is directly related to the perceived quality of experience and benefit of usage [22] and the existence of competitive alternatives [23]. User engagement can be considered as an assessment of the response of the BVI to the assistive app. Specifically, this involves a combination of interest, focus and enjoyment that “encompasses self-direction, interaction, emotion and choice naturally motivated by stimulating activities/actions” (see Noorhidawati et al. [24] and Marks et al. [25], among others).

This research presents a detailed analysis of the BVI needs and requirements concerning the design and development of assisting navigation systems. Specifically, this manuscript describes the processes of user needs analysis and requirement elicitation carried out by our team in connection to the development of two assistive navigation systems for blind and visually impaired people (Blind Route Vision and Blind Indoor Guide). For this purpose, seven main categories are identified for the classification of the user needs and requirements which are elicited from extensive interviews with the BVIs. To the best of our knowledge no previous work has so spherically examined and identified the perception and behavior of people with severe vision loss and blindness concerning Assistive Navigation Systems.

This is the first time that the needs and requirements of the BVI are presented in such a complete and structured way that outlines a useful framework for the development of assistive navigation systems. This framework aims to provide insights concerning features and approaches that will potentially increase the use rates of the navigation systems, along with the benefits offered to the BVIs. A very interesting example of such an approach that is emphasizing on integrated multipurpose assistive navigation systems is the combination of organized training offered to the BVIs with a training version of the corresponding navigation app in a simulation environment as well as in the field.

## 7.2 Related work

Over the last three decades, the design and development of location-based services for people with disabilities have been a central research topic of the accessibility literature (see, e.g., Loomis et al. [26] and Gleeson [27]). Concerning the case of assistive navigation systems for the BVIs, the elicitation and understanding of their needs, preferences and requirements, is necessary, not only prior but also throughout the development process. To this end, the main approach used in the relevant literature has been through interviews with members of the BVI to assess the importance of specific features or the accuracy of existing assistive navigation systems.

Azenkot et al. [28] conducted interviews with 13 blind and deaf–blind people to understand how they use public transit and what human values were important to them in this domain. They identified two key values, namely independence and safety.

Furthermore, essential literature that is eliciting user's navigation and safety requirements is listed below. First, Williams et al. [29] conducted interviews with BVIs and registered significant Personality and Scenario attributes describing their navigation behaviors. Additionally, Williams et al. [30] discovered during the interviews with BVIs remaining challenges concerning the navigation technology that come from the environment and the other sighted people. The researchers also identified what were the beneficial navigational cues for the participants, as well as what they wanted to know about their surroundings and the barriers they are confronted with.

Branham et al. [31] have distributed (conducted) an exploratory survey of 58 individuals with visual impairments and 10 interviews with blind people who discussed accessibility challenges relatively to physical safety imposed by other people. Moreover, they expressed the need to access visual cues that would allow them to better manage their safety. The ultimate goal is to design assistive tools based on ensuring a sense of interpersonal and physical safety.

Moreover, according to Ntakolia et al. [32], a set of user-centered design and system requirements concerning operational, functional, ergonomic, environmental and other optional features is defined after a series of interviews and questionnaires to the BVI. Specifically, they present the elicitation of requirements with the design of a novel system guiding the BVI to outdoor cultural spaces. The interviews were based on the BVI's difficulties, their ability to use smart technologies and their preferences on navigation. Consideration should be given to the fact that the particular requirements apply to every relevant assistive device.

To assess the quality of service provided by the assistive navigation system NavCog, Ahmetovic et al. [33] conducted interviews with BVI users. The interviews indicated that NavCog was still lacking some features they expected from a commercial navigation application, but they all expressed that the core turn-by-turn paradigm was something they would use.

Abdolrahmani et al. [34] used interviews to identify different levels of significance for the errors produced by imperfections of assistive navigation systems. Interestingly, they highlighted the importance of the context within which the error is produced. Specifically, some of the errors caused by imperfection of the technology may be classified as easy to ignore because their impact is minor or easily amended, while others may be classified as very significant, having implications on the safety and social status of the BVI user. However, because the same imperfection may cause errors of different impacts, the design and implementation of assistive navigation systems were tested.

Ahmetovic et al. [35] examined the interaction preferences of the BVI of various expertise and familiarity with a route with assistive navigation systems. Their conclusions provide useful information about the required adjustability features of the corresponding user interfaces.

Some more projects are focusing on user requirement analysis of navigational systems like Miao et al. [36] and Asakawa et al. [37] who report on a user requirement analysis for blind navigation in public buildings and museums, respectively. Moreover, Real and Araujo [38] reviewed the foundations and requirements of existing applications regarding the provision of environmental information. In their work, they focus on user-centered design for indoor and outdoor positioning taking into account their past experiences, technological state of the art, and user-related needs and constraints.

The aforementioned works and many of the works cited therein are excellent examples of how targeted interviews can provide valuable information for the design of assistive navigation systems for the BVI. However, these interviews, by construction, did not aim to cover most of the topics that characterize the needs, preferences and requirements of a BVI user. Our research, on the other hand, aims to elicit, classify and identify the broader set of prior needs and requirements of the BVI, thus allowing any design team of an assistive navigation system to efficiently set the desired aims, capabilities and features.

Because assistive navigation apps for BVI interact with the environment and auxiliary external devices as Bluetooth beacons and RFID transmitters (see, for example, Meliones and Sampson [16], Ghiani et al. [1], Guerriero et al. [39], etc.), it is not easy for BVI individuals to learn by themselves how to properly use the full set of the app's features. For example, learning how to use an app that aims to assist navigation in interior spaces (e.g., museums) may require that the BVI visits these locations. On the other hand, an outdoor navigation app may require that a sighted person (who knows how to use the app) escort and at the same time train the BVI on how to use the app. We argue that these requirements do not derive only from the user but also from the fact that the design of assistive navigation apps until now does not properly consider the required training framework within which a BVI can learn how to use them. Given the fact that a BVI user is usually not able to consider the factors on which a training framework depends, the corresponding user's elicited requirements are not analytical. This is verified by the discussions during our interviews with the BVI. Therefore, the degree to which the app is adjusted to the user's training requirements strongly relies on the ability of the app design team to include features that exclusively aim to assist in the training of the BVI. By the term “ease of learning” (EOL), we will refer to the degree to which these features facilitate the user to learn how to use the app. Based on the interview data and using abductive reasoning, we argue that these features play a significant role in the acceptance of the offered service.

Section 3 describes the BVIs who participated in the interviews and briefly outlines the whole procedure. Section 4 presents the classification of the elicited requirements of the BVIs after their responses being classified in these seven categories in the context of this research. This classification is then used in Sect. 5 to synthesize the elicited requirements and derive a framework within which the development of assistive navigation systems can optimally act as Gain Creators and Pain Relievers for the BVI, setting at the same time the foundations for the achievement of optimal adoption rates.

Special attention is given to the elicited demands raised by the BVI concerning the training approach on the use of these apps in Sect. 5.2. Following this, Sect. 6 describes the proposed assistive navigation system. Section 7 presents how user elicited requirements are met along with a discussion concerning the limitations and the future scope. Lastly, Finally, Sect. 8 concludes the chapter.

## 7.3 Methodology

### 7.3.1 Description of the interview participants

The interviews were conducted at the premises of the Lighthouse for the Blind of Greece, which is the main non-profit organization for education and assistance of the BVI in Athens. Thirteen male and female members of the BVI community participated in semi-structured interviews. The number of participants not only appeared to be in line with the literature on qualitative research (Guest et al. [40] and Adu et al. [41], or, concerning people with visual impairments, Wolffe and Candela [42], Kane et al. [43] and Guerreiro et al. [44], among others) but also proved, in practice, adequate because data saturation appeared to be already reached before the last interview.

The impairment of the participants ranged from severely impaired vision to complete blindness. Generally, each interview lasted at least 45 min. Undoubtedly, handwriting and proctoring an interview simultaneously can be very challenging. For this reason, we carefully prepared the subjects and the questions before the first interview which lasted more than one hour. From the third interview, however, our performance was significantly improved, and the interview duration dropped to about 45 min. The descriptive characteristics of the interviewees are presented in Table7.1.

### 7.3.2 A brief outline of the interviews

The general structure of the interviews was the following:

First, the participant introduced herself or himself. During this part of the interview, the BVI were asked about characteristics such as age, degree of vision loss, cause of vision loss and age at which this occurred. Then, they were asked about their employment status. They were also asked about how familiar they feel with digital apps. The next part of the interviews included a presentation of the features and capabilities of the apps as they were initially conceptualized by our research team. Finally, a detailed discussion followed, which included specific questions concerning the BVI’s indoor and outdoor navigation habits.

During this part of the interview, the BVIs were asked specific questions about their preferences and requirements that would ideally lead them to adopt and efficiently use the apps. These questions concerned requirements about the usefulness and capabilities, the functionality and the usability of the apps. The BVIs also had suggestions concerning the compatibility of the assistive navigation apps with other apps and services.

The discussion of each subject was separated into two sections. The first concerned the presentation of the apps and specifically the exhibition of the features that were initially included in the app to address the subject. The second section concerned the discussion on the subject and the recording of the answers of the interlocutor. Specifically, the interlocutor was asked about how he/she perceived the efficiency of the initial app design. Then, the BVI was urged to propose features for the app, which he/she believes are either necessary or that would significantly enhance the functionality of the app for the specific subject.

Table 7.1 Characteristics of the BVI who participated in the interviews

| | Gender | Age | Degree of visual impairment | Cause of vision loss | Digital sophistication |
|---|---|---|---|---|---|
| P1 | Male | 55 | Complete | By birth | High |
| P2 | Female | 35 | Severe | By birth | Average |
| P3 | Male | 36 | Complete | Diabetes | High |
| P4 | Male | 40 | Almost complete (95%) | By birth | Low |
| P5 | Male | 40 | Almost complete (95%) | By birth | Low |
| P6 | Female | 55 | Complete | Retinopathy (23 years old) | Low |
| P7 | Male | 40 | Almost complete (90–95%) | By birth | Low |
| P8 | Male | 40 | Complete | Cancer (7 years old) | Low |
| P9 | Male | 35 | Almost complete (> 95%) | Benign tumor (15 years old) | Low |
| P10 | Male | 60 | Complete | By birth | High |
| P11 | Male | 30 | Complete | By birth | High |
| P12 | Male | 40 | Complete | By birth | High |
| P13 | Male | 38 | Almost complete (90- 95%) | Craniocerebral injuries at 23 | High |

The questions and the overall discussion during the interviews were aiming to elicit user recommendations concerning not only desired characteristics of specific functions and the corresponding modules of the apps but also concerning specific factors that would facilitate the BVI to learn how to use them. It is worth noting that the term “ease of learning” is widely considered in the mobile applications’ literature concerning learning through the app and not learning the app itself. The consideration of these factors during the design of the apps is expected to enhance both the interest and engagement of the prospective users.

Each interview lasted for at least 45 min. The interviews with the BVI were recorded on paper. During this time, a wide range of subjects were discussed. Their responses were classified to facilitate the derivation of useful conclusions. To retain parsimony, the primary material was classified in the seven categories of Table 7.2 and presented concisely.

The primary material gathered in the form of analytical notes corresponds to many pages. It is worthwhile mentioning that just the relevant part of the answers of the BVI participants (excluding the questions and the full dialogue that led to each answer) filled 29 typed pages. Moreover, similarities were often identified between the stated requirements

*Table 7.2 Categories of interview responses*

| | | |
|---|---|---|
| (1) Special characteristics of the BVI | a. Perception of the Environment | f. |
| | b. Navigation (in general) | |
| | c. Pedestrian navigation | |
| | d. Use of smartphones and browsers | |
| | e. General features and suggestion | |
| (2) Requirements concerning usefulness and capabilities | a. Obstacle detection | d. |
| | b. Navigation | |
| | c. Additional characteristics | |
| (3) Functionality requirements | a. External stimuli | d. |
| | b. Audio/voice interaction between the BVI and the apps | |
| | c. Tracking and positioning accuracy and auxiliary devices | |
| (4) Usability Requirements | a. Characteristics/features of apps and devices | |
| | b. Device handling | |
| (5) Requirements concerning the training process of the assistive apps and devices | | |
| (6) Compatibility—parallel operation with other applications. Critique of applications, operating systems and infrastructures | | |
| 7) Other desirable features and general remarks | | |

or described characteristics from different interviewees. The findings presented hereafter resulted from filtering the answers with respect to common content, as well as to references concerning location-specific (and other) particularities which may be considered as additional noise in the data. For example, when a BVI is not satisfied with the telematics system of a specific Mass Transit System, organization or company, we focus on the elements of an arbitrary telematics system, which would be required to offer a satisfactory service to the BVI. Finally, the classification of the requirements relied heavily on the basic principles of the Technology Acceptance Model [45] and its successor, the Unified Theory of Acceptance and Use of Technology [46].

## 7.4 Classification of the BVIs' elicited requirements

The answers, suggestions and comments of the BVI were classified into seven main categories. These categories correspond to a broader concept of a requirement (see Hickey and Davis [47]) and include special characteristics and needs of the BVIs, requirements about the usefulness and capabilities of the apps, functionality requirements, usability requirements, requirements about the learning process of the assistive apps and devices, requirements concerning the compatibility and parallel operation of the apps with other apps and services, and other desirable features and general remarks about the assistive apps and devices. These categories were further divided into subcategories as presented in Table 7.2.

The classification of the elicited requirements to the categories of Table 7.1 is presented in the following section. Each of the following subsections corresponds to one of these categories. The subsections begin with a paragraph describing the category and, when required, the corresponding subcategories. The paragraph also contains a sample of the primary interview material that corresponds to the category, where the participants are referred to as P# where # is replaced by the participant number as it is presented in Table 7.1. To highlight the rate at which data saturation was reached, the requirements presented after each of these paragraphs are also followed by the number of the particular participants who first mentioned them (in parenthesis). It is of great importance to note that all the statements concern the opinions and preferences of the particular interviewees and state it from their own experience and point of view. Nonetheless, their statements concern what they believe for the BVIs in general, and not specifically just for themselves.

Furthermore, after the parenthesis in every sentence is noted how many participants mentioned the same or closely related topics. Therefore, the degree of acceptance of the reported elicited requirements in relation to the whole sample of interviewees is ensured.

### 7.4.1 Special characteristics of the BVIs

The first category of the subjects and information, which was elicited during the interviews, corresponds to the particular characteristics and needs of the BVIs. This category was further divided into 5 sub-categories. Specifically, we have identified the subcategories of particular needs and characteristics of the BVIs concerning (a) the way they perceive the environment, (b) their navigation by using any means of transport, (c) pedestrian navigation, (d) the use of smartphones and web browsers and (e) the way they perceive navigation in exterior and interior spaces. The BVIs were very willing to talk about these subjects and provided us with valuable information about their special characteristics and needs, which directly or indirectly relate to navigation. For example, P3 mentioned that "I have a good ability to hear and perceive sounds from two different sources at the same time" (sub-category a), while P6 said about the use of buses, "… if I know the route, I will use a "smart stop". I ask the bus driver. Some of us are bashful and do not use the white cane when they get off the bus" (sub-category b). P2 states: "I do not do other things while walking. If I need to do something else, I will have to stop. I believe that other people with visual impairment do as I do" (sub-category c). P7 said that "the bone conduction headphone is excellent but expensive" (sub-category d), while P11 said that "the bad thing is that I am afraid that I will not be able to adapt to the new technology. I am used to real keyboards instead of touch screens" (sub-category e). The full set of characteristics elicited by the interviews is presented below. (a) Perception of the environment. The BVIs in general:

(i) have enhanced the ability to hear and perceive sounds from two different sources at the same time. (P3), mentioned by 10;
(ii) can listen to reading at high speeds or pay attention to more than one sound source simultaneously. (P1), mentioned by 11;
(iii) have a very good memory, as well as a sense of direction and time. (P3), mentioned by 8;
(iv) can process sounds with increased speed and accuracy (e.g., in music, some are very good in dictation). (P2), mentioned by 8;
(v) are orderly and well organized. (P11), mentioned by 3;

(vi) When the BVIs do not have a complete loss of vision, they sense changes in the light (when there are not too many dwellings). (P3), mentioned by 7;

(a) Navigation (general):

(i) The most preferable means of transportation for BVIs is Taxi. Most of the BVIs choose taxis for their journeys. (P2, P4), mentioned by 2;
(ii) The younger BVI use the internet for choosing a means of transport, while the older ones prefer to be accompanied. (P2), mentioned by 7;
(iii) When moving, a BVI relies much more on his/ her memory than a sighted person does. (P1), mentioned by 8;
(iv) They prefer to arrange the call for taxis, as well as the payment, by phone, the internet or mobile apps (e.g. Taxi Beat with credit, prepaid or debit card). They do not trust taxis that are not connected to central reservation/call systems. They do not take a taxi randomly from the road. They always call a taxi by phone or the internet because this assures them that it will be a real one. (P4), mentioned by 7;
(v) Most of the BVIs choose (and prefer) to have someone to escort them. (P5), mentioned by 8;
(vi) When they use the bus, the BVIs use "smart stops" when they take a route they already know. They ask the bus driver where to get off the bus. (P6), mentioned by 7;
(vii) When they follow a track for the first time, they memorize characteristics of their route (step counting, direction, sounds, odours). They also often ask people they meet on their way. When they get off the bus, they rely on hearing, smell and finally touch, and count steps to move on the sidewalk. (P6), mentioned by 8;
(viii) They prefer using a taxi the first time they go to a destination. (P7), mentioned by 7;
(ix) Sometimes they are panicked when they go to unfamiliar places. They are often advised to visit only familiar places. (P8), mentioned by 5;

(x) In many countries, trucks may occupy the pavement in order to supply stores. This is considered by the BVI as a major danger. (P10), mentioned by 4;

(xi) Places, where special consideration should be given, are by priority the following: (P10), mentioned by 4;

1. **Subway Stations (English always with glass, no gap);**
2. Bus stop;
3. Obstacles on the road;
4. Stores;
5. Public buildings, Ministries.

(a) Pedestrian navigation:

(i) The BVIs have to prepare a plan of the route before their departure. They believe that it is dangerous for them to walk and at the same time adjust the route. Any adjustment or change can only be done if the BVI stops, or as long as he/ she is a passenger of any means of transport.
(P1), mentioned by 6;

(ii) The BVIs move slower than the sighted people while walking. They do not simultaneously make other movements while walking. If they need to do something else, they will have to stop (e.g., checking the cell phone and listening to the sounds of the surroundings). (P2), mentioned by 7;

(iii) In some countries, the BVIs prefer to walk on the road instead of the sidewalks because laws are not respected concerning not occupying the sidewalk. They move side by side, right next to cars. (P3), mentioned by 9;

(iv) Elderly BVIs are moving on foot at a fast pace. Young BVIs have a much slower pace. (P3), mentioned by 4;

(v) The number and steepness of the stairs are very important for a BVI. (P9), mentioned by 4;

(vi) The white cane identifies the stairs by hitting their upper side (the edge). (P10), mentioned by 4;

(vii) Some are especially bashful about using the white cane after getting off the bus. (P6), mentioned by 6;

(viii) The BVIs use hearing to perceive when cars are moving or if a car is coming in their direction. (P6), 6 mentioned;

(ix) They cross wide streets (such as avenues) using their hearing. Electric cars, which make no noise at all, may be very dangerous. (P10), mentioned by 4;

(x) The narrow roads make BVIs confused. There, they use the smells they have memorized from previous visits (e.g., they recall smells by ovens, and the like). (P4), mentioned by 8;

(xi) When they go to new destinations, the BVIs put up signs (memorize sounds, smells, etc.) and do not hesitate to ask other people. (P6), mentioned by 6;

(xii) They always follow the special tactile paving on the sidewalk to avoid permanent obstacles. If they make a mistake (step counting, loss of direction, etc.) and feel lost, they try to return to the sidewalk, and they start again from the beginning. (P2), mentioned by 5; (a) Use of technology:

- (i) The BVIs make extensive use of smartphone voice capabilities. (P2), mentioned by 6;
- (ii) Overall, iPhone usage is around 75% (clearly over 60%) while the remaining 25% uses android devices. It is very rare for a BVI to have two devices with both operating systems. (P3), mentioned by 7;
- (iii) The elder BVIs may not be interested in mobile applications. (P3), mentioned by 7;
- (iv) The BVIs are usually open to try a new application or device, which they perceive as useful and accessible (e.g., designed so that it can be used by the BVI). (P5), mentioned by 7;
- (v) They prefer bone conduction headphones. However, they are concerned about the cost. (P7), mentioned by 5.

(a) General features, psychological characteristics and suggestions:

- (i) Often, the BVIs are afraid of the idea of h aving vision. (P2), mentioned by 6;
- (ii) They are often employed in professions that require a particular ability to identify by touch (for example as physiotherapists). (P1), mentioned by 7;
- (iii) The BVIs find very appealing the idea of a museum visit. They believe, however, that only the possibility to touch three-dimensional miniatures or sculptural representations of the exhibits would make them truly feel this experience. (P3), mentioned by 6;
- (iv) While smartphones have voice capabilities, those who have at least minimal vision put the phone close to the eye probably because they do not want to accept their defective vision. (P7), mentioned by 5;
- (v) The image that a BVI creates for something or someone is usually better than the real one. (P1), mentioned by 6;
- (vi) The BVIs request a large variety of sculptures accessible to them at Tactile Museums. (P2), mentioned by 7;
- (vii) They also use the white cane to avoid colliding with other people. The BVIs believe that sighted people care about them when they hold the white cane. (P10), mentioned by 4;
- (viii) They learn mostly by word of mouth that an application is good and useful (e.g., e-radio, google translate, AMTS telematics). (P5), mentioned by 6;
- (ix) The BVIs are often interested in visiting new destinations. (P1), mentioned by 7;
- (x) For a BVI the order of importance of other senses is (P3), mentioned by 6:
    - **(1)** **Hearing;**
    - **(2)** Smell;
    - **(3)** Touch;
- (xi) The BVIs who are blind by birth are better adapted to the lack of vision, not only in practice but also in terms of psychology. They do not know how it is to be able to see. On the other hand, the BVIs who could once see are psychologically burdened. (P2), mentioned by 7;
- (xii) Mobile phones of the BVIs are often stolen. (P8), mentioned by 4;

(xiii) The BVIs are often familiar with having a wearable device. They believe it is a good solution to incorporate such a device on the white cane. (P12), mentioned by 2;

(xiv) Some of the BVIs are reluctant because they fear they will not be able to adapt to the new technology because of its complexity. (P11), mentioned by 3;

(xv) The BVIs fear that they will often block their smartphones when trying to make complex operations. (P11), mentioned by 6;

(xvi) It makes no sense to say “Do not Touch” to a BVI who visits a museum. This is because prohibiting the BVIs from feeling the objects through touch is equivalent to prohibiting a sighted person from looking at an exhibit. (P8, P12), mentioned by 2.

### 7.4.2 Requirements concerning the usefulness and capabilities of assistive navigation apps and devices

In this subsection, the requirements concerning the usefulness and capabilities of assistive navigation applications and devices are presented, as they were elicited from the interviews. These requirements have been classified into three sub-categories. This concern (a) obstacle detection, (b) navigation and (c) additional desired features of the apps. As P3 mentions, “… It is a problem to have obstacles at a different height at the same time…” (sub-category a), while P10 said that “it is important [the app] to announce the arrival of the means of transport” (sub-category b). Moreover, P3 stated that “I believe that it is also important to be able to inform a person of trust or the police about my position” (sub-category c). Next, all of the elicited requirements for this category are presented.

(a) Obstacle detection:

(i) The sonar should be capable of scanning both horizontally and vertically. (P1), mentioned by 4;

(ii) It should be possible to simultaneously detect multiple obstacles and report them appropriately, guiding the BVIs to manoeuvre with precision. (P3), mentioned by 5;

(iii) The sonar should be able to detect obstacles that are relatively high and not only ground-based in front of the BVIs, such as low balconies, awnings, signs, etc. (P3), mentioned by 4.

(a) Navigation:

(i) The app should be able to combine pedestrian navigation with the use of means of public transport. (P1), mentioned by 7;

(ii) The app should be able to notify the BVIs about the arrival of a means of transport (bus, train, etc.), its type, its direction and destination. Smart stops are very important. (P1), mentioned by 4;

(iii) There should be real-time information on public transport (e.g., connection to the AMTS telematics service). (P6), mentioned by 4;

(iv) The app should be able to identify the traffic lights on the streets, as well as their status. (P3), mentioned by 7;

(v) When the app notifies the BVIs about the status of a traffic light, it should be able to identify the danger that may arise from a driver who does not follow the signal of the traffic light. (P1), mentioned by 7;

(vi) The app should be possible to detect a wrong route and to correct or adjust the route in case of deviation from the selected path. (P2), mentioned by 10;

(vii) The apps should provide information about the entry or exit points from buildings or other restricted spaces such as parks, zoos, amusement parks, train stations etc. (P2), mentioned by 6;

(viii) The apps should provide information about where the stations or stops are located and suggest a route that the BVIs would have to follow to arrive there. (P1), mentioned by 7;

(ix) According to the BVIs, the app must inform them about the type and name of the shops that are located along the BVI's route. (P3), mentioned by 7;

(x) In interior spaces, such as museums, stores, etc., the app should be able to inform the BVIs about the location of points of interest, such as the WC, reception points, help desks or cashier facilities (depending on where the BVIs is located). (P3), mentioned by 7;

(xi) When the BVIs are in a train or an underground railway station, the app should be able to inform them about where to find the ticket machines and the cashier, as well as how to reach the pier of the train they must take. (P10), mentioned by 5;

(xii) It is desirable to be able to add multiple destinations or stops along a route. (P3), mentioned by 5;

(xiii) Navigation priorities: (P2), mentioned by 7:

**(1) Obstacles on the road or the sidewalk;** (2) Stores;

xiv) There should be a brief routing report of the total route in the start of the navigation. (P1), mentioned by 7.

a) Additional features:

(i) The data concerning internal spaces must be easily modifiable. For example, it must be easy to improve or modify a description of interior space (e.g., adding a museum exhibit, or changing its location). (P1), mentioned by 4;

(ii) It is also important to have a trusted person, or the police informed of the BVI's position. (P3), mentioned by 6;

(iii) The BVIs must be able to request assistance from the staff of a museum at any time. (P3), mentioned by 5;

(iv) It is very important to update and renew access information to stores as well as their name and type. (P3), mentioned by 5;

(v) The apps should give weather information. (P3), mentioned by 5;

(vi) The apps should display the battery's status. (P1), mentioned by 5;

(vii) The apps should have a lock function when it is in idle mode. (P1), mentioned by 6.

### 7.4.3 Functionality requirements

This subsection presents the elicited requirements concerning the functionality of the mobile assistive navigation apps. These requirements have been classified into three sub-categories. The first (sub-category a) concerns how the apps and the peripheral devices should behave concerning the external sounds, while the second (sub-category b) includes requirements concerning the interaction of the BVIs with the device through voice commands and directions, as well as through other types of sounds. Finally, the third (sub-category c) corresponds to requirements concerning the accuracy of tracking and positioning of the navigation system (app and auxiliary devices), as well as functionality requirements of the auxiliary devices. As P1 mentioned, "… it is very important that [the ambient sounds] are not covered by the sounds produced by the app because otherwise, it becomes for us very difficult to perceive the environment" (sub-category a). A very important issue that many BVIs mentioned was the identification and status of the traffic lights (sub-category b). Moreover, as P3 stated, any "GPS and sonar signal amplifiers should be discreet" (sub-category c). Of course, the elicited functionality requirements are much more, and are presented as follows. a) External stimuli:

i) The ambient sounds must not be covered by the sounds produced by the app, because the BVIs always use their hearing to perceive the surrounding space. Therefore, the use of a headset that covers both ears is excluded from the implementation of the assistive navigation system. One ear should be able to hear the sounds of the surroundings. (P1, P3), mentioned by 2;
ii) Only important cell phone information should be reported phonetically, and ambient sounds should not be depreciated or covered. (P1), mentioned by 5.

a) Audio/voice interaction between the BVIs and the apps:

i) Voice guidance is preferable to audio. (P1), mentioned by 7;
ii) It is necessary to have an audio signal on the traffic lights. (P1), mentioned by 7;
iii) In case that both traffic lights and apps produce
sounds simultaneously, these must be easily distinguishable. (P9), mentioned by 5;

iv) The user interface must accommodate real-time updates about the means of Mass Public Transit (MPT). (P7), mentioned by 4;

v) The app should provide voice reporting of key route identification options that may combine pedestrian navigation and MPT use. (P4), mentioned by 4;
vi) The BVIs should be able to choose between sound alerts or vibration as a notification method by the app about obstacles along their route. Whichever the choice, it should be possible to turn the alert on or off. (P7), mentioned by 4;
vii) It would be desirable that the apps notify the BVIs about the remaining time before a traffic light turns red. In particular, a countdown informing the BVIs about the remaining time would be useful. (P7), mentioned by 4;
viii) As far as the colour of the light is concerned, the BVIs would prefer to be notified by voice (e.g., "red light") instead of a specific sound. (P10), mentioned by 4.

a) Tracking and positioning accuracy and auxiliary devices:

i) Positioning accuracy should be as high as possible.

(P1), mentioned by 7; ii) Concerning indoor navigation, it is essential to have a precision pedometer that would be able to report both the number of steps and the distance travelled.

(P1), mentioned by 7; iii) External GPS and sonar devices should be discreet and not too apparent if they are placed on the clothes or the body of the BVIs. (P1, P3), mentioned by 4;

iv) The female BVIs would prefer that the external GPS device is placed on a belt, bracelet, or neck strap. Some BVIs would prefer a ring adjusted on the white cane. On the other hand, wearing a vest or a hat with a GPS device would not be efficient. They believe that it is easy to lose a hat, while it is not so easy to lose the ring on the cane. (P2, P4), mentioned by 2;
v) To have a watch that provides increased GPS accuracy would also be a good idea. (P7), mentioned by 5;
vi) vi) The sonar must refresh the information it provides at high frequency because some of the BVIs are moving at a fast pace. (P1), mentioned by 5;
vii) Concerning the use of a device on a companion dog, a significant number of the BVIs consider that the dog restricts their freedom since it requires commitment. Therefore, the majority of the BVIs would not prefer such a solution. (P9), mentioned by 3.

### 7.4.4 Usability requirements

This subsection presents the elicited requirements concerning the usability of mobile assistive navigation apps. These requirements have been classified into two sub-categories. The first (sub-category a) refers to the special characteristics and features of the apps and the peripheral devices that the BVIs would wish to have, while the second (sub-category

b) concerns device handling requirements. The elicited requirements presented below represent the statements of the BVIs during the interviews, which concern this category. For example, P2 notes: "I believe that since many of us do consume a lot of memory, the implementation should not be particularly burdensome in this area" (sub-category a), while P12 states that "you will have stored in the [smartphone's] memory a set of favorite routes" (sub-category b).

1) Characteristics/features of apps and devices:

i) The user interface on the touch screen must operate with clear and simple gestures. Keyboards are also useful. (P1), mentioned by 6;
ii) It would be highly functional for the BVIs to have textured keys, but the keyboard layout should be simple to learn. (P2), mentioned by 6;
iii) Still, many of the BVIs would prefer small key-boards like those of former types of cell phones, but with special features like the keyboard of Blackberry. (P11), mentioned by 3;
iv) Because the BVIs allocate more memory during their everyday activities, the apps should not be particularly demanding concerning human memory.
(P2), mentioned by 5;

v) Bluetooth headphones have the advantage that they do not have cables that may become entangled. On the other hand, they are more easily lost and they require to be charged often. (P1), (P3), mentioned by 2;
vi) The apps should use a button of the cell phone as a button dedicated to emergency assistance calls. (P6), mentioned by 5;

vii) The information that appears on the smartphone screen must be sequentially presented (column by column or row by row) because the VoiceOver app often has difficulty identifying separate lists or columns and present them one by one. (P7), 4 mentioned by 4;
viii) The BVIs prefer swiping gestures rather than tap-ping on the smartphone's screen. (P1), mentioned by 8.

1) Device handling:

i) It would be desirable that the search menu includes voice navigation, and that the app has the capability of voice activation of commands. Thus, the BVI would be able to dictate the destination address to the app and phonetically use its capabilities. (P1), mentioned by 7;
ii) The BVIs should be able to navigate within the configuration activity to find destinations either using voice commands or the keyboard. The existence of a destination verification signal or message is also important. (P1), mentioned by 7;
iii) It would help the BVIs in the use of the app if the app used a keyboard similar to the keyboard of the operating system of the BVI's smartphone. (P2), mentioned by 7;
iv) It would be useful that the indoor navigation app provides a destination index on the touch screen, with features such as scroll up and scroll down and sorting destinations alphabetically. (P1), mentioned by 7;
v) The BVIs prefer to use the touch screen through gestures instead of tapping on touch icons. They appreciate the usability of iPhone apps. (P3), mentioned by 5;
vi) It is important concerning the usability of the apps that their collaboration with the screen reader is not complicated. (P2), mentioned by 7;
vii) Screen readers should be able to fully read in detail the screen produced by the apps. Voice confirmation must be requested before performing each operation/
action (e.g., after a gesture or an icon tap). (P1, P5), mentioned by 2;

viii) Concerning outdoor navigation, it would be desir-able that the app provides a list of "favourites" (or preferable) destinations that the BVIs would be able to edit. (P7, P12), mentioned by 2.

### 7.4.5 Requirements concerning the learning process of the assistive apps and devices

This subsection presents the elicited requirements concerning the learning (or training) process that the BVIs should follow to efficiently and safely use the assistive navigation mobile apps. It must be noted that during the interviews, it was identified that the BVIs are very concerned about the complexity of the apps and how they could be used properly. Therefore, part of the interviews focused on the conditions which are believed by the BVI to be appropriate for learning how to use the apps. For example, P3 mentioned that "I would prefer to start learning the [interior navigation] app in a familiar space and not directly in a museum", while P6 stated that "otherwise I will be very anxious: Am I going to make it? would it be as I would like to?" These concerns along with other statements by the BVI about specific requirements led us to create this distinct category. These requirements are presented below:

1. Because the majority of the BVIs use either Android smartphones or iPhones, the apps should be offered for both operating systems. (P1, P3) mentioned by 5;

2. The training process of the BVIs on how to use the apps should take into account that the BVIs prefer to be educated in their familiar spaces (those they visit frequently), such as their schools or training rooms. The BVIs could also practice in-house navigation in their home or workplace. (P3), mentioned by 7;
3. The BVI's learning rates of the apps may vary significantly, as their familiarity with digital technologies ranges from zero to very high levels. Considering the increased complexity of the apps, given their full range of features, the training of the BVIs can take from half a day to even a week. That is, users are not a homogeneous group in adopting technologies. (P4), mentioned by 4;
4. The need for organised classes, in which the BVIs will be trained on how to use the navigation apps, was highlighted even by those BVIs who believe that they can learn the apps on their own. It should be noted, however, that some of the BVIs failed to assess the number, variety and complexity of the tasks covered by the apps. (P4), mentioned by 7;
5. Although complex enough, the benefits of the apps should be explained analytically in an easy-to-understand way, to motivate the BVIs to get involved in the training process. (P3), mentioned by 9;
6. When visiting a museum using the app, the BVIs must be confident that they will not fall and hurt themselves or cause damage to the exhibits. (P7), mentioned by 6;
7. Some of the BVIs may be hesitant to visit a museum using the app without being previously well trained on how to use the app in a museum. (P5), mentioned by 7;
8. Because many BVIs are initially hesitant to use anything that has increased complexity, any training class should be organised in such a way that the BVIs will be able to learn the apps step by step, so that they gain confidence in their abilities. (P4), mentioned by 7;
9. It was stated that it would be better if information about the museum is provided before the visit, such as audiobooks and recorded lessons which are very helpful, especially when given in short sections for very quick listening whilst on the road or at home. (P9), mentioned by 5;
10. It is of high importance that the BVIs should have already been trained using applications such as smartphones, i-pads, telematics, etc., before they visit museums or other similar places, so as to be capable to move and deal with any possible obstacles they could encounter. (P6), mentioned by 8;
11. The BVIs consider that part of their training on how to use the apps should take place at locations, indoor or outdoor, which the apps will be designed to be used for. (P4), mentioned by 7.

### 7.4.6 Compatibility—parallel operation with other applications. Critique of applications, operating systems and infrastructures

This subsection presents the elicited requirements concerning the compatibility and parallel operation of the assistive navigation mobile apps with other apps or services. These requirements have been classified into three sub-categories. The first (sub-category a) refers to the compatibility and parallel operation with other apps, while the second and third present a critique of the BVIs on other apps and operating systems (sub-category b) and infrastructure (sub-category c), respectively. Many of the BVIs are concerned about how screen readers will collaborate with the navigation apps. As P2 mentioned, "[the navigation apps should] allow screen readers to run in parallel" (sub-category a). Very useful was also the feedback provided by the BVIs about the current appeal of smartphone operating systems: As P10 stated: "On iPhones, we have the BlindSquare app which is fantastic and collaborates with Maps" (sub-category b). As far as the infrastructure review is concerned, one must consider that the BVIs in the interviews had the experience of living only in Greece. However, we were able to identify significant accessibility requirements. For example, P11 mentioned "I feel that when it's crowded, it's dangerous for me to be on the pier of the underground railway, and in particular when it rains and the shoes of other passengers bring water downstairs and it becomes slippery" (sub-category c).

a) Compatibility—parallel operation with other apps:

i) Applications should be accessible to screen readers.

(P1), mentioned by 7; ii) The use of the screen readers (such as iPhone's VoiceOver and Google's TalkBack) requires special attention as they create their own "conditions" on the screen, adding, for example, gestures that assist navigation through the smartphone's interface. (P1), mentioned by 7;

iii) The apps must be compatible with these conditions and not require that the screen readers are switched off. (P1, P3), mentioned by 7;
iv) In case a parallel operation with the screen reader is not possible, the screen reader should go into the background or switch off, and once the navigation app goes into the background, the screen reader must be reactivated. (P1, P2), mentioned by 5;
v) The navigation apps should allow other applications to run in parallel with them. (P2, P3), mentioned by
2;

vi) It would be very useful if the navigation apps could cooperate with image recognition apps that describe images, such as Google Lens. (P4), mentioned by 4.

a) Use and critique of other apps, operating systems:

i) The BVIs believe that the navigation services offered by Android devices (Google maps) and iPhones (Maps) suffer from inaccuracies and do not provide good route optimization, nor do they have a good menu. (P1, P7), mentioned by 2;
ii) Although the Google maps navigation app has a "countdown" feature for the distance before a turn or a stop, the BVIs believe that the notification of arrival takes place at the last minute without taking into account the reaction time of a BVI, but only that of a sighted person. (P1), mentioned by 4;
iii) The BVIs are satisfied with the performance of the iPhone's VoiceOver. (P3), mentioned by 4;
iv) The BVIs use the BlindSquare app extensively.
(P10), mentioned by 3

v) The iPhone has proven to be very functional in its use by the BVIs. (P3), mentioned by 4;
vi) Many of the BVIs believe that Apple's touch screen keyboard is very functional and, in fact, more functional than the keyboards of Android smartphones.

(P3), mentioned by 4; vii) iPhone touch screens respond to simpler and more efficient gestures than the touch screens of Android smartphones. (P1), mentioned by 5;

viii) A bias was identified towards iOS in comparison to Android, concerning the accessibility features. (P2), mentioned by 5;
ix) iOS is a more closed system than Android. As a result, it offers more efficient control and protection against viruses. (P4), mentioned by 4;

x) The BVIs find it important that smartwatches like Apple's iWatch offer a service that gives precise, on-time notification to relatives and people of trust in case of an emergency. (P4), mentioned by 4;

xi) Concerning voice interaction with the smartphone, the BVIs believe that the preset settings of iOS provide better usability than the corresponding settings in Android devices. (P10), mentioned by 3;

xii) In general, Apple is characterized by applications and services that are already configured and ready to use. Many of the BVIs believe that this fact offers increased autonomy when compared to the required installation and setup procedures of similar Android apps, which may require assistance from a sighted person (e.g., for the installation and configuration of Android's Talkback for the first time). (P10), mentioned by 3;

xiii) Many of the BVIs believe that the iOS operating system has more sophisticated automated features than Android. (P9), mentioned by 3;

xiv) It is also very useful for the BVIs that VoiceOver can collaborate with Netflix to read the subtitles. (P4), mentioned by 4; xv) The BVIs use image recognition apps (or capabilities of apps) while shopping in the supermarket to see when a product expires and for recognition of coins and paper money. (P4), mentioned by 4;

xvi) Many of the BVIs who use an iPhone do not trust

Google's Talkback. (P7), mentioned by 4; xvii) Google does not usually support the use of different means of mass transport in a single journey. (P11), mentioned by 2;

xviii) The BVIs believe that it would be useful if the screen readers have an option to spell the letters of a word. (P11), mentioned by 2;

xix) Unfortunately, screen readers propagate the errors of automatic translation services or apps. The BVIs believe that such services make wrong translations quite often, mainly due to a lack of understanding of the context of the specific phrase. (P3), mentioned by 4;

xx) Many BVIs would prefer to buy a more expensive smartphone if it had better accessibility features, including the already installed and configured apps.

(P7, P10), mentioned by 2; xxi) Some of the BVIs believe that attaching a mini keyboard to the smartphone increases its usability because this way the BVIs can understand the letters. However, other BVI stated that they would never prefer such a keyboard over the functionality a touch screen offers since they consider mini keyboards as obsolete. (P12), mentioned by 2;

xxii) The BVIs who reside in Athens Metropolitan Area are satisfied with the operation of the AMTS telematics application. There is also significant dissatisfaction with the Moovit application. (P3), mentioned by 4.

a) Infrastructure review:

i) Malfunctions or damages of traffic lights or in the means of public transport are not quickly repaired.

(P2), mentioned by 4; ii) In general, the BVIs residing in Athens metropolitan area are satisfied with the operation of the telematics app of the local civil transport organisation. However, they are not satisfied with the information provided by the Moovit app. (P3), mentioned by 4;

iii) The speakers on the buses, which are used by a tele-matics system (as the one of AMTS) often, should operate properly. Otherwise, the BVI may not be able to hear the messages informing them that they have arrived at the stop of their destination or the intermediate stops. So that such a system functions properly, regular maintenance of the communication systems must be provided. Moreover, appropriate control and information systems or processes should be used to promptly identify any hardware malfunction. (P11), mentioned by 2;

iv) If the BVIs are not notified early enough, the bus may pass the destination stop before they realise it. The information system or the process that will inform the BVI about where to get off the bus must be reliable. Otherwise, the BVI will not be able to get off the bus at the right stop. (P11), mentioned by 2;

v) The BVIs believe that the design of any underground railway system should take seriously into account accessibility and safety issues for visually impaired people. Specifically,

(1) **tactile paving should be used around the entry points of any station, as well as inside the stations,**
(2) special care should be given around benches or other obstacles that protrude beyond their bases, because the white cane can go under them and the BVIs are not informed as soon as they wish about their existence, or it’s difficult to find and use them, and
(3) before the rails, because they fear the gap between the pier and the trains. (P10), mentioned by 2;

vi) The BVIs find the escalators useful because they produce noise, which makes them easy to locate.

(P10), mentioned by 2; vii) The BVIs feel that it is dangerous for them to use the underground railway when the pier is crowded or when the floor is wet, which usually happens when it rains outside. (P11), mentioned by 2;

viii) The BVIs would appreciate any voice message informing them when the next train arrives. (P11), mentioned by 2;

ix) There is no integration or there is inefficient integration between the Telematic system of intercity and civil buses, as well as one of the railways. The BVIs would appreciate an integrated telematics system or a collaboration between separate systems. (P11), mentioned by 2.

### 7.4.7 Other desirable features and general remarks

Although the previous subsections presented a detailed classification of the elicited requirements of the BVIs, few of their ideas or opinions, which focused on desirable features of the navigation apps or concerned general remarks, could not be classified therein. These ideas, opinions and remarks are the following:

1. The use of Bluetooth beacons is very important for accurate indoor navigation. (P1), mentioned by 4;
2. Colour recognition is applied by the BVIs for the use of washing machines, but it may also have other applications such as identification of the colour of the traffic lights. (P4), mentioned by 4;

3. The BVIs often use clock position to understand the direction they have to follow. Therefore, it would be useful that the voice messages concerning direction description use the clock position system. (P4), mentioned by 4.

## 7.5 Induced general requirements

The previous sections presented the elicited requirements of the BVI, classified in a detailed set of categories and subcategories. This classification corresponds to the first treatment of the "raw material" provided by the interviews and should be considered during the Design, Development, Deployment and Distribution of any assistive navigation system for the BVI. Specifically, the information presented in Sect. 4 aims to assist the design and developing teams by providing a framework for the development of assistive navigation apps with potentially optimal adoption and use rates.

### 7.5.1 Synthesis

This subsection presents the main general results as they are induced by the detailed elicited requirements which were presented in Sect. 4. To this end, we will follow the order of classification presented in Sect. 4, with an exception concerning Subsection 4.5, which refers to the training of the BVI on how the navigation systems can be used. A special focus on this topic is given in the next subsection.

#### 7.5.1.1 Requirements concerning the special characteristics of the BVI

As mentioned in Sect. 4, the broad concept of the term "requirement" was used, which includes their special characteristics and needs. Subsection 4.1 highlighted these particular characteristics of the BVIs, with a special focus on navigation. The particular way the BVIs use to perceive the environment was identified, as well as the fact that the rest of their senses and their memory are trained to cope with the difficulties that arise because of their visual impairment. The preferences and needs of the BVI concerning the use of means of transport or during pedestrian navigation were also presented. It can be induced that the BVIs have a particular need for as much as possible controlled conditions of travelling and that they believe that any deviation of the initially programmed travel may easily result in disproportionate consequences for them. It was also identified that the BVIs may adopt a mobile app and, in general, a technological solution, as long as they feel confident that they can use it and understand the benefit from its use. As far as the benefit is concerned, however, this does not depend only on the app itself, but also on how the app is integrated into a

broader accessibility plan (as, for example, the existence of 3D miniatures of the sculptures in a museum, which would allow the BVIs to understand the exhibits through touch).

#### 7.5.1.2 Requirements concerning the usefulness and capabilities of assistive navigation apps and devices

Subsection 4.2 presented the user requirements concerning the usefulness and capabilities of assistive navigation systems. In other words, it presented the direct benefits the BVIs would wish to have by adopting the use of these systems. The need for detection of multiple, possibly moving obstacles with different shapes and at different vertical positions, was identified, along with the requirement for sensor signal update at frequencies higher than once per second. The BVIs also require a navigation system that would be able to combine pedestrian navigation with the use of other means of transport (providing real-time information for departure or arrival times). The importance of identification of traffic lights was also highlighted, and of the condition of the road to be crossed (e.g., incoming vehicles), independently, to cover the case where a driver does not (or is not able to) conform to the traffic light. Moreover, the navigation system should provide directions to the location and entry points of places of interest. As far as indoor navigation is concerned, again, the navigation app should be able not only to guide the user but also to inform him about service points, exits, etc. The navigation system should also easily adapt to modifications concerning the topology or the information about any point of interest. The BVIs showed a particular interest in museums that offer a haptic experience. Touching is by far the most useful way for them to understand an exhibit. Interestingly, the BVIs find particularly important the existence of a feature that allows notification of a trusted person, or even the police, in case of emergency.

#### 7.5.1.3 Functionality requirements

The functionality requirements of the navigation app are presented in Subsection 4.3. It was stressed that the interaction between the smartphone and the BVI user through sound should not cover ambient sounds. The importance of interaction with the smartphone through voice commands was also highlighted, in combination, however, with sound notifications and vibration, with the possibility to be customized by the user. The user requirement for a voice interface is compatible with the recent evidence about its superior effectiveness (see, e.g., Guerrón et al. [48]). This, should take into account the findings in Ahmetovic et al. [35] that link the verbosity level of interaction with the expertise of the BVI user (implying a requirement for adjustable verbosity level). Any additional device, such as a GPS amplifier, should combine discreet design and the possibility to be attached to the white cane or as a cloth accessory. Again, the importance of the traffic light information provided by the system was emphasized.

#### 7.5.1.4 Usability requirements

The BVIs prefer swiping gestures rather than tapping the smartphone touchscreen, along with as simple and not memory demanding as the possible design of the user interface. The auxiliary devices should not use cables. Interestingly, the BVIs highlighted the importance of the fact that they process information sequentially, and this rule should be followed when information appears on the smartphone screen. Navigation on the apps' menus should be possible through voice commands, while a list of "favorite" destinations would be very useful.

#### 7.5.1.5 Requirements concerning the learning process of the assistive apps and devices

Subsection 4.5 referred to the procedure the BVIs would have to follow to learn how to use an assistive navigation system efficiently and safely. Because of the importance of the corresponding findings, they are discussed along with ideas concerning this process in the following subsection.

#### 7.5.1.6 Compatibility—parallel operation with other applications. Critique of applications, operating systems and infrastructures

Issues concerning the desired (by the BVIs) compatibility and parallel operation of the navigation system with other apps/software are discussed in subsection 4.6. Parallel operation and collaboration of the navigation app with screen readers, the navigation services of Google and Apple, or other services, such as telematics services of mass transit systems, or apps that provide information about places and points of interest, was identified to be very important for the BVIs. Interestingly, the BVIs do not prefer over-customizable systems, because this increases the setup complexity. They believe that this factor makes Apple's services more accessible than the corresponding ones offered by Google. They find weaknesses in the translation services which are currently offered. Moreover, it must be noted that the BVIs cannot understand the speed of the vehicle they are using. In addition, they have to be trained to perceive a distance that is larger than a few meters. Consequently, when navigation services, such as Google maps, inform them about the distance to a significant point of their route they cannot understand how long it would take to get to this point. The navigation service should take into account the speed of movement concerning the reaction time of a BVI, and not only concerning the reaction time of a sighted person. Moreover, the Google maps navigation service suffers from inaccuracies, mainly due to the reduced GPS accuracy of smartphones, and does not provide good route optimization, nor does it have a good menu.

The BVIs would prefer that information from mass transit telematics systems would be announced through voice messages of the smartphone. It was identified that it is very difficult for the BVIs to compare prices and departure times of trains or buses. The BVIs proposed that the corresponding e-ticketing services present multiple prices and departure times in a structured way to facilitate screen readers. Moreover, the BVIs would prefer a fully integrated system of means of mass transit.

Notably, the BVIs provided useful information about desirable accessibility features of (underground) railway stations. A general conclusion concerning the comments of the BVIs about accessibility infrastructure is that its maintenance should be frequent, while adequate control systems should report any malfunction in real time.

#### 7.5.1.7 Other desirable features and general remarks

Other desirable characteristics of an assistive navigation system (Subsection 4.7) would include color or image recognition (or collaboration with apps that offer this service). Finally, as far as indoor navigation is concerned, the potential benefits of the use of Bluetooth beacons were appreciated by the BVIs. It must be noted that there is difficulty to implement or apply the full set of capabilities of a navigation system in indoor spaces such as supermarkets or malls where the GPS, 4G or 5G signal is extremely weak and the deployment of Bluetooth beacons seems to be unrealistic.

The following subsection focuses on the findings concerning the training of the BVIs on how to use a navigation system.

### 7.5.2 Training requirements

Before the first interview, the six requirements' categories, which were outlined in the previous subsection, had been identified. As early as the middle of the first interview, however, the plethora of the stated user requirements concerning indoor and outdoor navigation was leading the conversation toward the issue of the complexity of an adequate (concerning the requirements) assistive navigation system. Consequently (and naturally), this raised a concern about the ability of the BVIs to efficiently and safely use the assistive system. This concern was one of the main topics of conversation in all of the interviews and was expressed by the BVIs, mainly with statements concerning the need for training on the use of assistive navigation systems. It must be noted that concerning smartphone use by a BVI, such a need was identified by Rodriguez et al. [49]. However, in the case of assistive navigation systems, the complexity increases due to the interaction of the mobile apps with the environment, with external systems, as well as because the BVIs will be possible in motion while interacting with the corresponding apps. To summarize, this subsection highlights the fundamentally increased difficulty of use on an assistive navigation system, mainly because of its interaction with a dynamic environment. These remarks led us to include a new category of requirements in our analysis, namely, "requirements concerning the learning process of the assistive apps and devices," which was presented in Subsection 4.5.

It must be noted that the BVIs are divided between those who use iOS devices and those who prefer the Android operating system. Therefore, the "end-user" apps and interfaces should have versions for both operating systems. Second, the BVIs do not form a homogeneous group concerning technology adoption. Some of them require much more training time than others to feel confident to use an assistive device or app. All of them, however, require to first feel very confident about the safety offered by the correct and efficient use of an app, along with the benefit of its use, before deciding to devote time to learn how to operate it. This implies that the benefits that the assistive navigation system offers should be highlighted and explained in detail.

In addition to the presentation of the benefits, the training steps (or processes) that should be followed must be presented in such a way that will not avert the BVIs, but rather will motivate them to get involved. In other words, the involvement of the BVIs strongly depends on their confidence that they will be able to complete the training process, and, eventually, to efficiently use the app/system. That said, it is important that the way of communicating the benefits offered by the assistive system, as well as the communication during the whole training process, must be adapted to the age of the BVIs. For example, the trainer should consider the evidence that early and severe visual impairments can cause "irregular" language development during childhood such as echolalia and verbalisms [17], and significantly poorer use of language for social purposes, when compared with sighted children [50]. Moreover, the young BVIs and the sighted people may present difficulties in understanding each other's referents (see, e.g., Landau [51], for the case of BVIs children). These facts highlight the significance of detailed guidelines presenting the navigation system operation, while a step-by-step training process, with many examples, particularly when young BVIs attend the training session is also necessary. Another suggestion is to incorporate the aforementioned specific guidelines and other aspects of technology-featured O&M (Orientation and Mobility) training programs [52] with technologies specialized for navigation assistance. In other words, technology should be incorporated into O&M lessons so that BVI students can fully embrace technology in their daily lives for O&M purposes.

Concerning the training process, the interviews revealed that the BVIs range from those who believe that they would manage to learn by themselves how to operate the navigation apps, to those who would consider adopting and using the apps only if they first attended well-organized classes, which would increase their confidence level above a significantly high threshold. The complexity, however, entailed by the navigation process, raises the need to convince the "overconfident" BVIs to follow even a short training program with respect to the navigation system. Moreover, all participants stated that they would prefer to be trained in places familiar to them. Given the purpose of the assistive navigation system, any attempt to explore, demonstrate and teach its capabilities within a restricted environment seems very restrictive (or impossible). A possible solution to this problem could be offered by the use of simulated environments within a virtual reality framework. Virtual navigation has already proved useful. The use of virtual navigation tools before the beginning of the actual navigation allows the BVIs to mentally build a sequential representation of their route, which proves to be significantly assistive during the actual navigation [39]. However, the difficulty of the task increases when a navigation system must be simulated along with the environment (as well as their interaction). Another solution could be offered by the use of training versions of the apps, which could be easily parametrized by the instructor to simulate real conditions in places that are familiar to the BVIs.

*Figure 7.1. Pedestrian route trials—localization accuracy comparison between mobile embedded position system and Blind RouteVision system*

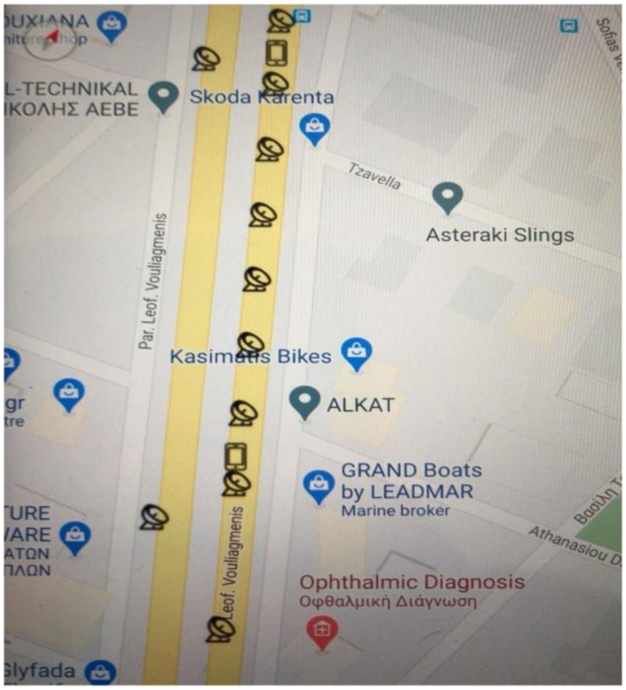

*Fig. 7.2. Car route trials for simulating public transport—localization accuracy comparison between mobile embedded position system and Blind RouteVision system*

## 7.6 System description and implementation details

The user needs and requirements analysis has been conducted during the initial phase of the development of two assistive mobile apps for autonomous navigation of the BVIs. These assistive apps are being developed in the context of the MANTO project (funded by the Greek RTDI State Aid Action RESEARCH-CREATE-INNOVATE of the National Operational Programme Competitiveness, Entrepreneurship and Innovation 2014–2020 in the framework of the T1RCI-00593 contract). The first mobile app (Blind RouteVision—see Figs. 7.1 and 7.2) aims to assist the BVIs during outdoor pedestrian navigation. The app's design includes enhanced GPS functionality and interconnectivity with other apps that may be useful during navigation, such as the corresponding service of Google Maps. The app is a part of an assistive navigation system that includes ultrasound sensors, synchronization with traffic lights and weather information, and utilization of information telematics of the Athens Mass Transit System (AMTS) for routes and urban transport stops. The initial version of the Blind RouteVision system is presented in the third section of [16].

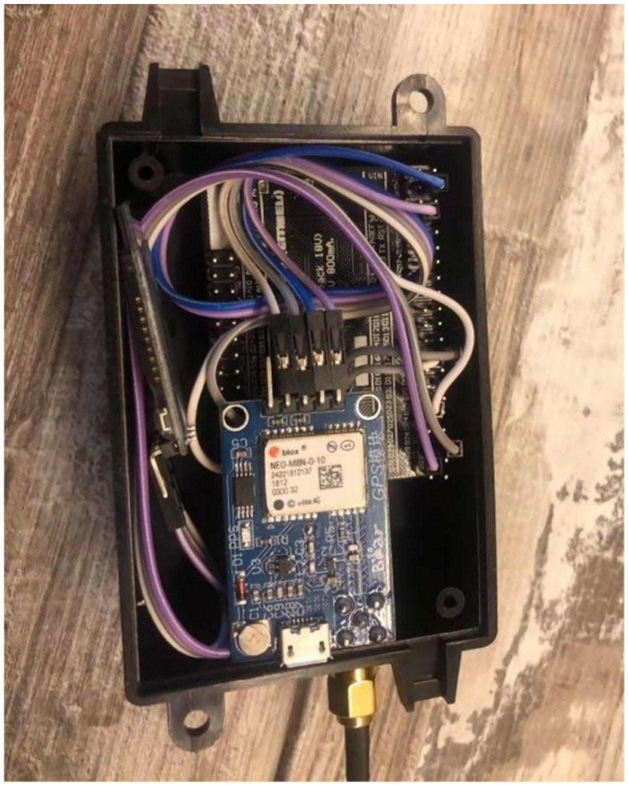

*Figure 7.3. Blind RouteVision outdoor navigation—advanced field navigation sensor*

The mobile symbol is the positioning of the embedded receiver, while the antenna is the positioning of our application. The smartphone application and its supportive external components consist of the aforementioned system for outdoor interactive autonomous navigation for the BVIs. Our developing system offers innovation in several fields.

First, it has better user location accuracy over phone GPS (see Fig. 7.3). This new system can achieve centimeter position accuracy by using three parallel systems with a choice between GPS / QZSS, GLONASS, GALILEO, BEIDU and by using the large surface of the GPS receiver antenna that cannot be integrated on smartphone devices, producing much better accuracy in the actual position of the user [53].

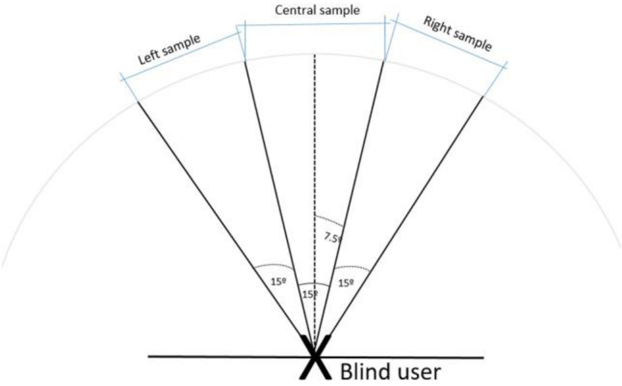

*Figure 7.4. Angle detection of the servo-sonar system*

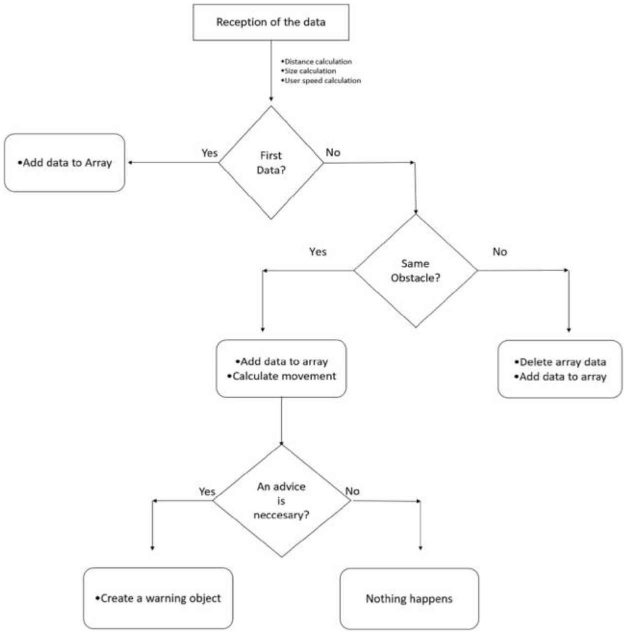

*Figure 7.5. Flowchart of the obstacle detection algorithm*

The second advance of this application is the improved transformation of WGS84 coordinates to Cartesian with the usage of our Spherical Trigonometry function, in addition to the already commonly used Haversine Formula. This solves the problem in calculating the user motion vector, which is the transformation of the user position from geographic coordinates (WGS84 system) to Cartesian coordinates. Until now, most transformations have been undertaken using the Haversine Formula, which has a 0.5% error rate. The latter, in practice, reflects in positioning errors of several meters, which make classical navigation inappropriate or very dysfunctional for the BVIs. Additionally, a sonar-based scanner for nearby impediments recognition is used to identify user obstacles as well, in terms of calculating their (a) distance from user, (b) size, (c) optimal avoidance.

The angle of the sensor is increased to cover additional space (Fig. 7.4). Therefore, the sensor is mounted on a servo mechanism, which will allow the sonar to rotate in such a way that it covers 15 degrees to the left and 15 degrees to the right from the global position, that is, the view angle of the sonar will be 45 degrees.

The sonar data are continuously received by the application. These data are used to calculate the user's distance to the obstacle, the size of the obstacle and the speed of the user (Fig. 7.5).

In order to explain the procedure, the simplest case is assumed, i.e., the lateral samples not having detected any obstacle. The exact position in which the object is found is not known, because if the sensor covers an angle of 15 degrees, mathematically, there are infinite points at 1.86475 m (the example distance that we have already obtained) in which the obstacle can be found. It can be assumed that the object has a width of 0.48679 m., and that to the left and right of that distance there is no object, so the user could avoid that obstacle simply by moving that distance to the left or to the right (Fig. 7.6).

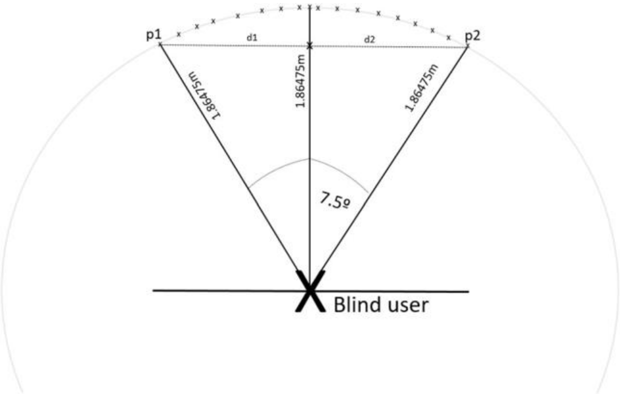

*Figure 7.6. Different frontal positions of the obstacle*

*Figure 7.7. Traffic sensor*

Next, this system also contains improved instructions based on patent-pending vector-oriented navigation [54]. For this, we use both a precise calculation for the position and a path of the user regarding the route of the navigation. The user's next possible position is calculated with the use of Markov chains. An additional characteristic of this system is that the navigational commands employ user-oriented and user-centered design (UCD) principles for the specific user-group of BVIs. Moreover, the application can guide with accuracy the BVIs to cross a traffic lights intersection equipped with the field sensor of the presented system [55, 56] (see Fig. 7.7). Practically there are three important results of our research for outdoor navigation that are summarized

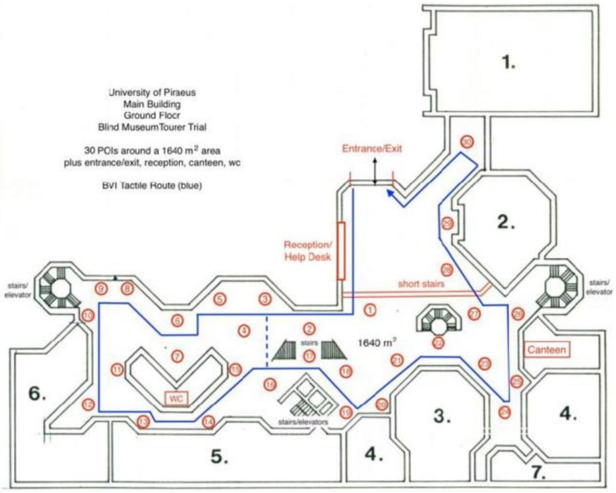

*Figure 7.8. Blind MuseumTourer indoor navigation and guidance system preliminary*

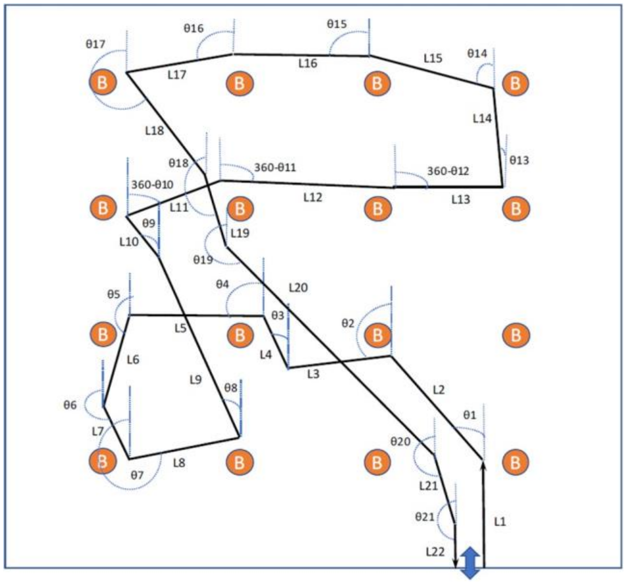

*Figure 7.9. Schematic depiction of the tracking capability of the proposed hybrid indoor positioning mechanism enhancing inertial dead reckoning with proximity processing of BLE beacons deployed in the indoor environment*

in this section: precise tracking and navigation, the special voice guidance and the recognition of the status of the signals. All of these are possible with great guidance accuracy and due to the high tracking accuracy mentioned earlier.

Moreover, a smart visual information system is being developed with machine and deep learning techniques. It is an embedded system recognizing visual information in real time. The primary goal was to be used outdoors, where the locations of the objects of interest are not known in advance. The system of smart visual recognition can also function in indoor spaces like the museum, although it is not necessary as the place and the exhibits are mapped.

The second mobile app concerns autonomous blind navigation in indoor spaces. Due to the fact that the GPS is not reliable for indoor positioning, the app is supported by a highly accurate indoor location determination subsystem which includes accessibility mapping of indoor spaces with overlays of the positions of points of interest (POIs) (see Fig. 7.8). Moreover, Bluetooth beacons are used as proximity sensors and location indicators. Figure 7.9 demonstrates a BVI subject's independent movement inside an indoor space, from the entrance to exit, and the monitoring of the motion trajectory in real time, modeled on rectilinear signals and orientations, implemented through the proposed mechanism for indoor positioning. When the BVI approaches a beacon, its distance from it is determined with great accuracy. Thus, the system can correct the possible error of the estimated motion Trajectory and re-evaluate the calculation of inertial dead reckoning parameters to the subsequent tracking. The app will inform the BVIs about the relative to the BVI's position of POIs and will use dynamic issuing of voice navigation instructions toward POIs considering the current position of the BVI. Blind IndoorGuide inherits the features of the Blind MuseumTourer system, as presented in [16]. It aims to extend the functionality of the Blind MuseumTourer beyond the case of museums. The conceptualization of the Blind IndoorGuide is discussed in [16].

A reliable and highly accurate indoor positioning system is being developed, which succeeds in centimeter-level positioning. This is achieved because it combines Bluetooth proximity beacons and a linear tactile path with a highly competitive dead-reckoning algorithm (Inertial Measurement Unit), which perfectly correlates many of the accelerometer's variables with linear interpolation and rolling averages with great precision. It also calculates the length of the steps [A. Tsigris and A. Meliones, "Highly Accurate Step Length and Walking Distance Estimation using Smartphones". unpublished manuscript].

Another advance is a patent-pending floor mapping method implemented as a server-side application (featuring a web GUI), which allows complete and rapid mapping of a complex multi-level interior multi-space, defining each space dimension, entry and exit points, tactile routes and points of interest. The application automatically calculates all the relevant distances. The indoor blind navigation application receives mapping automatically, either off-line or by approaching space based on GPS location [57]. To elicit the requirements of the BVIs, interviews have been conducted concerning autonomous navigation but also psychological characteristics and practices that are related to their impaired vision.

## 7.7 Discussion—toward a training framework for the BVIs

Developing navigation applications for the BVIs is an ongoing important problem in the world at large. Our research set out to explore new navigation technology for the BVIs by first identifying current navigation challenges and requirements, then defining possible device features and incorporating them into our proposed implementation.

The need for training the BVIs in using navigation applications is also an important issue. The term "training" most often corresponds to the method followed within an educational framework to overcome the consequences of visual impairment [58]. More specifically, a training framework on mobile assistive apps by the BVIs should include the efforts to persuade the BVIs to accept the technology and is divided into two parts. The first part concerns the apps' presentation to the BVIs, which includes goals, rewards and features to increase motivation and to reduce the factors that lead to negative attitudes toward their adoption. The second part involves straightforward recommendations for the BVI's training methodology.

In the following, we discuss the most important user requirements of each category, which are indicated by the corresponding numbering in parenthesis, in relation to operations and features that are present in this phase of the development, while we compare them with our proposed implementation and methodology. Furthermore, unsatisfied requirements at the present stage are also reported.

The research reports that one of the most important user needs is the ability of a smartphone app to train the user (4.5, x), except self-guiding him/her. Special emphasis should be given to the fact that the abilities and the learning rates of the involved subjects in using smartphones and available guidance apps differ to a great extent (4.5, iii). A major factor that influences this ability is their age. As it is clearly stated in subsection 5.2, the participating interviewers expressed their worries about their ability to use the assistive navigation technology effectively and securely. Moreover, it was highlighted that the fundamentally increased difficulty of the use of an assistive navigation system is caused mainly by its interaction with a dynamic environment.

For the above reasons, it has become clear how important it is to create a simulated environment that will function as a tool for the evaluation of the app and the user training simultaneously. This is achieved due to the fact that executed routes are being stored and rerun afterwards. In other words, simulated real data concerning user motion need to be more thoroughly detailed for training reasons than for evaluation and debugging reasons. Furthermore, the BVI's accurate position, where they tend to move and where is the final destination to fully understand the route and the application by extension are essential. The above details are not included in the simulation process of the evaluation.

In this light, regarding the implementation of outdoor navigation, our team developed a logger that stores and keeps track of the itineraries that have been taken and a simulation environment that helps the developers to test the application repeatedly, easier and safer than on the field. This results in the conduction of pilot tests that protect the BVIs from the dangers they must encounter on the streets and pavements. Moreover, they do not only show that the system is feasible, usable and functional, but also, they gather information useful in the design of the final system.

More specifically, with the use of the simulation process, we found and corrected a number of bugs. Examples of such bugs are the pronunciation of some wrong angles that influence even the combined transition or confusing instructions like the following one. While the app was saying "You are moving in the opposite direction," then it said, "Go straight ahead." Secondly, some mistakes in the GPS receiver have been identified. The weakening GPS signal under balconies or trees created problems in the calculations that were not treated well at the start but were dealt with afterwards.

Next, the user requirements that are exported from the interviews are discussed and related to operations and features that are present in this phase of the development. Furthermore, unsatisfied requirements are also reported.

At this point, it is important to highlight that the needs and the preferences of the BVIs are differentiated depending on many factors like their age, their culture and origin, their technological knowledge, their experience and finally their training in mobility with or without a guide. As a result, in our effort for better user satisfaction considering the wide variety of needs, our team includes in our implementation some alternative options to cover different needs of the BVIs.

Starting with the requirements concerning the perception of the environment (4.1a), our system supplies the users with induction headphones (4.1d, v) to be aware of the surrounding environment (4.3a, i, ii), which is a matter of great importance for their security. As a result, the auditory channel is not blocked, so both environmental stimuli and navigation instructions can be perceived and managed at the same time. Especially, if you take into account the fact that BVIs have an augmented ability to perceive and discriminate simultaneous sounds that stem from different sources (4.1a, i, ii). In our system concerning outdoor navigation, we support both guiding instructions depending on the hands of the clock (degrees) and simpler rectangular instructions (right, left, front, back and opposite) to cover the differentiated needs and preferences. Despite the BVI's good memory and sense of direction and time (4.1a, iii), the special navigational commands with the aid of the clock coordinates and the continuous provision of information for the accurate position of the user in relation to the map are very helpful.

The next subcategory's statements (4.1b) are also addressed with the combination of the application informing the status of conventional signals and traffic lights interoperability, route monitoring, high precision routing, real-time route correction, accurate real-time bus stop updates and near field obstacle detection with the aid of a continuously pendulum-like looking ahead ultrasonic sensor [59]. As a result, the need of having someone to escort them or visiting only familiar places can be omitted (v). Moreover, when using "smart stops" they do not have to ask the bus driver where to get off (vi) since all the stops, not only the next one and the destination, are announced from the app in advance. Regarding pedestrian navigation (4.1c), the application utilizes a sonar enabling positioning with high precision. For instance, it was reported by the participating interviewees that it was safer to cross the road instead of the sidewalks (4.1c, iii). Generally, with the advent of this navigation system that includes high-accuracy GPS tracking, routing of pedestrian mobility in real time and redefining of a route in case of an error in the navigation instructions or when there is user removal from the right route, the BVIs can be more independent as they are not obliged to ask for information from passers-by (4.1c, xi).

Another significant pillar concerning outdoor navigation is that our proposed system informs and prepares the BVIs regarding the local weather conditions (4.2c, v) to help them dress properly for walking outdoors. Additionally, a battery level button (4.2c, vi) is made after the requests from the expert users. The user is informed about the battery level of the external device through this button. There is also a lock button (4.2c, vii) that allows users to lock the curtain to prevent any accidental pressing on one of the other buttons. The lock curtain is deactivated by pressing three fingers on the screen at the same time.

In most existing apps, BVIs were obliged to plan and predefine their routes before their departure or between their stops (4.1c, i). On the other hand, in our system, this is improved since BVIs can adjust the route with voice instructions specific oriented to their needs and customs (4.1d, i). In case of a wrong selection of a road or route, or a deviation of a selected path, the app will restore the destination (4.2b, vi). Specifically, in case of wrong selection, the blind person will be asked if the destination the BVIs pronounced is the correct one, e.g., the application will ask to confirm that the application understood the selection well. In case the blind person deviates from the route, the application will recalculate the route to give him correct instructions. That seems to be one of the most persuasive arguments for the coverage of the BVI's requirements.

Concerning indoor navigation and specifically museum visiting, the BVI's interaction with the app concerns a single tap to hear an option or a double tap to confirm an option or speaking. The self-guided tour activity begins after the path selection. This activity manages real-time dynamic navigation within museum rooms, calculates the user's location during a self-guided tour and displays the exhibits along the tour. Complete user interaction with the application is achieved via a small number of simple voice commands but also distinct gestures, as the BVIs required in their statements.

Upon the entrance of a user into a museum room, the event is detected by the application, which loads the corresponding floor map and initiates the indoor navigation. The self-guided tour can be interrupted by the user at any time in case the user wants to dial a call or to proceed to the restroom or the exit. The guided tour is placed on hold until the user follows the voice instructions and returns to the interruption point.

The exhibits in the museum should primarily be perceived with the senses of touch (4.1e, iii) and hearing (4.1e, x) as BVIs consider that hearing, in particular, is the most important sense. They also require having instant contact with the helpdesk through an emergency button or making a call to the staff for asking help, or to a trusted person of their own in case of any need (4.2c, iii).

The BVIs, as they stated, need to have accessibility to as many sculptures as possible (4.1e, vi). Additionally, the users asked for easily customizable information, as it is likely that exhibits will be added or their position will be modified in the museum (4.2c, i). In these cases, the developers used a web application for importing cartographic data, managing to map the internal space [57]. The supervisor of the museum is putting detailed coordinates, dimensions and the required verbally descriptions of the exhibits. Finally, the application identifies available routes that it can follow with the use of special sensors of the system. This is a great solution as there is a great cost involved for the installation and the development team. All the above are feasible with our proposed design. Our team managed to simulate the role of a human museum guide or human escort of the BVIs through the creation of the presented application.

Moreover, our team's attempt to build a small, compact wearable device was driven by the need for easy device portability (4.1e, xiii). The latter is another significant aspect of the proposed system that concerns many requirements, and it is still under investigation. All the options of incorporating the GPS device in various preferable places according to the BVIs are being tested. In the beginning, the team gave priority to incorporate the device on the white cane, as the BVIs have declared in their requirements (4.1e, xiii). However, during the implementation, it became clear that it is not the best position to place the GPS device. Although the antenna of the receiver must be in an unobstructed position, placing the device on the white cane raises issues for the safety (possible damage) of the device. Conclusively, as the device is wireless, it can be attached to a pocket or in a case, whatever is more convenient for the user.

The requirements concerning obstacle detection (4.2a) are addressed with the utilization of the sonar sensor. As the latter itself has a limitation of a small viewing angle, the sensor is horizontally positioned higher than the middle height of an individual, for instance at chest height. This results in a simpler implementation. Otherwise, at a higher cost, the sensor can be accommodated with a more complex servo mechanism allowing the alternating movement of the sonar vertically and horizontally (4.2a, i). In this case, information on the height of the obstacle is more accurate, which is not possible only with horizontal scanning [59]. This results in the detection of obstacles that are in a higher position and not only on the ground (4.2a, iii). The evaluation of both solutions is ongoing.

Moreover, the obstacle detection algorithm detects continuous successive measurements and calculates relative velocities of objects in a collision course with the BVIs. The latter are being informed only of obstacles converging with their track to minimize the instructions issued by the sonar (4.3a, i). In this way, the safe transportation of the BVIs enforced with the reduction in unnecessary information is assured. In the case that the BVIs walks on the sidewalk, which may also have a bike path, the sonar will identify cyclists in a collision course with him and will inform him about these dangers and obstacles. Furthermore, when the BVI is moving on the side of the road, e.g., on the left, the sonar perceives the parked cars and selects not to unnecessarily inform the BVI who moves next to the parked cars about the “obstacles” to his left. Likewise, when the BVI moves on the side of the road and has the parked ones on the right.

The requirements (4.2b) are fulfilled by our proposed application exploiting the Public Transport Telematics REST API [60]. Specifically, the expert users asked for the combination of pedestrian navigation with the use of public transportation in real time (4.2b, i, iii), which is achieved with the real-time navigation modules and public transportation modules on the application.

Within our application for outdoor navigation, users can provide the desired destination verbally through speech recognition since the routes are not predefined. In this way, multiple destinations can be changed continuously depending on the user’s wish (4.2b, xii). Moreover, information is vocally provided about the location of bus stations or stops that the BVIs want to use (4.2b, viii). Another task achieved by the developers after the demand of the expert team of users is a brief report of the total route and the intermediate stops before the user starts the navigation process (4.2b, xiv).

During the route, voice instructions guide the users and indicate the optimal route with the lowest cost following the Dijkstra algorithm (4.2b, viii). When the BVIs are less than 100 m away from a point of interest i.e., the bus station, they are informed about it. Finally, when they are located at the bus stop, they are informed about the estimated time of arrival, as well as its type, its direction and its destination (4.2b, ii). Similarly, on the bus, the BVIs are vocally informed about their current stop, the next stops and the distance to destination (4.2b, iii).

Currently, the system compares the speed of the BVIs and if the number has passed a threshold, that means that the BVI is on the bus. Otherwise, the BVI is moving on foot. Alternatively, in the case of slow-motion of the bus in traffic jams, there is a differentiated and simplified option in the way the system is being informed. To solve this problem, which was identified in the pilot tests, we have implemented a button for the relevant information about boarding and exiting the bus instead.

Concerning the security of the BVIs, during the interviews, it was found that they felt more comfortable if a trusted person or the police can automatically receive their location (4.2c, ii). For this purpose, among the basic functions of dialling/answering calls and notifying of an emergency, another function was added to the app, to directly send the coordinates of the location of the BVIs to the corresponding person through a button.

An equally significant aspect of the requirements for navigation that the authors should highlight is the ability to identify the traffic lights and their status on the streets. This is achieved due to traffic lights sensors, which inform the application for the level of the traffic lights (two different states, red and green) and the remaining time until the status of the traffic lights changes. Additionally, the system decides which is the traffic light that the BVI is interested in crossing the passage based on the user’s movement (direction).

According to the responses of BVIs, it is of paramount importance to be informed about the movement of cars, bicycles and other obstacles in front of their path. For instance, it would raise great safety issues, in case a driver does not follow the signals of the traffic lights (4.2b, v). However, location-based systems are inefficient to find the real-time accurate position of a moving car due to 4G latency. Therefore, the incorporation of the innovative intelligent system for the real-time provision, along the path of the BVIs, of abstractive visual information is of fundamental importance. The specific module can recognize objects and patterns in still and moving images, also providing distance and motionrelated information, which is communicated by the autonomous navigation application vocally (4.2b, i) to the user.

An additional user requirement, which will be included in a future version of the developed application is the provision of information regarding the entry or exit points of buildings or other designated areas such as parks or the type and name of shops along the BVI's route (4.2b, vii). Such features are included in separate applications in Blindsquare, which is widely used from the BVIs.

An equally significant aspect according to the BVIs is the capability of being informed about ticket machines, the pier of the train, the entrance and exit in an underground railway station or an above-ground station (4.2b, xi). In light of the recorded user needs, upgraded versions with more capabilities will be offered by the research team, for outdoor and indoor navigation.

Functionality requirements (4.3) are covered for the most part according to the pilot tests. The basic requirements concern the reduction in vocal information from the app, especially the irrelevant, non-essential or noisy repetition to perceive sounds from the surrounding environment (4.3a, i, ii). This has been achieved with the instructions scheduler and the bone conduction headphones. Specifically, via the timer, which is a processing distributor, the frequency that the voice instructions are repeated is set. In this way, the frequent repetition of instructions in a relatively short period that confuses the safe navigation of the user is avoided. In other words, only crucial information is transferred in an acceptable frequency for the BVIs accredited by evaluation tests.

The requirements described in (4.3c) are the primary goals of our team's implementation. Continuous monitoring of the user's geographical coordinates and high density and accuracy of reported locations are achieved by incorporating an external high-precision GPS antenna, which is the optimal cost–benefit solution for the desired accuracy. Moreover, the development of an algorithm that improves the calculation of the relative position of the BVI has also contributed to the efficiency of the app.

In case sound-enabled traffic lights are in the BVI's path then the produced by the app instructions and warnings should be distinguishable and serve as an additional confirmation. In this context, a feature for the self-management of the sound levels was embedded in the app for both traffic lights warnings and navigation instructions. As a result, sounds are not being produced simultaneously confusing the BVIs.

The requirements described in (4.4a) concerning the outdoor navigation are satisfied by the Talkback service, which is an Android component that enables text-to-speech functionality allowing the loud reading of instructions and general information. This works for the convenience of the users, as they are accustomed to this. More specifically, all the necessary functions, like swiping gestures (4.4a, viii) or serial display of options (4.4a, vii) are implemented in a way that is familiar with the BVIs. Furthermore, there is no issue about particular favorite keyboards and their features (4.4a, iii) as free text and speech recognition is utilized for the implementation.

The requirements described in (4.4b) concern the inclusion of a searchable menu with voice capabilities (4.4b, i). By exploiting this menu, the user can navigate within the configuration activity, change settings, or select a destination very easily (4.4b, iv). Another important element is voice confirmation (4.4b, vii), which is also included in the museum navigation app. For example, as the name of the exhibits are addressed, the visitor has the opportunity to answer vocally (yes or no) if he wants to continue with analytical or with a short description for each sculpture.

Additionally, there is a destination index for indoor navigation in the museum (4.4b, iv), where the users can scroll up and down with their fingers. In the case of outdoor navigation, a list of “favorites” destinations (4.4b, viii) that the user can call, and the app will guide him/her there, is not yet included. However, the specific functionality will be included in future versions.

Finally, the last set of requirements (4.6) comprises the integration of basic tools such as the screen reader and common in the field applications such as VoiceOver and Talkback with the described navigation apps in both platforms IOS and Android. It is of vital importance to integrate such functionality since without the screen reader, our app would be difficult to use (4.6a, ii, iii, v). In the same domain in order to avoid the errors of automatic translation services (4.6b, xix), our team embedded a button that states which commands (restricted number of acceptable words or phrases) can be recognized by the native Android app.

To summarize, although there is space for improvements according to the pilot tests, the user needs and requirements as stated in the interviews are covered to a great extent. Furthermore, the users are informed through the application about the status of the traffic lights that have real-time updates and monitoring through traffic light sensors (a patent-pending field sensor has been proposed by the project team), which is a significant positive result for traffic lights and high precision, real-time route monitoring. The users are then informed about the color of the traffic light (red, green) and the remaining time to change the current status of the color. The information update can be achieved rapidly with great precision even on the sidewalk toward the walkway.

A limitation of the initial design is that the special needs of blind and low vision users are not sufficiently distinguished. Although it is common to analyze the needs of BVI people, in our experience blind and low vision users can have substantially different needs for navigation assistance. A similar problem applies to people with congenital and late visual impairments.

Additionally, the subjects examined in this study are only Greek. Worldwide involvement of subjects recruited through web communities would result in more general conclusions. However, given the common impacts of vision loss to every BVI in the world, it is reasonable to assume that the preferences of the BVI, along with the solutions they are choosing to overcome them are to a certain degree invariant of location. As such, although the requirements express personal preferences, opinions and suggestions from that localized group, it can be considered as a useful basis for researchers in the field and developers of relevant applications. Nevertheless, it should be acknowledged that a different sample of users may have derived to different requirements in some per cent because some of the proposed features can be inconvenient or impractical during a user-based evaluation.

The aforementioned restrictions arise from the fact that there is difficulty in finding and recruiting a big amount of people with serious visual impairments for the interviews. That is why it is perceived that quantitative analysis concerning BVIs is a more time consuming and demanding task. Our future work includes continuing the research and reducing the above limitations.

We support the view that to adequately cover the topic, a quantitative study should take place, which belongs to our plans for future work. Although we do not claim that all requirements are included, or every detail is addressed, we believe that the wealth of our findings is adequate for the description of a framework for the development of assistive navigation systems for the BVIs. Interestingly, we identified the important role that a training version of such a system, mainly a mobile app, could play in significantly improving adoption and use rates. We also identified that even the BVIs with good abilities in using mobile apps would prefer to test the navigation system in a controlled environment before trying it in real conditions.

Moreover, an expansion of the participant group including diversity in key areas of age, gender, technology usage and location will take place to provide an adequate basis on which to develop scenarios for future work. The latter will lead to the achievement of more user and Tam-centered design processes.

## 7.8 Conclusions

The purpose of this chapter was to present in detail the elicited user needs and requirements for the design and development of assistive navigation systems for the BVIs. Such systems should aim to offer the BVIs enhanced autonomy, independence, productivity, opportunities for social inclusion and, consequently, quality of life. The chapter presents the classification of user needs based on the raw interview data.

Thirteen members of the BVIs community participated in interviews, which resulted in a very rich primary dataset**.** The analysis of this dataset resulted in the identification of seven main categories of requirements and several subcategories. The outcomes of the interviews and the reported findings are analyzed to define a taxonomy of user needs that should be considered by designers and developers of assistive navigation systems.

Interestingly, a category emerged that includes requirements concerning how the BVIs should be trained on the use of assisting navigation apps (or, more generally, systems). The importance of this category was highlighted by all participants during the interviews. It was probably because they already knew how complicated and risky navigation can be for those who cannot visually perceive the environment. As a result, an assistive navigation system that aims to be adopted by the BVIs should be multi-purposed and able to interact with the environment and interconnect with other digital services.

The main tool that would allow such a system to meet the expectations of the BVIs regarding autonomous navigation is the smartphone, along with the necessary assistive navigation apps. In this research, it was proposed that training versions of the apps should be available to the instructors of the BVIs. These versions should be easily customized by the instructors to offer the BVIs the opportunity to be trained in familiar places before using the apps in real-world conditions. The importance of the training version was implied by the stated requirement by all the participants that they should be very confident about their safety and ability to use the assistive navigation apps before they finally depend on them.

The elicited requirements presented in this chapter provide insight not only concerning the optimal user-oriented design of the apps but also about the auxiliary devices of an integrated assistive navigation system.

Considering the limitations presented in the previous section, this classification, along with its content and a corresponding evaluation method, aims to become a useful tool for the researcher or the developer involved in the development of digital services for the BVIs. It also aims to offer effective digital accessibility solutions to the BVIs. In conclusion, our goal in the future is to create metrics with which we can scientifically document and calibrate a system that supports the navigation of the BVIs.

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# Chapter 8 (Content partially published in #6)

## Smart traffic lights for people with visual impairments: A literature overview and a proposed implementation.

**Keywords**: Blind outdoor navigation, cloud-based technology, computer vision, GPS positioning, machine learning algorithms, maps-based navigation, smart traffic lights, wearable devices

## 8.1 Introduction

The issue of developing assistive technologies for the navigation of people that are blind and visually Impaired (BVIs) has attracted the interest of a plethora of cities worldwide (ISO, 2014). According to Yeon Lee and Mesfin (2020), legal blindness refers to the USA's Social Security.

Administration, which considers an individual legally blind when they have a central visual acuity of 20/200 or worse. According to the same source, the World Health Organization (WHO, 2020) provided data indicating that 2.2 billion people have a near or distance vision impairment globally, out of which 1 billion people are those with moderate or severe distance vision impairment or blindness. Most people who suffer from visual impairment or blindness are older than the age of 50; however, vision loss can afflict people of any age. The likelihood of more individuals experiencing visual impairment is predicted to rise as the population grows and ages. In addition, due to geographical inequalities, the prevalence of distances for vision impairment is predicted to be 4 times greater in low- and middle-income countries than in high-income ones. Notably, a total of 90% of blind individuals live in developing countries. These data also indicate that for each blind person worldwide, there are 3.4 individuals with low vision, with a country and regional variation between 2.4 and 5.5 individuals.

Chan et al. (2018) stated that visual impairment and blindness mainly affect the elderly individuals in the United States. Wolfram et al. (2019) state that in Germany the number of elderly people will rise dramatically, increasing age-related ocular diseases, and this will result in a higher number of people with vision loss. The prolonged life expectancies are likely to escalate the prevalence of visual impairment, according to Naipal and Rampersad (2018). Moreover, they define visual impairment as reduced visual performance that can be remedied neither by surgery nor medication.

Habib and Irshad (2018) stated that the adolescent population of visually impaired individuals experience a low quality of life in terms of physical and psychological health and well-being as well as social relations and the environment. According to Khorrami-Nejad et al. (2016), quality of life could be improved by providing education, employment, and expanding social programs for BVI individuals. Moreover, Wang et al. (2017) depicted in their research that there is a strong association between global variations in vision loss and socioeconomic factors at a national level.

Chan et al., 2018 attempted to estimate the prevalence of visually impaired and blind individuals in the United States between 2017 and 2050 and projected an increased rate of vision loss from age-related causes; moreover, 480,000 new cases each year of mild low vision, 180,000 cases of moderately low vision, and 134,000 legally blind cases have been estimated.

Detecting and recognizing pedestrian traffic lights is obligatory when crossing roads. The latter is of paramount importance because they are critical parts of an urban landscape, and they consist of safety issues, especially for people with blindness and visual impairments. Independent mobility and specifically crossing a road at a traffic light is a challenge for these people. Based on the aforementioned, it seems that the use of traffic lights concerns a large portion of the citizens in each city. Indeed, smart traffic lights can help individuals with vision and hearing disorders as well as the elderly individuals have a smooth and safe passage on a road (Coughlan & Shen, 2013). To date, a wide variety of technologies have been developed to assist individuals with visual impairments in walking and crossing the roads. Conclusively, a smart traffic light system would also promote the quality of life of individuals who are visually impaired and who, according to Högner (2015), need special programs that would help with the reduction of traffic hazards.

In this article, we present an overview of the works found in the literature along with the requirements analysis after the conduction of participatory work with users and proposed initial implementation. The remainder of the article is organized as follows: The second section provides background information concerning the history and the evolution of the traffic lights and existing implementations and methods utilized in the literature, while the third section presents the materials and methods used in the context of our proposed system. The initial and intermediate results, the requirements of our implementation along with the participatory work of interviewees through their requirements classification, are discussed in the fourth section. The fifth section concludes the article. Finally, in Appendix A, there is a table comparing tools, methods, features, restrictions, and evaluation with metrics found in the literature.

## 8.2 Related work – history of traffic lights worldwide and their evolution until today

Traffic lights have changed and evolved greatly since they were first implemented in 1912 in Cleveland, Ohio, by Lester Wire (Palsa et al., 2019). Back then, they were only red and green and would be operated by a policeman in a nearby booth. Later, with the advent of computers in the 1960s, traffic lights would become automated, and automation was implemented with great success. As humanity evolved so did technology, and wireless technologies have since been applied to traffic lights. An example is Vehicular Ad Hoc Networks which are used for communication purposes among vehicles. These techniques cannot be directly used to guide people with visual impairments because they are specifically optimized for circular or elliptical lights, while pedestrian traffic lights have different shapes (Chiang et al., 2011; Habib & Irshad, 2018; Sooksatra & Kondo, 2014). On the other hand, other solutions that are designed for smart vehicles but are not specialized for circular or elliptical traffic lights can be useful in identifying pedestrian traffic lights.

Independent mobility and specifically crossing a road at a traffic light is a challenge for people with visual impairments. Some solutions involve sound. Many different models and variations in acoustic traffic lights are in use. Especially, systems that generate sounds signaling the duration of the work interval and others that provide talking messages have been developed and used in several cities. In Italy, people with visual impairments push a button that makes a sound when the light is green for pedestrians, whereas, in Germany, a sound always plays for pedestrians when the light is green. In both developing and underdeveloped countries, the majority of pedestrian traffic lights lack sound aids. Unfortunately, in many countries either not all lights have either of these facilities, and even where they do, they are not always working. The route guidance devices that exist offer mapping directions but struggle to fix critical safety concerns such as when to cross at an intersection, which necessitates knowledge of the position of traffic signals and moving objects such as vehicles.

According to Chen-Fu (2012), both individuals that are BVI heavily rely on walking for transit; for that reason, the United States has passed the American with Disabilities Act (ADA), which enabled the establishment of accessible pedestrian signal (APS) systems; they are described as sound cues that are installed in the traffic light systems, allowing the visually impaired to know when it is safe to cross a road. This type of traffic light could be perceived as a 'smart traffic light.' Chen-Fu (2012) also states that, with the advent of smartphones, an app could prove helpful for the guidance of people with visual impairments and at the same time be readily accessible.

## 8.3 Existing implementations for smart traffic lights for people that are BVIs

Cloud-based technology could allow for the promotion of a safer transit experience for people with visual impairments. According to Angin et al. (2010), the timeliness of reactions and precision are the two most important aspects of the challenge of traffic light detection. The latter developed traffic lights detector as an initial component of a two-tier architecture context-aware navigation system which are 'Mobile Navigation and Awareness Server' (mNAS) (any smartphone device in the market) and the 'Cloud Navigation and Awareness Server' (cNAS). Ihejimba and Wenkstern (2020) proposed a solution, DetectSignal, that provides high-speed and low-latency traffic signal notification, both for individuals with visual impairments. Wearables are potentially helpful in this context; Huang et al. (2017) developed a wearable device that would provide an improved transit experience to visually impaired individuals, compared to traffic light buzzers. Cheng et al. (2018) suggested the use of RGB-Depth images obtained also by a wearable device in the intersection navigation. Furthermore, with the use of various detectors, people with visual impairments would have the capability to find the starting point of crosswalks, to perceive the status of crossing signals (crossing light signal), and to detect the pedestrians' walking path and its state.

Cohen and Dalyot (2020) established that the combination of temporal data about the pedestrian traffic flow, generated via machine learning algorithms, and the available data of the OpenStreetMap database can significantly increase the reliability of route planning algorithms for blind pedestrians. Similarly, Manavella (2015) proposed the development of a wearable device that would identify traffic signals and allow people with visual impairments the safe passage through intersection crossings with the use of an algorithm. Color-blind individuals also come across challenges when faced with traffic lights. Mobile phone cameras would also assist the visually impaired. Sharma (2016) suggests that a computer vision-based system for pathfinding and navigation aid could enhance the mobility of visually impaired individuals and provide independent travel.

Mobile devices could also be used to detect traffic lights. People who are blind or visually impaired must acquire accurate and fast object recognition and obstacle detection, which necessitate the use of computationally intensive image and video processing algorithms. Mascetti, Ahmetovic, Gerino, and Bernareggi (2016) and Mascetti, Ahmetovic, Gerino, and Bernareggi, et al. (2016a, 2016b) proposed a reliable method of traffic light recognition using mobile devices and providing unsupervised transit for the visually impaired through image capturing and identification that enables them to gain visible traffic light images in a variety of lighting conditions due to time and weather. Ghilardi et al. (2018) suggested a method for detecting pedestrian traffic lights and computer vision techniques based on deep neural networks and images captured by mobile devices after discovering a significant gap in the literature. Furthermore, Ivanchenko et al. (2010) developed a prototype software application for mobile phones which uses computer vision algorithms to analyze video acquired by the built-in camera and then informs and warns the user in real-time when the Walk light illuminates.

Periša et al. (2015) suggested new service-based research on Near-Field Communication (NFC) and Real-Time Locating Systems (RTLS). Currently available technologies like RFID, Wi-Fi, NFC, and Bluetooth are proposed to find the precise location of people with blindness and visual impairments, which is very useful for their safe movement of the traffic network. Specifically, concerning their crossing traffic intersections, their identification, and informing the traffic intersection management system, the user must have an RTLS tag, which is indicated by an antenna pointed in the direction of the movement of users who are BVI Consequently, the RTLS controller sends details to the traffic light system.

Ahmetovic et al. (2011) with ZebraLocalizer explored the detection and localization of crosswalks using data in real-time from the camera and accelerometers as well as the development of an iPhone prototype application with an interface model tailored to individuals that are visually impaired or blind. Furthermore, Castillo-Cara et al. (2016) implemented a hybrid system based on the use of GPS and Bluetooth 4.0 BLE technologies along with a mobile device that people with blindness and visual impairments may use in indoor/outdoor environments. Concerning outdoor navigation, it is proposed a smart traffic light controller as well as the development of a Google Directions API and Google Maps Geocoding API-based framework.

However, technology is not the only mean that could assist the transit of visually impaired individuals; the design is also important. Oliveira et al. (2015) stated that the classic ‘red on top, yellow in the middle, green at the bottom’ traffic light design must become standardized to allow colorblind individuals a safer transit experience.

Nevertheless, helping those in need is not the only reason why a city should invest in upgrading its traffic light systems. Nguyen-Ly et al. (2019), which handle the case of people that are colorblind, stated that upgrading the traffic light system also saves energy, facilitates the economy by reducing maintenance costs, and its installment would come at a low price as it is achieved with low effort. Moreover, according to the Smarter Cambridge Transport Organization (2019), upgrading to smart traffic lights would reduce congestion, thus reducing time spent driving and, therefore, enabling the regulation of air pollution, prioritizing public transportation, and enabling a better response to traffic incidents. Moreover, the influence of a low efficient conventional traffic system affects the economic, health, financial, and environmental domains, so, it stems from the above that smart traffic lights are an issue of great importance.

Interestingly, there are also other types of smart traffic light implementation proposals found in the literature. Namely, Ortiz-Figueroa et al. (2020) presented an information system for the management of intelligent traffic light infrastructure. Ghazal et al. (2016) proposed a system that would be based on a microchip microcontroller through which traffic density would be assessed using infrared sensors. This would implement dynamic timeslots based on traffic conditions, thus reducing waiting times and allowing for a smoother driving experience. Similarly, Liu and Smith (2015) discuss a traffic system that would prioritize the allocation of green time to the most congested traffic lanes, based on vehicle count and flow, through data that would be accumulated by vehicle presence detectors mounted on intersections.

Almawgani (2018) suggested a smart traffic light controlling system that used an image processing technique to switch the traffic lights automatically. This research depended on programming and connection between Arduino and MATLAB software to detect and count the number of vehicles. In this way, the estimated time for each lane was calculated to control the traffic light. In addition, Biswal et al. (2020) proposed a different traffic light system based on the popular use of the internet and voice-control technology through which traffic lights could be controlled, using commands such as red, green, yellow, and stop. Further, Moran et al. (2017) proposed a hybrid, city-wide urban navigation system for those who require assistance with transit, by combining GPS technology and vehicle-to-vehicle communication of parked cars, and RFIDs from traffic lights to provide a safe transit experience.

Jawabreh et al. (2020) proposed an upgrade in which traffic lights would be enabled to communicate with each other through the use of an algorithm, wireless communication, and microcontrollers, thus allowing for the assessment of traffic conditions and promoting an optimal traffic management system. Bsharat et al. (2018) proposed a similar means of upgrading traffic lights, as they suggested upgrading the traffic light system with programmable logic controllers, which would count how many cars are waiting at each traffic light, compare the number with other intersections, and allow for the consideration of emergencies. Like the aforementioned studies, Elbehiery et al. (2014) proposed an application that can be used by individuals who are visually impaired and blind to freely and safely navigate city terrain with no assistance. Moreover, Ochoa and Oliva (2018) suggested that cities must be reformed into smart cities and integrate technological means to regulate traffic and promote quality of life. More specifically, they presented a hybrid intelligent application based on bat algorithm and data mining that assists individuals who are color-blind with identifying traffic lights, thus allowing safer driving experiences for these disadvantaged members of the population.

The use of technology is a ‘one-way street’ in the implementation of improved traffic light systems. According to Horijon (2017), developing ‘smart’ cities has become a polarizing debate, as there are four forces that regulate traffic: (a) politics, (b) means of identifying drivers, (c) new means of regulating drivers, and (d) the changes in which both public and private factors govern traffic management. As a result, it is observed that traffic regulation has become data-driven by developing more advanced technological means of observing and governing human traffic. This raises both practical questions, in terms of expenditure and implementation, and privacy concerns, as the principle of privacy has become more challenging in many aspects of everyday life.

Recently, according to Barlow et al. (2003) and Crandall et al. (2001), novel smartphone applications, such as the Mobile Accessible Pedestrian (MAP) Signal system, have also been developed to provide information concerning the intersections to individuals that are blind or visually impaired. In general, this system uses the MAP and SPaT information received by the smart device to orient the pedestrian, assist the user in confirming the exact location, and provide verbal information regarding the signal state. Therefore, this system could improve their ability to cross each street safely. This system is used in many cities in the United States, including New York (‘Mobile accessible pedestrian signal system’, n.d.).

Interestingly, an innovative smart traffic light system has been installed in Thessaloniki, Greece (‘The “smart” contemporary traffic lights’, 2019). It is worth mentioning that these traffic lights do not simply have an audible alarm only for individuals that are BVI and want to cross the sidewalk. Especially, each traffic light has a button at the level of the hand. After pushing the button, the user is informed by the device regarding the exact point where he or she is located in the city. Moreover, the user could understand if the traffic light is green through the vibration it has, as it presents the embossed image of the route. The same device can be connected via Bluetooth to the mobile phone and, therefore, more information can be collected, thus, making it easier to locate passage ( 'The "smart" contemporary traffic lights', 2019). Such features seem to be useful and effective for the navigation of people with visual impairment in their city.

The survey of Diaz et al. (2015), which is not oriented only to people that are BVI, organizes various approaches to traffic light detection, thus emphasizing key research fields in computer vision. The review classifies the various works into the following issues: features extraction according to color or shape properties, classifiers, and prior information through digital maps. To the best of our knowledge, this is the first comprehensive review of the available literature on the use and design of smart traffic lights for individuals with visual impairment. In this review, we provide an in-depth analysis of both available traffic lights infrastructure and proposals to improve the existing infrastructure for the benefit of visually impaired individuals. We hope that the information presented in this work regarding the use of smart traffic lights in cities worldwide may help city authorities design new, modern, and efficient systems for the safe navigation of individuals with visual impairment in their cities.

El-Taher et al. (2021) have undertaken a thorough survey on assistive outdoor navigation in which the authors break down the navigation area into a series of navigation phases and tasks, among them pedestrian traffic lights detection and recognition. In addition, they present tables with crosswalk, obstacle avoidance, and pedestrian traffic lights datasets.

## 8.4 Specifications of smart traffic lights, actual applications, and challenges

Smart traffic lights are similar to regular ones with the difference that they employ the latest technological means to provide an improved experience to all involved commuters. The European parliament has filed a motion that acknowledges the need for the inclusion of individuals with disabilities. Namely, it calls nation members to do more for individuals with disabilities. More specifically, the European Commission recognizes that innovative forms of free communication tools for blind individuals, such as accessing information services with special regard to online services, are also essential for them to be able to fully enjoy their rights, including calls for the reduction of barriers to the freedom of movement of people with disabilities, via the adoption of a European Mobility Card, based on mutual recognition by the Member States of disability cards and disability benefits and entitlements to make it easier for people with disabilities to study, work, and travel (Gyselinck et al., 2014). Moreover, annual reports of the European Commission call for increased efforts to achieve individually tailored navigation-based services for the blind and those with serious visual impairments, making specific recommendations while considering dynamic technological development. This would ensure progress is both achieved and continuous, and multimodal door-to-door transport is possible, as set out in the White Paper titled 'Towards a competitive and resource-efficient transport system' (European Commission, Directorate-General for Mobility and Transport, 2011). The US government, however, recognizes the sound made by vehicles themselves as an added safety cue for the blind, and therefore, does not endorse specific types of cars (i.e., electric cars with low to zero sound emissions). Moreover, the US government was set to pass the Smart Stop Lights Act ('Less Traffic with 5 Smart Stop Lights Act of 2017', 2017), which is based on real-time data from Los Angeles, California, where smart traffic lights have been installed and saw a reduction of travel time by 12% and increased speeds by 16%. In Pittsburgh, Pennsylvania, through the installation of smart traffic lights, there has been a considerable reduction in air pollution because of the reduction of idle stopping of cars (40% reduction) and decreased travel time (26%).

In practice, the government of Barcelona ('Barcelona Ciutat digital', n.d.), Spain, guarantees that the city is sufficiently developed to support the needs of all citizens using digital means, including the eradication of social exclusion and the promotion of mobility. Moreover, the installation of new traffic lights is complete with loudspeakers that will assist in the transit of the visually impaired. Advanced Pedestrian Information and Communication Systems are also used at the traffic lights in Tokyo to inform people with visual impairments of the color of traffic signals. Shortly, they use radio communication devices mounted to traffic light poles and they inform them through auditory guidance ('Smartphone-linked traffic lights helping guide visually impaired in Japan', 2020).

Nevertheless, the development and use of such systems may present several obstacles that should be overcome and constitute a challenge for the city authorities and the programmers. Especially, the main issue is that the spatiotemporal coverage of traffic information is not enough for optimal control, and the cost for construction and maintenance of such systems is high (Alaidi et al., 2020). Indeed, in such cases, special hardware infrastructure should be installed at each (signalized) intersection to provide information concerning the user's precise location and the status of signal lights. As a first step, such traffic lights could be placed, if not everywhere, at least in key parts of the city, such as hospitals, universities, public services, and cultural heritage sites, where many people move and cross the adjacent roads. Another solution to limit the energy cost is to easily power the whole system using solar energy, as proposed by Nguyen-Ly et al. (2019). Thus, using a solar energy system the traffic light system would become very compact, economical, and flexible for traffic systems, where motorbikes are used as the main means of transportation, and, therefore, the proposed system could be installed at more intersections according to Nguyen-Ly et al. (2019).

Moreover, synchronizing multiple traffic light systems at adjacent intersections of a city is a complicated issue, as various parameters influence its use and could lead to accidents and traffic jams. A possible solution for this issue, which has been suggested by a previous study, would be the use of a programmable intelligent controller. Specifically, this controller would evaluate the traffic density using IR sensors and accomplish dynamic timing slots with different levels (Ghazal et al., 2016).

Finally, another challenge for the programmers of such systems is the possibility of programming errors. Undoubtedly, complex intersections present the biggest challenge to visually impaired pedestrians and are considered the places where assistive technology is most needed. However,

|  | Gender | Age | Degree of visual impairment | Cause of vision loss | Digital sophistication |
|---|---|---|---|---|---|
| **P1** | **Male** | **55** | **Complete** | **By birth** | **High** |
| **P2** | **Female** | **35** | **Severe** | **By birth** | **Average** |
| **P3** | **Male** | **36** | **Complete** | **Diabetes** | **High** |
| **P4** | **Male** | **40** | **Almost complete (95%)** | **By birth** | **Low** |
| **P5** | **Male** | **40** | **Almost complete (95%)** | **By birth** | **Low** |
| **P6** | **Female** | **55** | **Complete** | **Retinopathy (23 years old)** | **Low** |
| **P7** | **Male** | **40** | **Almost complete (90-95%)** | **By birth** | **Low** |
| **P8** | **Male** | **40** | **Complete** | **Cancer (7 years old)** | **Low** |
| **P9** | **Male** | **35** | **Almost complete (> 95%)** | **Benign tumor (15 years old)** | **Low** |
| **P10** | **Male** | **60** | **Complete** | **By birth** | **High** |
| **P11** | **Male** | **30** | **Complete** | **By birth** | **High** |
| **P12** | **Male** | **40** | **Complete** | **By birth** | **High** |
| **P13** | **Male** | **38** | **Almost complete (90–95%)** | **craniocerebral injuries at 23** | **High** |

Table 8.1 Characteristics of interviewees

such places present the biggest challenge to computer vision algorithms. Interestingly, to overcome this issue, Coughlan and Shen (2013) have suggested the ‘Crosswatch’ project, which is a smartphone system based on the development of a computer vision program using other information sources, such as geographic information systems (GIS). Indeed, such systems associate data with the respective geographic location and sensor data. Therefore, given the pedestrian’s current location (GPS indicates the accurate location to determine the nearest intersection) and bearing (indicated by the smartphone compass), a GIS can search information associated with that specific intersection, such as the intersection layout (including crosswalk lengths and directions), as well as the presence and location of signs, crosswalks, and signals. Ivanchenko et al. (2008) developed the first camera phone-based system that offered real-time orientation information determined by visual cues at traffic intersections. In the improved version of Ivanchenko et al. (2009), a new computer vision algorithm and 3D analysis to estimate crosswalk location relative to the users who are BVI are introduced. The results of the literature survey are summarized in Table 8.1 which is provided as an Appendix A at the end of this article.

## 8.5 Materials and method

Our research aims to successfully address the daily pedestrian mobility accessibility problems of individuals, who are BVI, contributing decisively to the social inclusion and independence in social and professional life through safer autonomous navigation, as well as training and preparing public and private entities to be autonomously accessible to these users.

The first mobile app of our project (Blind RouteVision) aims to assist people being blind or visually impaired during outdoor pedestrian navigation. The application’s design includes enhanced GPS functionality and interconnectivity with other apps that may be useful during navigation, such as the corresponding service of Google Maps. The app is a part of an assistive navigation system, which includes ultrasound sensors for real-time recognition and avoidance of obstacles along the BVI’s path, synchronization with traffic lights and weather information, and utilization of telematic information of the local Mass Transit System for routes and urban transport stops. The initial version of the Blind RouteVision system is presented in Meliones and Sampson (2018).

*Figure 8.1. External GPS device*

The first version is supported on Android smartphones exploiting the Google Maps service to navigate the user using voice instructions. It integrates an external embedded microcontroller, which interfaces with a GPS receiver demonstrating extremely high precision in reporting the user position (see Figure 8.1) as well as a sophisticated sonar sensor for real-time detection and avoidance of obstacles.

In addition, it retrieves information about bus timetables and stops in real-time. The app will further integrate a machine learning-based innovative visual information functionality. The first version of the external device (see Figure 8.2(a)) includes the Atmega 2560 microcontroller and the GPS receiver U-Blox NEO-6M. The second version (see Figure 8.2(b)) includes the Atmega 328p microcontroller and the GPS receiver U-Blox NEO-8M. The size, consumption, and cost of the device have been reduced, while at the same time, it has a larger memory with optimized management and recognition of the battery level.

The proposed application provides accurate navigation instructions according to the specific requirements of the BVIs with the following features:

- Destinations are selected via a voice interface.
- Special voice commands for the blind, as opposed to the unsuitable and imprecise voice instructions, for standard navigation applications.
- An innovative real-time course tracking and correction mechanism of great precision for people who are BVI
- Capability for pedestrian routes to be combined with routes of public transport, incorporating guidance for bus approaches and real-time information for bus stop waiting times
- Information regarding traffic light intersections

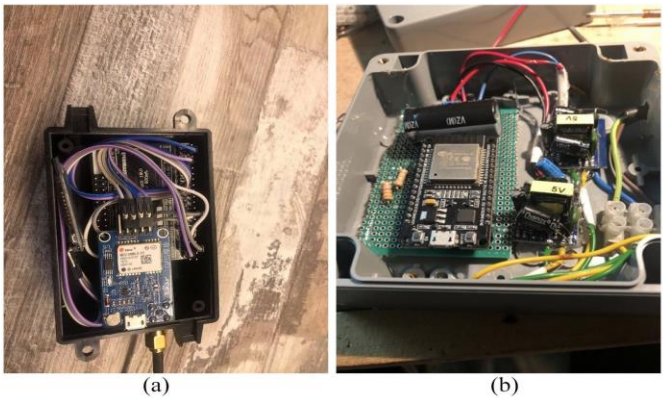

(a) (b)

*Figure 8.2. (a) Blind RouteVision outdoor navigation – Advanced Field Navigation Sensor; (b) Traffic light blind crossing device.*

We propose the implementation of a proof of concept, capable of integrating into any traffic light and informing the blind user when the traffic light turns green and for the time that remains to cross the road until the traffic light changes. In addition, the user is provided with vocal information on how many islets the intersection has and the direction of the vehicles at each intersection. The combination of the application with information on the status of conventional signals is a significant positive result for traffic lights and route monitoring. Moreover, our application equipped with the field sensor of the presented system (Filios & Meliones, 2021a) (see Figure 8.3) can guide with accuracy people with visual impairments and blindness to cross a traffic lights intersection.

Practically, there are three important results of our research for outdoor navigation that are summarized in this section: precise tracking and navigation (Filios & Meliones, 2021b), special voice guidance, and the recognition of the status of the traffic lights signals (see Figure 8.4). All of these are possible with great guidance accuracy and due to the high tracking accuracy mentioned earlier. In Figure 8.4, we depict high accuracy and density in finding the user's location. Furthermore, as can be seen from the picture, the user moves in the line formed by the antennas, while the built-in receiver of the mobile shows him on the left, in a parallel path. The error of the embedded receiver of the mobile is obvious due to the points shown in the image with the mobile phone, in contrast to the many points that are represented with the satellite dish which are the reported points of the external receiver. The average value of the deviation of the GPS of the mobile phone and the external receiver is approximately 10 m. In addition, at the point of interest concerning the traffic light, the deviation reaches 12 m. Approaching the traffic light when the distance is less than 10 m according to the scale, we have reference points mentioned every 2 to 3 m, incorrectly reported position from the receiver of the mobile greater than 10 m, and reported positions from the receiver of the

*Figure 8.3 Traffic sensor (the field sensor is the upper box).*

mobile phone at intervals greater than 10 m. The latter shows that our implementation has good guidance accuracy concerning the position, the level, and the available crossing time.

A usage scenario is presented for the operation of the application regarding traffic lights (Figures 8.5–8.10).

At this point, it should be emphasized that most of the related work involve limited efforts for intersection crossing, while our system adopts a holistic approach offering great accuracy and reliability within a comprehensive system for reliable transition and outdoor navigation. To sum up, high-precision routing, real-time route correction, accurate real-time bus stop updates, and traffic light interoperability will create a unified and fulfilled system that is competitive and unique in the market.

## 8.6 Initial, intermediate results, and requirements analysis

During the initial and intermediate phases of the development of the two assistive mobile apps for autonomous navigation of individuals that are BVI, user needs-and-requirements analysis was conducted and refined, respectively. These assistive apps are being developed within the MANTO project (funded by the Greek RTDI State Aid Action RESEARCH-CREATE-INNOVATE of the

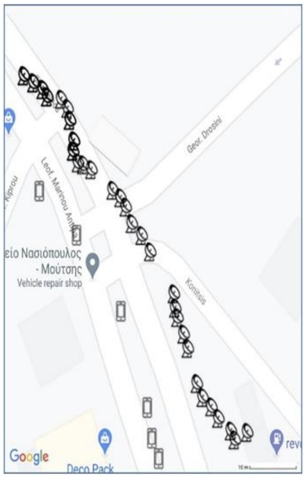


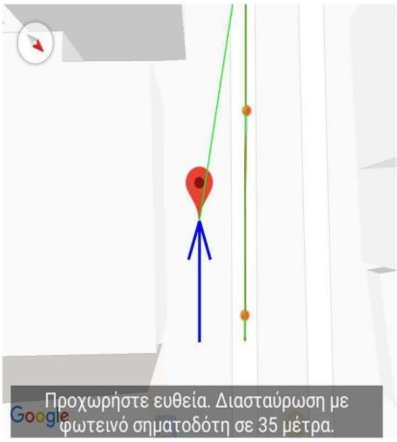
*Figure 8.4 GPS module (represented by the antenna) compared with the phone GPS (represented by the mobile phones) – The real path is the line (row) of antennae.*

National Operational Programme Competitiveness, Entrepreneurship and Innovation 2014–2020 in the framework of the T1RCI-00593 contract).

## 8.6.1 Three phases of the evaluation – general description

In more detail, to accurately identify the problems and preferences, a thorough requirements analysis was conducted by interviewing the members of the community, highlighting the specific characteristics of this group. The questions regarding the applications of navigation assistance concerned both the general use of digital technology by citizens who are blind and the future improvements of the applications' functionality. To this end, during the final trials of the applications, more interviews will be held on a larger scale through Google Forms. These interviews will seek feedback from both native Greek and international users on how to improve the functionality of applications which will be subsequently, processed utilizing the Social Model of disability (Barnes, 2019) as a guiding philosophy.

The interviews of the initial phase described subsequently were conducted before the prototypes of the applications themselves were displayed to the users. Thus, the participants' views were not biased by their operational characteristics or appearance. As the respondents were experts in the



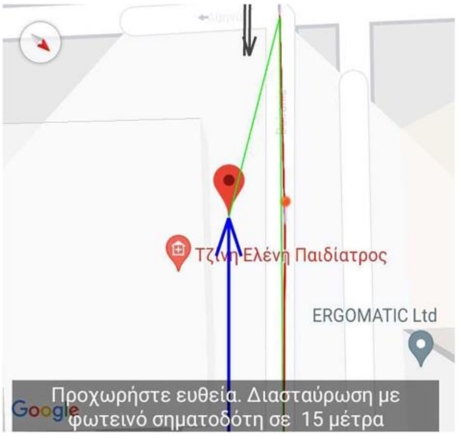
Προχωρήστε ευθεία. Διασταύρωση με φωτεινό σηματοδότη σε 35 μέτρα.

*Figure 8.5. Go straight ahead. Approaching traffic light intersection at 35 m.*

field and had significant experience in the use of technology working with people with related disabilities, the questions were designed to tap into their knowledge and experience as to what applies to other visually impaired people as well. During the mid-term evaluation phase, users were presented with prototype versions of the applications and were asked whether the requirements they had expressed at the beginning of the interviews were satisfied, which of them had been met and which issues need to be resolved or improved. The responses were then analyzed, and the results were used to improve the third phase of testing.

### 8.6.2 Interviews with people with BVI

The interviews were conducted at the premises of the Lighthouse for the Blind of Greece, the main nonprofit organization for the education and the assistance of people who are blind or visually impaired in Athens, Greece. The interviewees in the preliminary phase were six male and female individuals with vision problems ranging from complete blindness to severely impaired vision, whereas in the interviews concerning the mid-term phase of the evaluation 13 members participated. Each interview lasted at least 45 min. The table below presents the descriptive characteristics of the interviewees of the middle phase evaluation.



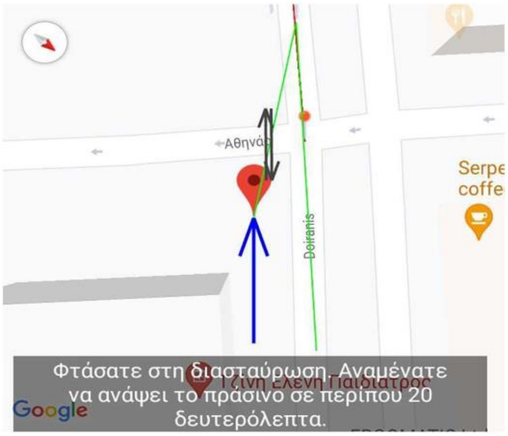
Προχωρήστε ευθεία. Διασταύρωση με φωτεινό σηματοδότη σε 15 μέτρα

*Figure 8.6. Approaching traffic light intersection at 15 m.*

The results of the interviews (answers, suggestions, and comments) identified the following key issues regarding the ease of use and usability of applications by people with blindness or visual impairments. These categories correspond to a broader concept of a requirement elicitation process (Hickey & Davis, 2004). These issues were classified into the following requirements: special characteristics and needs of the people who are BVI, requirements about the usefulness and capabilities of the apps, functionality requirements, usability requirements, requirements about the learning process of the assistive apps and devices, requirements concerning the compatibility and parallel operation of the apps with other apps and services, and other desirable features and general remarks about the assistive apps and devices. These issues were classified into the following requirements:

a. Requirements for special characteristics and needs (perception of the environment, characteristics of the pedestrian navigation)

b. Application requirements (obstacle detection, navigation and capabilities of changing, notification of a trusted person about the exact position of a BVI person),
c. Functionality requirements of applications and devices (keeping external stimuli unobstructed/uninterrupted, complete and seamless voice and audio interaction between BVI individuals and the application, improved placement accuracy),



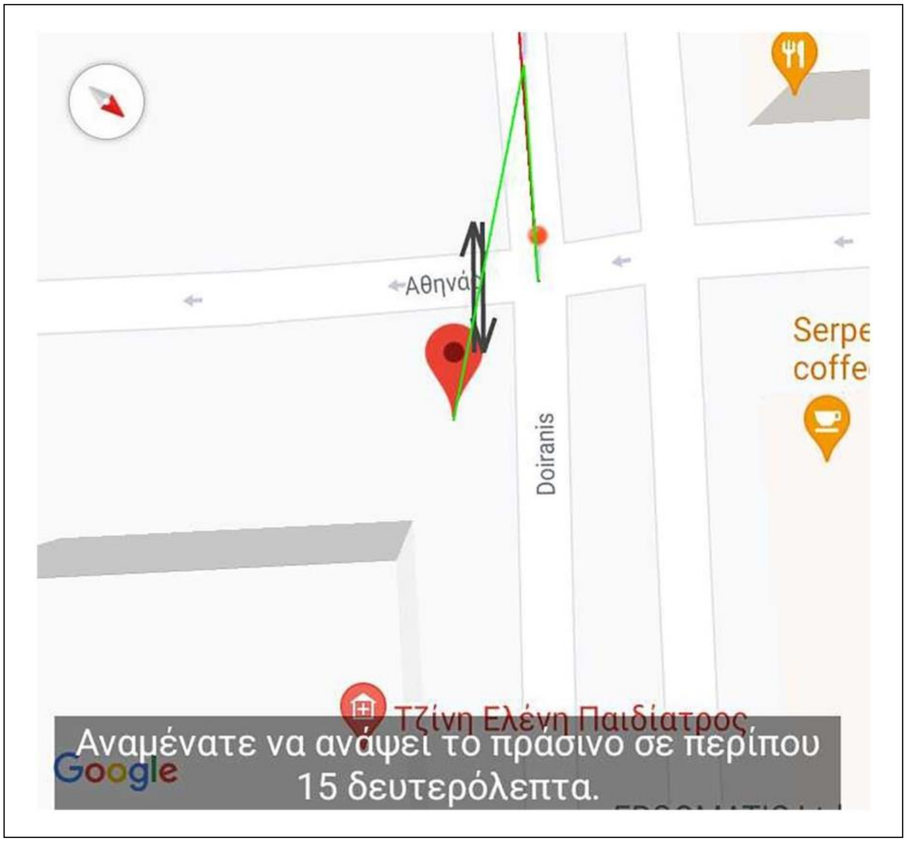
Φτάσατε στη διασταύρωση. Αναμένατε να ανάψει το πράσινο σε περίπου 20 δευτερόλεπτα.

*Figure 8.7. You have reached the intersection. Green will light up in about 20 s.*

d. Usability requirements (how the device and the application features will be user-friendly, simple operation, and voice function),
e. Requirements for the learning process (These are many and varied and include the natural environment – places where all aspects of applications can be tested effectively and safely – as well as methods and elements related to teaching and promoting our applications), and f. Compatibility requirements and parallel operation of these applications with other applications and screen readers.

These categories were further divided into subcategories as presented in Table 8.2.

Prior to describing the feedback specific to the traffic lights solution, we briefly outline the main points that were highlighted during the phase of the interviews. In particular, the user requirements concerning the usefulness and capabilities of assistive navigation systems are presented in terms of the direct benefits people with blindness and visual impairments wish to gain by adopting these systems (Theodorou & Meliones, 2021). The need for the detection of multiple, possibly moving obstacles with different shapes and at different vertical positions, was identified along with the requirement for the sonar sensor to notify the blind users at a frequency that is higher than once per second, as stated by one of the three experts. The user also requires a navigation system that could combine pedestrian navigation with the use of other means of transport (providing real-time information for departure or arrival times). During the interviews, the preferences and needs of people with visual impairments concerning the use of means of transport or during pedestrian navigation were also presented (Theodorou & Meliones, 2020, 2021). It can be concluded that people with blindness and visual impairments have a particular need for the most controlled conditions of traveling and that they believe that any deviation from the initially programmed travel may easily result in substantial adverse consequences.

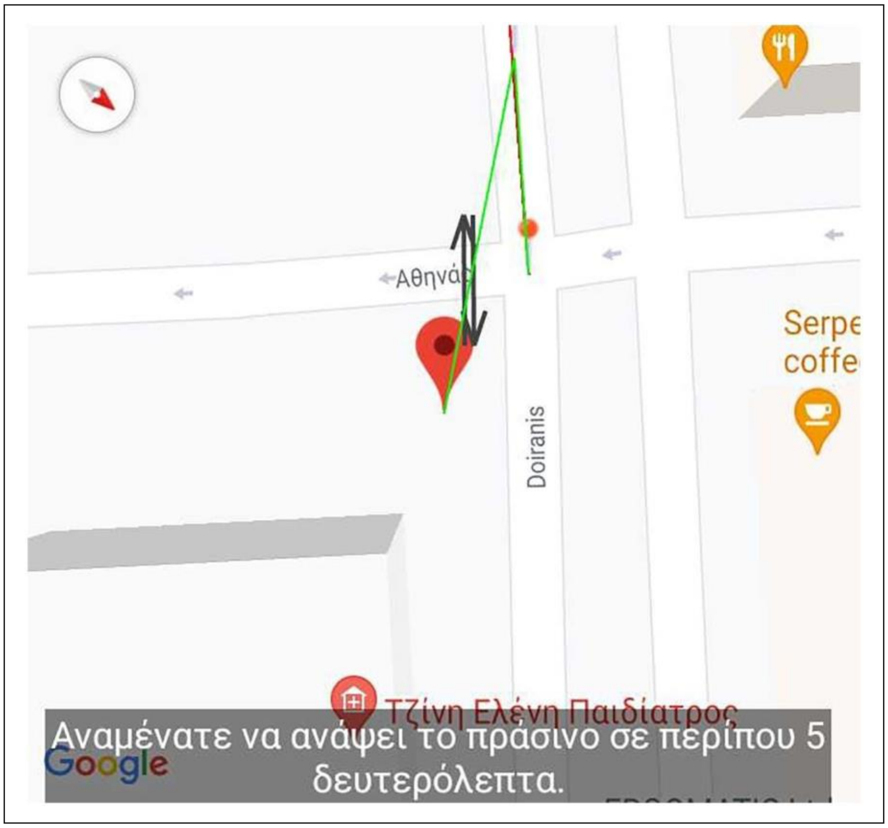


Αναμένατε να ανάψει το πράσινο σε περίπου 15 δευτερόλεπτα.

*Figure 8.8 Wait for the green to light up in about 15 s.*

It should be noted that a very important requirement that was mentioned by many interviewees concerns the identification and status of the traffic lights. These interviews guided our team to develop the relevant traffic light system. Subsequently, the evaluation of the traffic lights' functionality, which intends to help people with serious impairments or even total loss of vision to pass through the crossings with safety, is taking place, as the trials on the field were delayed until an acceptable level of safety was reached. In this case, the trials with blind users in the field started at an advanced stage (close to the final phase) to minimize the associated risk. In total, the focus of the research was on studying, on one hand, the qualitative characteristics derived from the analysis of the users' needs and preferences and, on the other hand, the quantitative characteristics of user experience via the use of questionnaires in the final phase of the evaluation (Fenton & Bieman, 2014).

Concerning the audio/voice interaction between the user and the apps, the participants highlighted the need for the existence of an audio signal on the traffic lights. In the scenario where both traffic lights and the app produce sound simultaneously, they must be easily distinguishable. Participants also stated that concerning the infrastructure review, malfunctions, or damages to traffic lights or in the means of public transport are not quickly repaired. Therefore, they stated that the maintenance of the software should be frequent, while adequate control systems should report any malfunction in real-time. For such a system to function properly, regular maintenance of the communication systems must be provided. Moreover, appropriate control and information systems or processes should be used to promptly identify any hardware malfunction.

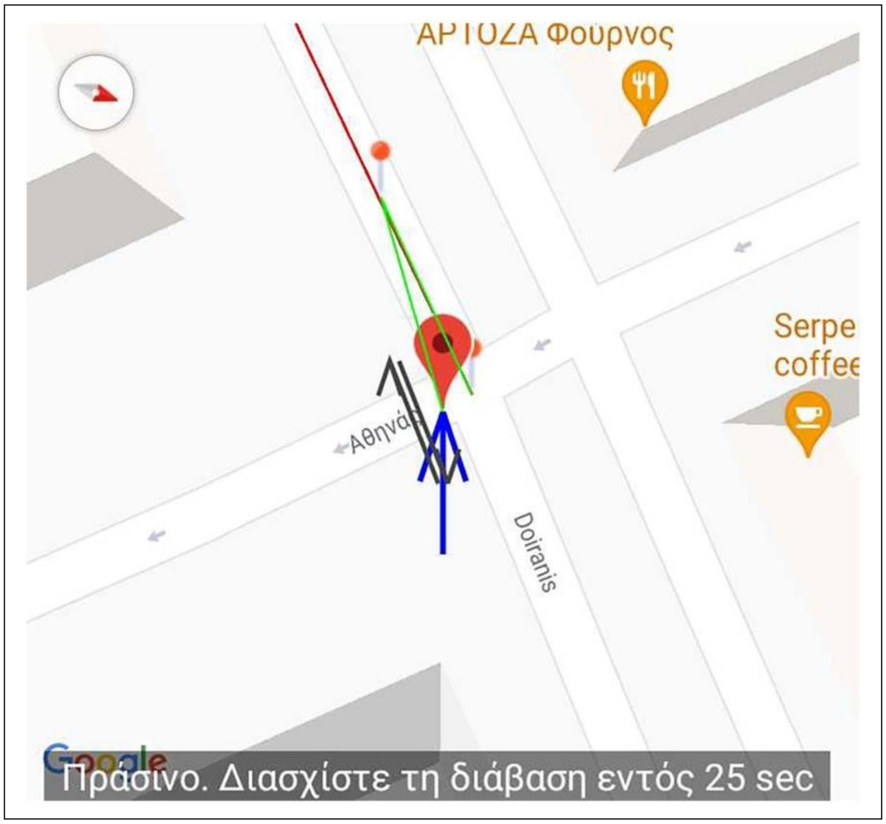


Αναμένατε να ανάψει το πράσινο σε περίπου 5 δευτερόλεπτα.

*Figure 8.9. Wait for the green to light up in 5 seconds*

Furthermore, the software should be able to identify possible threats to the individual even when the status of the traffic light is red. In other words, the field sensors' data stream must be continuously processed to guarantee and validate at the same time the safe passing of the blind individual. Safety is a requirement of paramount importance, and its conservation should not be threatened at any point of the route. According to one participant,

> “when the app notifies the user regarding the status of a traffic light, it should be able to identify the danger that may arise from a driver who does not follow the signal of the traffic light”, as well as “it must be possible to identify the danger at traffic lights even when the application has correctly stated that the blind person should proceed.”



Πράσινο. Διασχίστε τη διάβαση εντός 25 sec

*Figure8.10. Green. Cross the passage within 25s*

Another remark that stresses the above statement made by most of the participants is the fact that they try to avoid, whenever possible, passages with high volume traffic. To satisfy the requirement of safety, a traffic light system needs to provide the following information, as first presented by Peraković et al. (2013), including information on location, guidance and navigation, objects surrounding the user, traffic intersections, the method of traffic control, traffic light status switching, operability of the system, and successful passage crossing notifications. Another parameter identified by Periša et al. (2015) is user speed that influences the traffic light service for pedestrians who are BVI as it is directly related to the amount of time the traffic light remains on the green phase. Moreover, from our research, we have identified as important parameters the directionality of the vehicles as well as the passing of multiple consecutive cross-sections. As a result, it becomes evident from the above discussion that a large set of parameters needs to be considered to produce usable results.

## 8.7 Discussion and conclusion

After considering the existing literature review and the different use cases of navigation of people with blindness and visual impairments, we decided to approach and focus on the following characteristics–aspects of the accessible traffic lights. The importance of identification of both traffic

| | |
|---|---|
| **1. Special characteristics of visually impaired people** | **a. Perception of the Environment**<br>**b. Navigation (in general)**<br>**c. Pedestrian navigation**<br>**d. Use of smartphones and browsers**<br>**e. General features and suggestion** |
| **2. Requirements concerning usefulness and capabilities** | **a. Obstacle detection**<br>**b. Navigation**<br>**c. Additional characteristics** |
| **3. Functionality requirements** | **a. External stimuli**<br>**b. Audio/voice interaction between people who are visually impaired and the apps**<br>**c. Tracking and positioning accuracy and auxiliary devices** |
| **4. Usability Requirements** | **a. Characteristics/features of apps and devices.**<br>**b. Device handling** |
| **5. Requirements concerning the learning process of the assistive apps and devices** | |
| **6. Compatibility–parallel operation with**<br>**other apps other applications. Critique of applications,**<br>**operating systems and operating systems and infrastructures** | **a. Compatibility and parallel operation with**<br>**b. Critique on other apps,**<br>**infrastructure** |
| **7. Other desirable features and general remarks** | |

*Table 8.2 Categories of Interview*

lights and factors involving the road to be crossed (e.g., incoming vehicles and drivers not obeying the lights) is highlighted. One important aspect for the user who is blind is to know the exact place of the traffic lights by being able to hear and understand the audio alert. Another important aspect is knowledge of the width of the road and therefore how many lanes in which direction and how far it is to cross. In addition, of great importance is an awareness of pedestrians crossing from the other side of the road. It is also worth highlighting that people with blindness or visual impairments need an indication that moving obstacles (other people) are crossing over the road and being alerted to them.

To summarize, we can state that technology should become a part of an organized society when it can improve the quality of life of individuals who are in need and at the same time assist in the maintenance of a clean, safe, and inclusive environment (Chang, 2012). It is projected that the rate of individuals who are visually impaired will rise in the future, and for that reason, appropriate measures must be taken under consideration by governments and decision-makers across the world. Smart traffic lights comprise a very sensible and essential upgrade for the safe navigation of visually impaired individuals, and with the advent of smartphones and mobile devices, they can provide an even further improved experience for those in need of independent transit. However, policymakers must always take serious note that all innovations that involve the accumulation of personal data must be implemented with safeguards that ensure privacy and safety for all.

Finally, in our proposed initiative, the users are informed through the smartphone blind navigation application in real-time about the status of the traffic lights. Real-time updates and monitoring through traffic light sensors are significant positive results for traffic lights and high precision, real-time route monitoring. Regarding this, a patent-pending field sensor, described in Filios et al. (2021a, 2021b), has been proposed by the project team. The users are then informed about the color of the traffic light (red, green), the remaining time to change the current status of the color, the direction of the vehicles, and the number of crossings. The information update can be achieved rapidly with great precision even on the sidewalk toward the walkway. The literature review indicates that a holistic integrated system that connects navigational applications with traffic lights control systems is missing.

Our research with the support of the local authorities contributes to this aspect by proposing a methodology for the necessary data exchange and the cooperation of both systems (accurate navigation and crossing intersection with the aid of smart traffic lights). We offer a variety of possible solutions that span from field solutions which include the installation of external devices on traffic lights and on traffic light hubs, guaranteeing zero latency, to a more centralized one, via the use of the central administration tool of the Attica Region, in an attempt to minimize the costs associated with the field sensors. The latter will be evaluated in terms of the safety issues induced by the additional latency. As a near-future work, we intend to tackle the challenge of verifying in a timely manner the safety of our solution that helps blind individuals cross traffic lights. Toward that direction, the integration of our MANTO project partner Irida Labs visual system will significantly aid our cause. In particular, after the application has detected the status change of the traffic light from red to green light, the visual subsystem can verify that there does not exist a car that violates the traffic light indication. Finally, another aspect worth exploring is the added latency of the proposed system and its implications regarding the near real-time responsiveness in practical scenarios. Given the different degrees of complexity of the real-life scenarios, we can predict that there will be cases where the system’s latency will exceed the desired level of responsiveness. For that reason, we strongly recommend the blind individuals compensate for any transient shortcomings of the application’s functionality by utilizing their strong sense of hearing at all times.

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# Appendix A

**Table 3.** Overview of traffic light technologies aimed at blind and visually impaired individuals.

| Work | Tools and methods | Features | Restrictions | Evaluation–Metrics | Comments |
|---|---|---|---|---|---|
| 1 Ray – Castillo-Cara et al. (2016) | 1. Hybrid BNE4.0/GPS mobile device<br>2. AVR microcontroller<br>3. Google Directions API and Maps Geocoding API<br>4. TextToSpeech Google API | 1. Low cost, complexity and power consumption<br>2. Robustness, accuracy and timeliness of provided information | 1. Only traffic lights state-provided<br>2. Requires stable Bluetooth connection<br>3. High maintenance cost (regular battery replacement in beacons)<br>4. Use of filters and tuning of parameters, for example, power level | 1. transmission range = 3 m around a traffic light | 1. Two beacon IDs per traffic light for state recognition<br>2. No information on how the mobile is informed for new entries–IDs |
| 2 'n-in-1' traffic light system – Nguyen-Ly et al. (2019) | 1. Laser and photoresistor sensor combined with Arduino nano<br>2. ARM microcontroller<br>3. LEDs display: 84 addressable WS2812B LEDs<br>4. 28 LEDs to implement countdown timer display | 1. Low cost, power consumption, maintenance costs, easy installation and operation<br>2. Simpler and significantly more economical compared to camera-based systems<br>3. effective in case motorbikes are a main means of transportation<br>4. solar power<br>5. traffic congestion reduction<br>6. addressed to color-blind<br>7. integration of all three traffic signals into a single display block | 1. not addressed to BVIs, but color deficiencies<br>2. demand active scanning of environment involving continuous physical activity | 1. The minimum average power consumption is 2.00 W | 1. addressed to the motorbike transportation system<br>2. not addressed to BVIs, only to color-blind |
| 3 DetectSignal – Ihejimba and Wenkstern (2020) | 1. Raspberry Pi 4 (Linux)<br>2. AWS cloud Server<br>3. Mobile Device | 1. Cloud-based IoT edge computing solution<br>2. Reads traffic lights state and synchronizes it with AWS cloud server<br>3. Tolerance in big numbers of concurrent users<br>4. Highly available and scalable | 1. High cost of the controller (BOM)<br>2. High power consumption<br>3. Cost-effective for users due to their obligatory constant interaction with the server<br>4. Overall big complexity | 1. On average, response time is 19.20 ms, lowest response time is 10.22 ms, peak response time is 36.05 ms | 1. Low network latency required for real-time exchange of information<br>2. No information on how state recognition of traffic lights is achieved |
| 4 IoT-based system – Biswal et al. (2020) | 1. Android application<br>2. Arduino UNO R3 controller<br>3. voice-controlled smart traffic (VCST)<br>4. Bluetooth module (HC-05)<br>Light Sensor<br>5. Temperature and Power Metering Sensors<br>6. ZigBee Module | 1. energy optimization<br>2.low-cost, low power, reliable<br>3. user-friendly smart grid architecture<br>4. voice commands<br>5. traffic-flow-based smart (LED) street light | 1. no security issues are referred<br>2. missing security by advanced authentication schemes<br>3. short-range coverage (range 100 m) | 1. range 100 m, may be linked through long-distance coverage module | 1. Lack of powerful communication network |
| 5 Mobile-Cloud Collaborative Traffic Lights Detector–Pelin, Bhargava & Helal (++) | 1. context-aware navigation<br>2. cloud computing infrastructure<br>3. local navigation capability<br>4. other contextual data<br>5. compass integrated into the mobile device | 1. extensible, minimal infrastructural reliance, wide usability<br>2. access to resources that could provide a lot of contextual clues<br>3. computational power available through Cloud Computing providers<br>4. location-specific resources available on the Internet to provide maximal context-awareness<br>5. easy to use, portable, affordable device<br>6. compass integrated into the mobile for more accuracy | 1. Requires fast image-processing for locating and detecting the status of traffic lights<br>2. network latency could create a bottleneck on the timeliness of response received by the user<br>3. Continuous Internet Connectivity<br>4. short battery life of the mobile device | 1. Average response time for original frames: 660 ms | 1. real-time image-processing needs computational resources – mobile devices with limited computational capacity and battery life, cause inaccurate detection<br>2. image-processing is infeasible without communication of devices with external resources<br>3. time-consuming simplification of gathered information to convey to the user<br>4. user feedback might demand a significant cognitive effort<br>5. high video transmission time to the remote server |

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**Table 3.** (Continued)

| Work | Tools and methods | Features | Restrictions | Evaluation–Metrics | Comments |
|---|---|---|---|---|---|
| 6 Real-Time Detection of Pedestrian Traffic Lights –Ghilardi et al. (2018) | 1. Image-processing<br>2. computer vision approach with Faster R-CNN deep neural network<br>3. public dataset with 4,399 labeled images of pedestrians traffic lights, the Pedestrian Traffic Light Dataset (PTLD) | 1. embedded in a mobile device | 1. The precision score of Faster R-CNN is small but competitive | 1. Faster R-CNN results for classes Go and Stop:<br>2. 0,37 fps<br>GO Recall (%) 97.7<br>GO Precision (%)93.5<br>STOP Recall (%) 98.9<br>STOP Precision (%) 90.2 | 1. Faster RCNN is much more time-consuming during prediction time, so a sampling strategy is necessary<br>2. the simplification of the gathered information is time-consuming<br>3. user feedback has a significant cognitive effort |
| 7 Zebralocalizer – Ahmetovic et al. (2011) | 1. computer vision functionality on a smartphone<br>2. data acquired from camera and accelerometers<br>3. information about crosswalks | 1. identification and localization of crosswalks<br>2. no additional infrastructure required at each intersection<br>3. real-time feedback about orientation and location relative to a crosswalk<br>4. device orientation doesn't influence recognition and rotation technique, low processing complexity | 1. delay due to network latency | 1. 70% of zebra crossings recognized<br>2. all users were able to cross the road (about 6 m wide) in a short time ranging from 3 to 5 sec<br>3. the use of accelerometers increases the accuracy | 1. to guarantee safe road crossing, algorithm false-positives = 0<br>2. user attention should not be diverted from haptic and auditive stimuli<br>3. mental workload should not be increased with overmuch information |
| 8 TL-recognizer – Mascetti, Ahmetovic, Gerino, and Bernareggi, et al. (2016a, 2016b) | 1. accelerometers and gyroscopes<br>2. computer vision techniques<br>3. dynamic method for exposure adjustment (sky pixels segmentation and external luminosity)<br>4. messages transferred through audio, haptic (vibration) and graphical information | 1. computational and human-based experiments (2 BVIs and 2 low-visioned)<br>2. robust (working in different illumination conditions)<br>3. efficient (running several times a second on smartphones) | 1. constant hand interaction from the user for conveying feedback and for carrying the device effectively<br>2. fatigued pedestrians from carrying the device | 1. precision = 1, (no traffic light is erroneously detected)<br>2. the two blind subjects needed a slightly longer time (up to about 5 s) than the two partially sighted subjects (22)<br>3. computation time is in the order of 100 ms, FPS = 10 (34)<br>Tuning<br>Recall = 0, 85<br>Computation time = 113 ms<br>Evaluation<br>Recall = 0,81<br>Computation time = 107 | 1. audio should not divert the BVI's focus on the surrounding audio scenario<br>2. no accelerometer measurements for each frame<br>3. precision and recall are computed on streams of images, not on single images |
| 9 ZebraRecognizer – Mascetti, Ahmetovic, Gerino, and Bernareggi (2016) | 1. pattern matching technique to recognize zebra crossings<br>2. software module that<br>a. rectifies selected features<br>b. removes projection distortion<br>c. measures precise zebra crossing's position<br>3. comparison with 2 different algorithms for line segment detection: a customized version of EDLines and Line Segment Detector (LSD) | 1. quality of recognition (precision and recall)<br>2. recognition accuracy and estimation of user relative position<br>3. efficiency on mobile devices<br>4. processing images acquired at a high frame rate from the camera<br>5. no false-positive<br>6. a low number of false negatives<br>7. regular updates on BVI's position<br>8. not being overwhelmed with too many audio messages | 1. calculation of 'lateral distance left' and 'lateral distance right'<br>2. EDLines don't recognize the whole stripe edge (inaccurate border computation)<br>3. the absolute value of the difference between distance (frontal, angular, or left/right shift) and predicted (correct) one is an error value<br>4. difficulty in checking for sudden changes (rotation angle–capability for quick rotating)<br>5. distance approximation<br>6. inaccurate projection of user position on CLS<br>7. problems with app debugging, parameters tuning and performance measuring | 1. in a few non-consecutive frames the error is around 1 m<br>2. IMAGE acquisition process time is 25 fps<br>3. average error of rotation angle is 2.2°<br>4. estimation time of CPU implementation is 2.5 ms and 9.67 ms for images with resolution 90_160 pixels and 180_320<br>5. estimation time with the LSD is 3 times longer than with EDLines<br>5 with the GPU implementation of anchors extraction improved 30%<br>6. 93% correct identification of zebra crossings<br>7. in 96% of cases<br>frontal distance: error smaller than 50 cm, rotation angle: error smaller than 10° | 1. data used for evaluation are not public, so quantitative evaluation is impossible<br>1. low execution time for the identification process<br>2. improvement of all main steps of recognition algorithm<br>3. less computational costs |

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## Table 3. Continued

| Work | Tools and methods | Features | Restrictions | Evaluation–Metrics | Comments |
|---|---|---|---|---|---|
| Mobile Accessible Pedestrian (MAP) Signal system–NYC 'Mobile accessible pedestrian signal system', n.d.) | . reception of MAP (Mobile Accessible Pedestrian signal system) and SPaT (Signal Phase and Time) information from a smart device<br>. communications in the DSRC spectrum<br>. MAP message (location of crosswalks, pedestrians and device's features) determines the orientation<br>. SPaT message instructs path condition<br>. Communications to/from traffic controller will use DSRC (5GHz. 1609.x, J2735) message sets<br>. use of MAP and SPaT messages from PED pedestrian application<br>. use of SCMS (Security Credential Management System) for authentication of SPaT and MAP messages from roadside units<br>. special permission to use the PED call feature | . security<br>· avoidance of Certificate Revocation List CRL) issues and misbehavior detection management<br>. use of SCMS<br>a. Wi-Fi locally between PID (Personal Information Devices) and RSU at the intersection<br>b. 4G/LTE data exchanges between PID and server that provides SPaT and MAP info | . Special hardware infrastructure at each signalized) intersection | | . security and subscription issues with the use of the application<br>. enrolment certificates for app and licensed user |
| Mobile Accessible Pedestrian Signals MAPS)–Chen-Fu (2012) | . prototype MAPS<br>. The smartphone app will scan for Bluetooth devices and use the found geo-ID (MAC address) to obtain geospatial information of intersections previously stored in a database.<br>. signal and intersection geometry information<br>. tactile input (single/double-tap<br>. Text-To-Speech (TTS<br>. Smartphone app wirelessly communicates with the traffic signal controller to obtain real-time Signal Phasing and Timing (SPaT) information<br>. a roadside device installed inside the traffic controller cabinet to obtain SPaT<br>. Bluetooth-based geo-ID tag | . The APS system generates auditory cues continuously to help blind pedestrians locate the pushbutton<br>MAPS takes advantage of the low-latency capability of DSRC to coordinate cooperative communication among pedestrians (waiting at the crossing), traffic signal controllers and approaching vehicles<br>. MAPS reduces the need for users to visually locate and click a pushbutton at an intersection crossing<br>. Pedestrian dead-reckoning solutions using high-performance sensors can provide a better navigation solution<br>. data communication environment with DSRC to provide timely decision support and intersection information | . Special hardware infrastructure needs to be installed at each (signalized) intersection to inform the user precise location and status of signal lights.<br>effectiveness depends on the accuracy of smartphone sensors<br>the noise, the pushbutton locating, and the installation and maintenance costs associated with current APS systems.<br>· pushbutton location of the current APS system is difficult to locate (4) | 57% of the participants trust the MAPS system<br>. User satisfaction = 1.04 system usability = 0.95 using bipolar scales between −2 and 2 | . acoustic signals from APS systems are often confusing (8)<br>. modern roundabout intersection design presents more challenges for safe crossing<br>. more wayfinding skills for orientation and mobility training to find the beginning of crosswalk are necessary |

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**Table 3.** (Continued)

| Work | Tools and methods | Features | Restrictions | Evaluation–Metrics | Comments |
|---|---|---|---|---|---|
| 12 Wearable devices with RGB-Depth images utilization – Cheng et al. (2018) | 1. the customized wearable device–Intoer ('Intoer', n.d.)<br>2. Addition of Sliding window algorithm and renewed SVM classifier to previous crossing light detection algorithm<br>3. RGB image-based AECA (adaptive extraction and consistency analysis) algorithm<br>4. extraction of primary crosswalk stripe candidates by three-layer feed-forward neural network<br>5. the exploitation of RGB and depth images acquired by a wearable system | 1. computation of detected objects' distance to the BVI<br>2. detects crosswalks or crossing lights even under severe weather conditions<br>3. depth information into consistency analysis in comparison to AECA<br>4. multiple targets at urban intersections detected<br>5. extraneous candidates ruled out by geometrical properties<br>6. the separate candidates split by obstacles are merged,<br>7. similar candidates formed into consistency sets. | 1. false detections of pedestrians ruled out by the proposed detector | 1. 200 ms speed processing time<br>field tests at six intersections<br>2. subject manages to reach the starting point of crosswalks at five intersections<br>3. At all the six intersections the subject identifies the state of crossing lights correctly | 1. the detector has more depth information into consistency analysis in comparison to AECA<br>2. Improvement of detection precision compared with mere RGB images<br>3. temporal-spatial analysis guarantees stable detection results by comparing recognition results in the current frame with those in former frames |
| 13 A wearable tactile traffic lights assistive device (WTTLAD) – Huang et al. (2017) | 1. wearable tactile traffic lights assistive device (WTTLAD)<br>2. hand vibrotactile signal design<br>3. three vibrotactile codes for different traffic light colours<br>4. vibrotactile Wi-Fi signals match the frequency of traffic lights and confirm that signals are received by WTTLAD<br>5. tactile vibration rather than hand exploration | 1. user performance experiments with 2 subject – tests (visually impaired and blindfolded) in two fields: in a laboratory (indoor field) and at a road intersection (outdoor field)<br>2. verified usability | a. reduced hearing in a noisy traffic situation<br>b. type or frequency of a sound is not understandable<br>c. the signal must be stronger and distinctive<br>d. tactile senses cannot substitute any other perceptual channel | 1. average correct recognition rate = 96.67%<br>2. blindfolded spent more time ($M = 40.33$ s, $SD = 19.91$) than the visually impaired ($M = 38.83$ s, $SD = 9.07$) in the indoor field<br>3. t-test results, no significant difference in operating times between the two subject groups in the indoor field ($p = .773 > 0.05$), outdoor field ($p = .637 > 0.05$)<br>4. significant difference between experimental fields ($F = 121.38$, $p < .01$) | 1. Problems of intersection buzzers (examples)<br>a. two types of birds' sound difficult to distinguish<br>b. confusion when combined with traffic noise<br>c. difficulty in recognizing auditory information increases in noisy environments |
| 14 RTLS and NFC system–Periša et al. (2015) | 1. RTLS (Real-time Locating Systems) (identification system)<br>reader with Wi-Fi antenna and controller;<br>transponder (card or tag);<br>central computer<br>2. RFID<br>3. Bluetooth (headset)<br>4. NFC protocols at frequencies of 2.4 GHz (802.11b and 802.11g) and 5 GHz (802.11a) - transmission speeds up to 54 Mbit/s<br>5. white cane, mobile terminal device (external or integrated GPS receiver), device speakers | 1. increased intermodal container transportation, mobility, safety and overall effectiveness<br>2. identification zones compute accurate information about distance<br>3. developed user's perception and mobility through info about environmental and traffic intersection infrastructure | 1. user speed (proportional to the length of the green process) confuses the BVI users<br>2. RFID: Active – (battery life 2-7 years, the possibility of sending multiple data), Passive–(less expensive, smaller)<br>3. Bluetooth: Possibility of voice and data transfer<br>4. Wi-Fi: access speed<br>5. NFC: Low energy consumption | 1. passive tag data = 48 to 736 bytes<br>2. active tag = 64 bytes to 32 KB, and read-only = 20 bit<br>3. transmission speeds of Bluetooth SIG (V 4.0LE) = 25 Mbps.<br>4. NFC technology, data transfer rate up to 424 kbit/s<br>5. point-to-point communication less than 0.2 m.<br>6. survey = 144 users, mean value of ten measurements (Vk = 0.55 m/s)<br>7. Evaluation accuracy of customer satisfaction with current audio (62% = bad) and tactile information (58% = bad) | 1. RFID Advantages<br>Active – More complex and more expensive<br>Passive – Range up to 0.5 m, less memory<br>2. Bluetooth Advantage<br>Limited distance, low peak flow<br>3. Wi-Fi Advantage<br>Security, transfer speed<br>4. NFC Advantage<br>Small distance |
| 15 Crosswatch – Ivanchenko et al. (2008)<br>16 Improved Crosswatch – Ivanchenko et al. (2009) | 1. computer vision algorithm<br>2. off-the-shelf Nokia N95 camera phone (portable system)–dual ARM 11 CPU with a CPU clock rate of 332 Mz<br>3. acoustic signals coupled with vocal feedback<br>4. coding in Symbian C++<br>5. 3D analysis, visual cues | 1. two tests with BVIs<br>2. reliability, efficiency, feasibility<br>3. the precise location of crosswalk patterns of two different types (the continental and two transverse lines)<br>4. detection of illuminated walk signal in less than a sec | 1. precise device position (portrait or landscape) is kept, but BVI may rotate the device while in motion<br>2. constrained algorithm design and implementation because of limited memory and CPU power | 1. algorithm processes approximately 3 fps<br>2. from 90 training images, only one is misclassified<br>3. true- and false-positive rates = 72% and 0.5%<br>4. First test: right answers to all 15 different traffic intersections about the existence of zebra crosswalk<br>Second test: better alignment using system feedback (qualitative measurement) | 1. no added infrastructure needed<br>2. standard off-the-shelf cell phone technology (inexpensive, portable, multipurpose, nearly ubiquitous)<br>3. the measurements will be improved<br>a. high-level model verification stage<br>b. acceptable maximum system error rates<br>c. appropriate training procedures |

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**Table 3.** (Continued)

| Work | Tools and methods | Features | Restrictions | Evaluation–Metrics | Comments |
|---|---|---|---|---|---|
| 17 Crosswatch system – Coughlan and Shen (2013) | 1. computer vision algorithms<br>2. GIS information<br>3. sensor data<br>4. built-in smartphone speakers<br>5. real-time feedback | 1. two blind volunteer subjects (no light perception)<br>2. accurate information of pedestrian orientation relative to crosswalk and status of a traffic light with unreliable non-visual cues<br>3. user's location defined more precisely than with GPS alone<br>4. useful for navigating new intersections, or as a learning aid for familiarizing with an intersection<br>5. locate precisely a walk button | 1. functional and technical issues with computer vision and sensor components, especially on adverse illumination and weather conditions or fading of crosswalk paint<br>2. capturing picture panorama by swiping the smartphone in a circle is inefficient<br>3. holding camera far enough from horizontal (not visible intersections), inability to use image panoramas<br>4. built-in smartphone speakers not practical in noisy urban environments<br>5. active scanning of the environment (continuous physical activity)<br>6. errors of inaccurate GPS readings<br>7. complicated intersections | 1. spatial precision is better than a meter<br>2. test: image panorama demonstration (audio tones issued by the system at roughly 20° intervals)<br>a. sampled the entire 360° horizontal field from multiple, overlapping views and<br>b. consisted of images taken with a camera held roughly horizontal. | 1. no added infrastructure needed<br>2. other possible improvements and<br>a. use of bone conduction headphones<br>b. using more tactile feedback<br>c. differentiated ways to enter commands<br>d. provision of training materials<br>e. provision of free and open-source (FOSS) software<br>3. other possible variations<br>a. explicit instructions with synthetic speech<br>b. 3D spatialized sound–stereo headphones |
| 18 Machine learning prediction models for pedestrian traffic flow levels – Cohen and Dalyot (2020) | 1. machine learning methods and computerized route planning algorithm for predicting pedestrian traffic flow levels<br>2. geographic information layers in OpenStreetMap (OSM)<br>3. participatory mapping of crowdsourced data and geographic information<br>4. Random Forest algorithm | 1. machine learning algorithms accurately generate necessary temporal data<br>2. available crowdsourced open mapping data with reliable route planning algorithms<br>a. open mapping data without limitations, charges, or legal, administrative restrictions<br>b. global-scale data mapped in OSM with numerous location-based services<br>c. OSM database–mapping of diverse geospatial data types not existing in other global databases<br>3. best results | 1. micro-mapping issues in geographical features in OSM<br>2. data did not include pedestrian traffic levels for overcrowded and dense streets. | 1. prediction results by implementing six machine learning algorithms<br>2. 70% of samples were used for training and 30% for testing<br>3. successful prediction – 95% of testing data<br>4. average accuracy values of all methods are between 0.533 and 0.952, while standard deviation values are between 0.001 and 0.066<br>5. RF prediction method achieved highest, lowest accuracy value of 0.946 with 95% probability Precision 0.921, Recall 0.916, F1 score 0.918 | 1. additional extensive data received from BT sensor systems or other sensory infrastructure |
| 19 MANTO project (Filios & Meliones, 2021a, 2021b; Theodorou & Meliones, 2022) | 1. sub-meter GPS positioning,<br>2. user path vector,<br>3. cloud service for traffic light field sensors,<br>4. real-time recognition of traffic light state and duration,<br>5. appropriate vocal instructions for BVIs<br>6. short-range wireless network,<br>7. Bluetooth server (Bluetooth long-range) | 1. A fulfilled system containing<br>a. precise tracking and navigation<br>b. special voice guidance based on the hands of the clock (degrees) and simpler rectangular instructions (Right, left, front, back and opposite)<br>c. real-time recognition of the status of the traffic light signals on par with advanced guidance and high tracking accuracy | 1. GPS coverage<br>2. availability of telecommunication networks and external service API (e.g., unavailability of public transportation telematics system, use of Google Backup with no real-time info) | 1. sub-meter accuracy contribution | 1. training capability in secure and simulated conditions<br>2. functional pilot field deployment in the city of Athens, local authority support for large scale deployment |

VCST: voice-controlled smart traffic; PTLD: Pedestrian Traffic Light Dataset; LSD: Line Segment Detector; MAP: Mobile Accessible Pedestrian; RGB: red green blue; GIS: geographic information systems; API: Application Programming Interface; AWS: Amazon Web Services; RCNN: Region-Based Convolutional Neural Networks; FPS: Frame Per Second; CLS: Closest Line Segment; GPU: Graphical Processing Unit; NYC: New York City; DSRC: Dedicated Short-Range Communication; MAC: Media Access Control; SVM: Support Vector Machine; RFID: Radion Frequency Identification; KB: Kilo Byte; SIG: Special Interest Group; RF: Radio Frequency; BT: Bluetooth; BOM: Bill of Materials; LED: Light Emitting Diode; GO: Command; PED: pedestrian; MHz: MegaHertz; MANTO: Name of the project

# Chapter 9 (Content partially published in #7)

## An Extended Usability and UX Evaluation of a Mobile Application for the Navigation of Individuals with Blindness and Visual Impairments Outdoors—An Evaluation Framework Based on Training

**Keywords**: UX (user experience); usability; mobile app; user-centered training; visual impairments and blindness

## 9.1. Introduction

Globally, vision loss is the third most frequent disability. The incidence of eyesight loss is expected to climb as life expectancy and population growth increase globally. Although the modeling projections have limitations, the extended increase in prevalence and the global numbers of blindness and vision impairment (such as the number of blind people increasing to 38.5 million by 2020 and 115 million by 2050) demonstrate the magnitude of the challenge [1]. For the next three decades, it is projected that individuals with moderate to severe visual impairment will increase to more than 550 million people, up from approximately 200 million individuals in 2020 [2]. According to the World Health Organization (WHO), about 90% of people living with Moderate and Severe Visual Impairments (MSVI) are in low-income regions, raising serious issues for social and economic growth in these areas [3].

The increase in visual impairment and blindness in both developing and developed nations can be attributed to several reasons, including inheritance, accidents, illnesses and the ageing population, while the severity varies by gender, the individual's income and the country's economic status. In practice, the latter largely influences the way of tackling such a crisis as it enables access to the most up-to-date vision correction research or medication that could have prevented or reduced cases of this disability in the first place. Although there are cost-effective therapies for preventing or treating most types of vision loss, their availability varies greatly between nations and regions. The relationship between vision loss and socioeconomic factors might help with public health planning. Furthermore, complementary to addressing these challenges is the use of various assistive technologies [4].

The inconveniences of the current assistive devices for the blind and visually impaired and the inter-related socio-psychological attributes [5] had always been an area of great interest for various researchers around the world as some of these technologies are too technical, not portable or impractical to use. Advancements in technology allow for the improvement of these limitations. Despite significant progress and a wide range of technical solutions that resulted in several frameworks, navigation assistance devices are still not extensively utilized, user approval is poor [6] and many of them, as described in some very interesting literature reviews covering blind navigation [7–9], are restricted in scope.

In this chapter, we present a blind navigation system developed as part of the MANTO [10–12] project, called BlindRouteVision, that enables users to safely navigate to destinations with an option to include Public Means of Transport, its Usability and UX evaluation tailored to the special needs of this target group, and the specialized training tool and sessions developed to increase the acceptance of the proposed solution that conforms to the basic theories, principles and merits of Special Needs Education. BlindRouteVision also enables the passing of marked pedestrian crossings near traffic lights with zero latency notifications, as well as detecting obstacles in the user's path with the aid of a custom-made ultrasonic-based obstacle detection system. In Section 1.1, we present past and current solutions to the problem of navigation for people with blindness and visual impairments. Section 1.2 presents the architecture and the basic principles of operation of our proposed solution along with the design process we employed to produce the artefact. Subsequently, Sections 2.1–2.5 present the methodology with which we conducted the usability and UX evaluation, while in Sections 3.1–3.7, we present the data findings of the analysis. Following the presentation of the basic functionality and the UX results, in Section 3.8, we perform a comparative evaluation with the current state of the art in the literature and commercial applications for blind navigation. In Section 4, we discuss the lessons learned, the various limitations of both the technical solution and of the Usability and UX evaluation process, as well as the future directions addressing these limitations. Finally, in Section 5, we briefly summarize the main points of the chapter.

## 9.2 Background

Smartphones are now widely used by individuals of all ages and backgrounds. The main benefits of such solutions are the offered portability, adaptability, convenience, and user-friendliness [7,9]. This section categorizes the developed smartphone-based solutions targeting people that are blind and visually impaired.

Different types of sensors embedded on smartphones are utilized in [13–27] to record real-world environment data and, subsequently, employ the available smartphone processors to interpret the data and signal events.

Lin et al. [27] developed an assistive navigation system based on a smartphone application that can be used with an image recognition system. The system can operate in one of two modes: online or offline, depending on network availability. When the system is turned on, the smartphone takes a picture and transmits it to the server to be processed. To distinguish between distinct obstacles, the server employs deep learning algorithms [28,29]. The system's primary drawbacks are its high-power consumption and the requirement for high-speed network access.

The TARSIUS system [30] was designed to help people better grasp visual scenes in outdoor settings. The TARSIUS mobile app, a web server, a remote support center and Bluetooth LE/iBeacon tags deployed along streets at sites of interest are all part of the system. However, the deployment of Bluetooth beacons all over the streets, which is expensive and may create signal interference, is one of the TARIUS system's key problems.

ENVISION [31] employs a special approach to identify static and dynamic obstacles reliably and correctly from a real-time video stream captured by a smartphone with an average hardware capacity. If the obstacle identification and classification modules can assist the target users in gaining a better grasp of the environment, the system may be improved even further.

Lock, Cielniak and Bellotto [32] present a multimodal user interface that employs audio and vibration signalling to send navigational information to the target user. This effort is part of the "Active Vision with Human-in-the-Loop for the Visually Impaired" (ActiVis) project. The limitation is that it depends on Arcore to run, which is not supported by all smartphone devices.

The Tactile Wayfinder [33] is made up of a tactile belt and a Personal Digital Assistant (PDA) that runs a Wayfinder program. The app keeps track of the user's position and path. The information is provided to the tactile display when the travel direction has been determined. The vibrators in the belt can provide information to the user about navigation directions. The problem in this application is the difficulty in the adoption from the users due to the external equipment required for its correct operation.

Tepelea et al. [34] describe a smartphone-based navigation system for blind people that makes use of the MEMS (Micro-Electro-Mechanical Systems) built into smartphones. Information to the user is communicated via a Text-to-Speech (TTS) interface and the app utilizes WiFi and Bluetooth to connect to external modules. The suggested portable system is effective, inexpensive and compact; however, it has not been tested in use cases including buildings or outdoors scenarios.

Alghamdi et al. [35] proposed a new approach for visually impaired and blind persons, to help them in interior and outdoor navigation by displaying their position and leading them to their destination. The system uses RFID technology that covers approximately a distance of 0.5 m. The test results demonstrate the accuracy of the suggested framework to be in the range of 1 to 2 m. However, the system's accuracy detecting mechanism is not well-defined.

Tanveer et al. [36] developed a walking aid for the visually impaired based on a smartphone-enabled custom-made wearable device. When the obstacle's position is recognized, the smartphone application creates Bengali/English speech signals. GPS is used to determine the latitude and longitude of the user, and the blind person's position is tracked via a Google Maps-based application. The overall reported error rate is around 5% in the case of concrete and floor tiles. However, in some conditions, this method fails, with a notable example being spaces with floor elevation.

Patil et al. [37] propose a system (NavGuide) that creates a logical map of the surroundings to provide feedback to the user about obstacles, wet floors and ascending staircases. It consists of (1) six ultrasonic sensors, (2) a wet floor detector sensor, (3) a step-down button, (4) microcontroller circuits, (5) four vibration motors and (6) a battery for power supply. The system is mounted on the users' shoes and vibration is the main way of interaction. The battery is reported to last, on average, around 600 min, but this is highly dependent on the used case scenario. Furthermore, the authors mention that the proposed solution is not heavy while the cost is low. They also demonstrate the effectiveness of the system in minimizing collisions with obstacles, especially when compared with the more traditional white cane. However, the system cannot detect pits or downhills, downstairs or wet floors prior to the user stepping on it.

Vidula V. Meshram et al. [38] propose a custom-made system mounted on a cane (NavCane) for both outdoor and indoor navigation that supports the following: (1) priority information about obstacles in the path without causing information overload, (2) obstacle detection at the foot, knee, waist and chest levels and scaffold objects up to the chest level and (3) object recognition in known indoor settings. The system consists of several components including: (1) five ultrasonic sensors, (2) a wet-floor detection sensor, (3) an accelerometer, (4) an RFID reader, (5) a contact button, (6) a vibration motor, (7) a GSM module, (8) a GPS module, (9) a single board small computer (SBSC) and (10) an external battery for the power supply. The user interacts with the system via audio signals and vibration motors. The reported battery consumption is, on average, over 600 min, the proposed system has a relative low cost while the added weight does not put a high burden on the user. The evaluation of the system involved 80 visually impaired people and demonstrated among others that collisions with outdoor objects were significantly reduced. Nonetheless, the system has the following limitations: (1) unable to recognize objects in unfamiliar indoor environments and in head-level obstacles, (2) the reported deviation is 4% between the actual and detected distance measurements of obstacles and, finally, (3) the identification of descending staircases as well as slopes is successful only if NavCane is held upright, forming approximately 90 angles with the floor plane.

Rahman et al. [39] present a system that works in unfamiliar environments and detects obstacles around the individuals' left, front and right direction. It consists of (1) three infrared sensors, (2) a raspberry pi, (3) an external power supply and (4) headphones. The user interacts with the system via audio signals sent to the user's headphones and a vibration motor. According to the authors, the cost is USD 45 and its net weight is 368 g. The evaluation of the system shows an average accuracy of 98.99% and error rate of 1.006%. Finally, the system is limited in terms of ground objects' identification, while the authors do not present the power consumption requirements.

Chang Wan-Jung et al. [40] present a system that detects aerial obstacles and fall events on roads. When a fall event occurs, an urgent notification is sent to either family members or designated caregivers. The system consists of (1) wearable smart glasses, (2) an intelligent walking stick, (3) a mobile device app and (4) a cloud-based information management platform for sending the relevant notifications. The user interacts with the system with the help of vibration motors mounted on the cane. Experimentation with the system shows an average fall detection accuracy of up to 98.3%. However, the system cannot recognize front aerial and ground images such as traffic signs and traffic cones, while the authors do not disclose any information related to the power consumption requirements, the cost and the weight of their proposed solution.

Cardillo et al. [41] propose a system utilizing a microwave radar mounted on top of the traditional white cane that makes users aware of the presence of an obstacle in a wider and, thus, safer range. It consists solely of a microwave radar while the user receives feedback via acoustic warnings and vibration. According to the authors the system is cost-effective as it made of commercial components and lightweight, while there are no data on the power consumption required. Experimentation with the system shows a detection range of 0.5–3.5 m. Nonetheless, the system is still an early prototype and other limiting factors, such as size, have not yet been considered.

Cardillo et al. [42] present a system that warns the user about the presence of humans in complex environments with the concurrent presence of multiple moving targets. The main method of detecting human obstacles is a novel range alignment procedure that detects the chest displacement. It consists of a white cane with a mm-wave radar mounted on top of it. The user receives feedback via an acoustic and/or haptic interface. The weight of the proposed solution is estimated to be low while there are no data from the authors on the power consumption requirements or the cost. The effectiveness of the proposed solution is validated via both simulated and experimental results. A weakness of the system is its reduced effectiveness for stationary human targets.

Kiuru et al. [43] present a system based on a frequency-modulated continuous wave (FMCW) radar principle where it detects obstacles in a 25-degree horizontal angle, covering a 0.9 m-wide area at a distance of 2 m in front of the user. The system's vertical angle is approximately 70 degrees, making it possible to detect obstacles 1.4 m above the position of the sensor at a 2 m distance. The radar-based device is worn as a heart rate monitor and the user receives feedback via sound or vibration. The range from which the prototype vibrates or issues voice instructions is set to 3.5 m. The authors report that the prototype is light and the battery lasts for up to 4 or 5 h max when full functionality is on. However, there is no information regarding the cost of the proposed solution. On the downside, the authors do not perform an experimental evaluation of the system besides a user satisfaction study claiming an overall score of 3.8 out of 5. Furthermore, we can conclude that the battery is not ready for everyday use while, from our experience, not all blind individuals are particularly happy with a solution that demands a wearable device to be attached around their chest.

Islam et al. [44] propose a walking guide system that detects obstacles in three directions (front, left and right) and road surface potholes using an ultrasonic sensor combined with a convolutional neural network (CNN). It consists of (1) ultrasonic sensors, (2) a single Board Computing (Raspberry PI), (3) an RPI camera, (4) headphones and (5) an external power supply. The system is mounted on the user's head, receiving feedback via audio signals. According to the authors, the proposed solution costs USD 140 and weighs around 360 g. Information about the power consumption requirements is not provided. The experimental results report an accuracy of 98.73% for the front sensor with an error rate of 1.26% (obstacle 50 cm distance), while image classification achieves accuracy, precision and recall of 92.67%, 92.33% and 93%, respectively. However, the system's requirement of headphones raises issues to the blind and visually impaired as it could potentially cover ambient sounds critical for their safety. Furthermore, even though the objects and potholes are detected, the system cannot categorize them and, finally, the system's size and weight raise questions about its wearability.

Elmannai W. M. et al. [45] present a system to avoid front obstacles utilizing sensorbased and computer vision-based techniques, as well as image depth information and fuzzy logic. It consists of (1) a FEZ spider microcontroller, (2) two camera modules, (3) a compass module, (4) a GPS module, (5) a gyroscope module, (6) a music (audio output) module, (7) a microphone module and (8) a wi-fi module. The user receives feedback viaj audio signals. According to the authors, the system costs USD 242.41 and weighs 180 g. Information about the power consumption is not presented. Experimentation with the system shows an achieved accuracy on detecting objects of 98% and 100% accuracy in avoiding them. Nonetheless, the system may not be able to detect either walls or large doors due to the size of their representation on the image and, finally, it is not the most cost-effective solution.

Duh, P. et al. [46] propose a system based on a novel global localization method (VB-GPS) and image-segmentation techniques with a single camera for a better scene understanding of detecting and warning about moving obstacles, providing the correct orientation in real time or supporting navigation between indoor and outdoor spaces. It consists of (1) two servers, one for MBL and the other for semantic segmentation, (2) a local computer, (3) a wearable camera and (4) a smartphone. The latter is used by the user to receive feedback via audio signals. The experimentation section demonstrates the precise locations and orientation information (with a median error of approximately 0.27 m and 0.95), the ability to detect unpredictable obstacles and to support navigation in indoor and outdoor environments. The authors do not provide any information about the energy requirements, cost or weight of their solution. Recognized weaknesses of the system include (1) its reduced reliability due to its sensitivity to network communication delays, (2) poor localization and scene-understanding results in rainy days or at night and (3) prepared information about static objects in advance via a landmark map.

Lin et al. [47] present a deep-learning-based assistive system with an obstacle avoidance engine that learns from an RGBD camera, semantic maps and pilot's choice-of-action input. It consists of (1) a smartphone, (2) earphones, (3) a stereo based RGBD camera, (4) a wearable terminal with sunglasses and

(5) an external PC. The system provides a voice interface to the user, it weighs no more than 150 g and achieves an accuracy of 98.7% in daylight conditions and 97.9% at night. The authors do not include any information at all about the power consumption requirements and the cost. Among the weakness of the system are its susceptibility to different lighting scenarios and its form factor impacting wearability.

Younis et al. [48] propose a new context-aware hybrid hazard classification assistive technology to help bring attention to possible obstructions or hazards to people with peripheral vision loss. The system provides capabilities such as hazard detection recognition, hazard tracking and real-time hazard classification modules. It consists of computerenabled smart glasses equipped with a wide-angle camera and a MacBook laptop. The user interacts via visual and audio signals. Experimentation with the system reveals a 90% True Positive Rate (TPR), 7% False Positive Rate (FPR), 13% False Negative Rate (FNR) and an average testing Mean Square Error (MSE) of 8.8% on both publicly available and private datasets. The authors present no information about the power consumption requirements, the cost or weight of the proposed solution. Among the weaknesses of the system are the fact that it is an early prototype and the limited personalization for the notification style.

Yang et al. [49] present a unified approach based on seizing pixel-wise semantic segmentation providing qualified accuracy while maintaining real time speed and reduced latency over vision-based technologies with monocular detectors or depth sensors. It consists of (1) smart glasses, (2) an RGB-D sensor (RealSense R200) and (3) a set of boneconduction earphones. The system provides real-time acoustic feedback by synthesizing stereo sounds (clarinet sound). The experimentation section reports an accuracy of 96% in the context of traversable area parsing using the real-world TerrainAwarenessDataset, outperforming other state of the art solutions. The authors do not disclose information about the power consumption requirements, cost or weight of their proposed solution. A weakness of the system concerns a lack in perceiving crosswalks and traffic lights, hazardous curbs and water puddles.

Bai et al. [50] propose a wearable assistive device that allows navigation in unfamiliar environments, as well as object detection and object recognition based on a lightweight Convolutional Neural Network (CNN). It consists of (1) a Red, Green, Blue and Depth (RGB-D) camera, (2) an Inertial Measurement Unit (IMU) mounted on a pair of eyeglasses and (3) a smartphone. The system utilizes an audio module for user feedback that emits a beeping sound for obstacle alert, uses speech recognition for user commands and uses speech synthesis for conveying information about the environment. The experimentation with the system demonstrates a decrease of the time required for navigating on the order of 5–10% and an 87% reduction in obstacle collision. The system's cost is relatively high and has a medium weight, however, there is no information on the power consumption requirements. Among the limitations of the system include the inability to detect smallsized obstacles and staircases, while there is no tactile feedback. Finally, the proposed solution is an early prototype.

Long et al. [51] present a fusion system for perceiving and avoiding obstacles. It consists of a millimeter wave radar and RGB-depth sensors, while it provides a stereophonic interface to the user. The experimentation with the system reveals an expansion of the effective detection range up to 80 m compared to using only the RGB-D sensor. Nonetheless, the proposed solution is bulky and has a high cost. Furthermore, the system is limited to detecting objects and not recognizing them, while it is not portable as it still runs on a PC.

Cheng et al. [52] propose a system for crossings that uses RGB-Depth images to inform the user about the crosswalk position (where to cross roads), crossing light signals (when to cross roads) and pedestrian state (whether it is safe to cross roads). It is able to detect multiple targets at urban intersections. The utilization of RGB-Depth images allows for both increasing detection precision when compared with plain RGB images and to convey the distance of the detected objects. The system consists of wearable smart glasses and provides user feedback via a voice interface. The cost of the proposed solution is relatively high while the weight is estimated to be low, and the authors do not include any information about the power consumption requirements. The system is evaluated on real scenarios with success, while the reported time for processing a frame is at 200 ms. Among the limitations of the proposed solution are the inability of operating in night scenarios. Finally, a more elaborate experimentation section would allow for a more extensive evaluation of the system's capabilities.

Yu S. et al. [53] present a system aiding crossing intersections by utilizing a modified convolutional neural network version of LytNet based on MobileNetV3. The latter runs on a smartphone device and feedback is provided to the user via auditory and vibration signals. According to the authors, the DNN model achieves a classification accuracy of 96%, an average angle error of 6.15 while running at a frame rate of 16.34 frames per second. The cost and weight are directly related to the smartphone device of choice, while there is no information regarding the power consumption requirements. Among the limitations of the system are the lack of support for crossing intersections at night, being an early prototype and region locked, as well as the specific orientation and position requirements of the smartphone device.

Ihejimba et al. [54] propose a highly available, highly scalable, low-latency IoT edge computing solution for traffic light notification. It consists of (1) a Raspberry Pi 4 (Linux), (2) a smartphone device and (3) access to the AWS cloud. The user receives feedback via voice instructions and vibrations. The evaluation of the system demonstrates the average response time to be around 19.2 ms, the lowest response time to be 10.22 ms and peak response time to be 36.05 ms. The cost and weight of the proposed solution is moderate and light, respectively, while there is no information on the power consumption requirements. Nonetheless, since the system is Cloud based, it cannot truly guarantee low-latency and it is sensitive to connectivity issues. Furthermore, the system has no accurate and precise knowledge of the user's GPS location, and it is not capable of local offline decisions.

For a more extensive overview of the available solutions and policies related to smart traffic lights and crossing intersections worldwide, it is recommended for the reader to refer to the study of Theodorou et al. [55].

Saez, Y et al. [56] present a system that assists mobility in public transportation based on RF communicating modules. It allows one to request a bus service by giving information to bus drivers, boarding the correct bus and reaching the destination easily and safely. The system consists of three modules: (1) MOVI-ETA, (2) MOVI-STOP and (3) MOVI-BUS. Specifically, the MOVI-ETA module includes an ATmega328P microcontroller (eight bits, sixteen MHz, AVR architecture) and an HC-12 wireless serial port communication device. The MOVI-STOP module includes two microcontrollers, two TI-CC1101 RF transceivers and an HC-12 device. Last but not least, the MOVI-BUS module includes two microcontrollers and two TI-CC1101 RF transceivers. The user holds the MOVI-ETA module and interacts with it via audio and vibration signals. According to the authors, the proposed system has a low cost and is estimated to be lightweight. However, they do not provide information regarding the power consumption requirements. Various field tests demonstrate the feasibility of the proposed solution. Among the weaknesses of the system are (1) the requirement of holding an extra custom-made device, (2) the changes and extensions to the infrastructure regarding stops and buses, (3) the communication range, (4) the average number of transmission errors, (5) the placement-dependent signal power reception, (6) the reliability that depends on the specific conditions of the environment, (7) the lack of multi users and multi buses arriving at stops in the test scenarios and, finally, (8) the lack of usability studies are considered.

Yu, C et al. [57], propose a system that provides a seamless bus reservation service with minimal notification by utilizing the available bus telematics system and tactile surface indicators at bus stops. It utilizes a smartphone device while the user can interact with the service via auditory signals in the case of blind individuals, as well as via a GUI for people with low vision. The system also utilizes vibration motors for providing feedback. According to the authors, the cost and weight is low and light, respectively, while they do not include information concerning the power consumption requirements. The experimentation with the proposed solution is limited as neither metrics were presented, nor large field tests conducted. Furthermore, although it minimally disrupts the bus driver, it still requires cooperation.

See A. R. et al. [58] presents a system that enables object and obstacle detection in a single app. It only requires a smartphone with a single depth camera. The user interacts and receives feedback from the application via voice, audio, gestures and vibration. The cost of the proposed solution is relatively low and is lightweight, however, the authors do not provide information about the power consumption requirements. The experimental results demonstrate the ability of the system to detect outdoor objects at a distance of 1.6 m. Among the limitations of the solution are the inability to identify the name and type of the detected object, as well as the number of detected objects being currently limited to the ones with which the system is trained.

Last but not least, Meliones A. et al. [59] proposed an obstacle detection algorithm as a component of a mobile application that analyzes, in real time, the data received by an external sonar device. Its main function is to detect the existence of obstacles in the path of the user and to emit information, through a voice interface, about the located distance, size and the potential motion and to advise as well how the user can avoid them. The proposed system consists of a smartphone, and an external device. The latter is comprised of the Atmega 328p microcontroller, the U-blox NEO-8M GPS receiver, the HC-SR04 Ultrasonic sensor and the MG90S Micro-servo motor. The user interacts with the device and receives feedback via voice instructions. The proposed solution is cost effective (EUR 60) and lightweight. The experimentation results demonstrate extensively the effect of the proposed solution on the CPU, memory load and battery life. Furthermore, a number of real-life scenarios with different types of obstacles and the generated results demonstrate the effectiveness of the proposed detection algorithm. Overall, the proposed system shows reliable and robust results even when using cost-effective wider ultrasonic beam sensors in the context of a sparse city environment with wide pavements. However, in the context of a denser city-like environment, the cost-effective sensors demonstrate poorer results, mainly due to their reduced directionality. This limitation can be alleviated by integrating the existing outdoor blind navigation framework with narrow/pencil beam ultrasonic sensors that can produce efficient results in this context as well. However, this happens at the expense of significantly increasing the cost, signifying a non-optimal solution of the proposed system. The object detection system as well as the entire outdoor navigation system, the evaluation of which is the scope of this chapter, is described in the following section in more details.

## 9.3 System Description

The proposed implementation aims at supporting people with limited vision or complete blindness to navigate with high precision and safety in outdoor spaces without the aid of guides. The system provides continuous feedback to the blind person containing critical information, via issuing voice instructions, that pertains to ensuring the correct and safe navigation of the individual as well as detecting obstacles and, subsequently, providing guidance on how to avoid them. The system is comprised of two subsystems that are tightly integrated. These include a wearable device incorporating an external GPS receiver with high precision tracking pedestrian mobility in real-time, a second device with an ultrasound sensor mounted on a servo mechanism functioning similarly to a sonar, an Android application that acts as the central component of the system and, finally, an appropriate (custom-made) voice interface to enable fast and accurate user interaction with the application. The user, via the application's voice interface, can select the desired destination. As soon as the destination has been selected, the navigation process starts. To provide robust navigation information for blind individuals, the application receives data from both the Google Maps service and the Athens Public Bus Transportation (OASA) real-time telematics service that includes timetables and stops of urban transport services. The data are, subsequently, fed into a novel routing algorithm that provides high-precision navigation coupled with the ability to configure complex routes that may include Public Means of Transport mobility.

A carefully designed set of voice instructions provides the required information to ensure the correct and safe navigation of the users, as well as to convey information about potential obstacles along their path. The voice system interaction (instructions, information and options requesting user response) is better experienced via the use of bone conduction headphones, not suppressing the environment sounds which is critical for enhanced perception and safety in blind outdoor navigation. In general, the role of the application will be supportive of the users' actions and will prioritize their safety as it will include the possibility to make emergency calls. Figure 9.1 shows the high-level architecture of the proposed system.

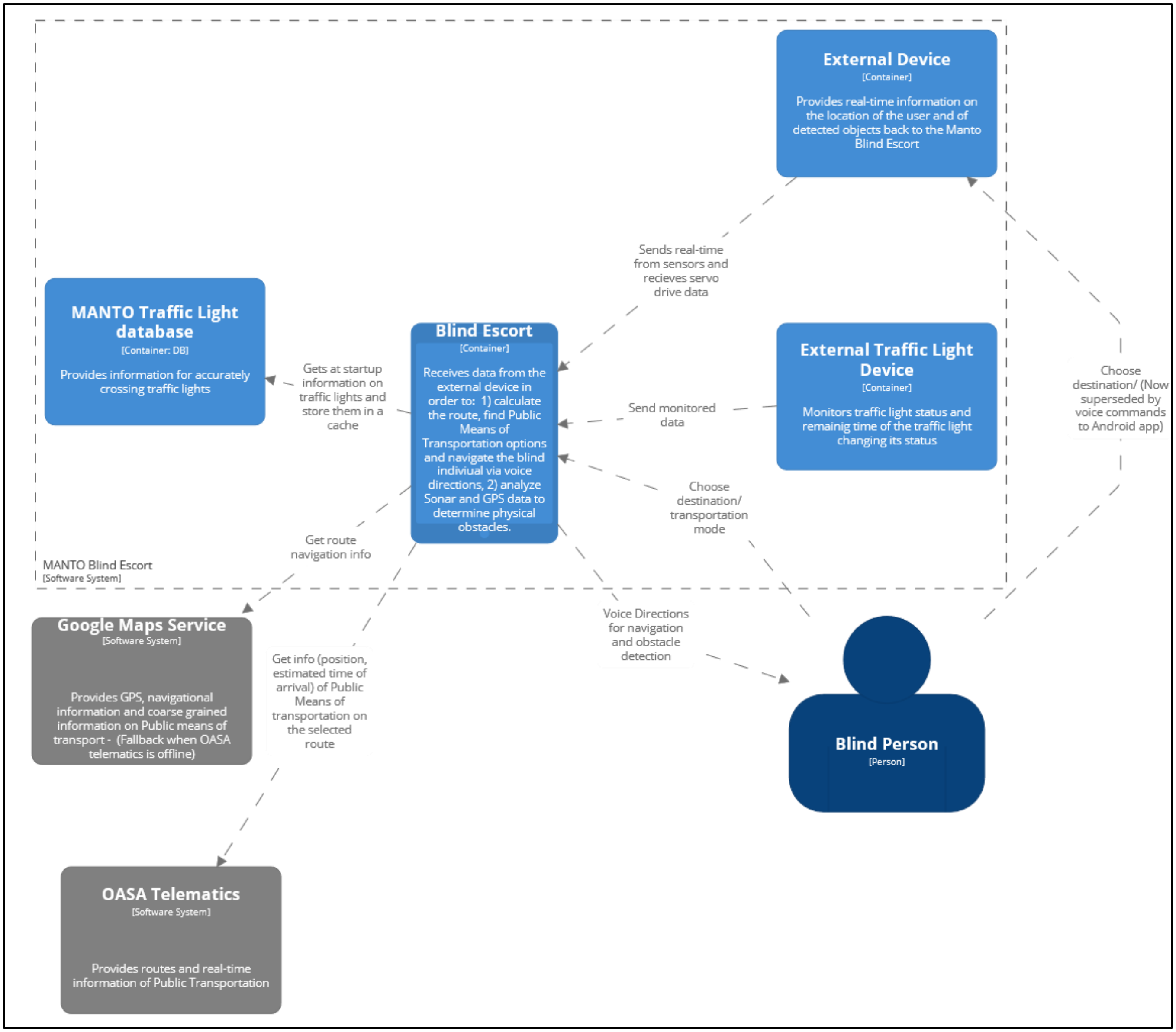


*Figure 9.1 Architectural diagram of the application*

### 9.3.1 Design Process

For the conceptualization and the implementation of the prototype, we followed a cognitively informed design process [60]. This approach integrates the usual iterative process of the engineering method with cognitive factors and processes related to how individuals attempt to solve their problems systematically. Moreover, this cognitive design framework promotes a set of principles-criteria that include safety, reliability, reinforcement and preferences, and emphasizes the inclusion of the immediate beneficiaries in the design process as well. In our case, the developed solution addresses the problems of navigating blind and visually impaired individuals in outdoor spaces.

The first step of this participatory design is to create an understanding of users' needs [61]. Thus, we start with the needs assessment and, since the broader social context affects these needs, we also have to take into consideration the social constraints. We assume that individuals who are blind have similar skills as do the sighted, but that the richness of their environmental information is severely hampered [61]. Conducting interviews with the disabled population helped to unearth the cognitive processes involved during navigation, a requirement of this design approach, for enabling the functional needs assessment. The benefits of these activities are all about making the practices explicit, including stated preferences, habits and psychological features of blind and visually impaired individuals with respect to the use of mobile technology [61], as well as the multiple psychological constructs, such as interest, focus, enjoyment [62,63] and the benefit of usage [64]. For example, visually impaired users prefer routes that are often not the shortest ones, but are based on users' proficiency and preferences [65]. The above, besides providing a basis for understanding the required functionality to support, also helps in engaging the user and potentially increasing the perceived quality of user experience, which is also a critical goal of the proposed solution. Furthermore, this will help with another important aspect of the proposed navigation application which is for the content of the issued instructions to be of high quality by leveraging the users' situational context to reduce navigation errors.

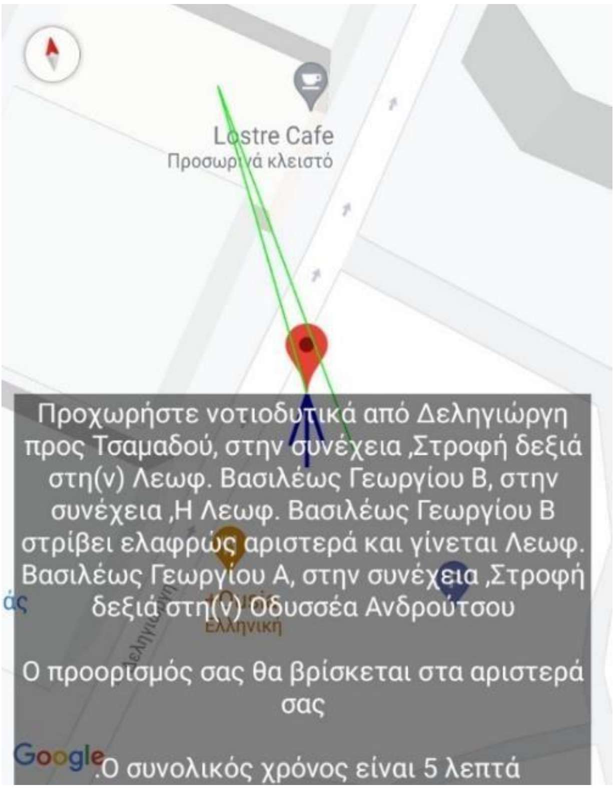
Last but not least, we considered all the useful recommendations given in [7] during the design and implementation phase. These include the following: an appropriate choice of real-time object detection methods, mitigation of the extensive learning time, comfortability in carriage and usage, the right amount of information given for safety reasons, the avoidance of social stigma, proper management and security of personal and private data.

### 9.3.2 Subsystem Interaction

The navigation starts with the app prompting the user to provide input regarding the desired destination and whether to utilize any available means of public transport, in particular, public buses, since this is supported in the current version. After the user's confirmation of the desired destination, the app proceeds to the stage of planning the navigation route and issues a high-level description of that. Simultaneously, the external device starts a loop in which it continuously collects data from the sonar and GPS sensors and sends them to the central Android application via Bluetooth, which in turn acts by modeling and analyzing them. In particular, the application, after receiving the data from the external device, starts two processes. The first is to navigate the user via leveraging the Google Maps service and to update its current list of the available Public Means of Transport to that destination. The second is to analyze the sonar and GPS data received from appropriate sensors integrated into the external device. The former is used to detect obstacles on the path of the user while the latter is used to report back to the user his position with a negligible margin of error (<1 m). In this way, the continuous flow of data received from the external wearable device allows for the system to adapt to the dynamically evolving environment. To better understand the interaction of the aforementioned components, the reader may refer to Figure 9.1. The MANTO project contribution involving reliable ultrasonic obstacle recognition for outdoor blind navigation is presented in detail in [59].

### 9.3.3 Tracking—Navigation with Great Accuracy Exploration of the Application

This section presents the assessment, conducted during the pilot stage of the MANTO project, of the high accuracy navigation capabilities, the correction of the user's routing and the repositioning back on the navigation path in case the user accidentally deviated from it. The figures are snapshots taken from the smartphone while the application is running and navigating the user to the destination during the pilot stage. Specifically, they depict the application's information regarding the position of the user (red pin), the vector of the direction along the navigation path (green line) and the corresponding voice instruction (grey box). To accurately navigate the user when approaching corners, the application starts issuing the turn instructions more frequently by leveraging the higher tracking density of the external GPS receiver (see Section 1.2.5) and the functionality of the scheduler (see Section 1.2.4). When the user selects the desired destination, the navigation starts by providing an overview of the total route and an estimated time of arrival (see Figure 9.2).



Προχωρήστε νοτιοδυτικά από Δεληγιώργη προς Τσαμαδού, στην συνέχεια ,Στροφή δεξιά στη(ν) Λεωφ. Βασιλέως Γεωργίου Β, στην συνέχεια ,Η Λεωφ. Βασιλέως Γεωργίου Β στρίβει ελαφρώς αριστερά και γίνεται Λεωφ. Βασιλέως Γεωργίου Α, στην συνέχεια ,Στροφή δεξιά στη(ν) Οδυσσέα Ανδρούτσου

Ο προορισμός σας θα βρίσκεται στα αριστερά σας

.Ο συνολικός χρόνος είναι 5 λεπτά

*Figure 9.2. Navigation with great accuracy—text in figure: "Head southwest on Deligiorgi toward Tsamadou. Next, turn right onto Leoforos Vasileos Georgiou B. Next, slight left onto Leoforos Vasileos Georgiou A. Next, turn right onto Odissea Androutsou. Your destination will be on your left. Overall estimated time is 5 min".*

Next, as the user moves along the navigational route, the application issues instructions guiding the user during straights and turns. In case of a mistake, the application will issue recovery instructions to place the user back on the correct navigation path. Figure 9.3 depicts the case where the user makes a mistake and instead of taking a right turn, a left turn is made placing the user's vector in the opposite direction to the designated destination. When the app detects the error, it issues instructions based on the hands of the clock informing, in this example, that the correct direction is between 6 and 7 o'clock. After the user makes the correct adjustments, the application issues the instruction to move ahead in Grigoriou Lampraki street (Figure 9.3—right).

Finally, all the above are part of a trial route where the blind user, accompanied by members of the research team, started from the exterior space of the University of Piraeus at Deligiorgi 114 towards the departments' laboratories at Odyssea Androutsou 150.

Μεταξύ παρά είκοσι πέντε, και μισή

Συνεχίστε ευθεία προς Γρηγορίου Λαμπράκη 132

*Figure 9.3. (left–right). Repositioning the user back to the correct navigational route—text in left figure: "Between 6 and 7 o'clock"; Text in right figure: "Continue onto Grigoriou Lampraki 132".*

### 9.3.4. Real-Time Voice Instruction Scheduler

This module is responsible for selecting the voice instructions to be issued by the Android device to the user. The goal is to, firstly, meet the real-time requirements and, secondly, to manage all the issued instructions and their emission frequency to the user. This is achieved by a completely fair scheduler that utilizes a Red-Black tree as its underlying data structure. The weight of each tree node is calculated by considering the priority and time order of the instructions as well as the number of attempts made to issue the latter. It is worth mentioning that great emphasis was given to the second part of the aforementioned goal as it was a major requirement highlighted by the analysis of the interviews. Specifically, the blind users requested for the application to offer the minimum amount of information at a reasonable rate to secure that the users will be the least distracted from the emitted sounds. Therefore, to avoid disturbing the user from consecutively issuing instruction notifications, we designed appropriate priority levels by distinguishing them into the following types:

- Corner: it concerns the case of an upcoming turn with the highest priority.
- NavigationFlowCritical: It concerns the case of an instruction of critical importance. It is mainly used for instructions that help users to recover from an error back to the correct navigational path, leveraging the vector of the user's path. It is classified as an interrupt job.
- NavigationFlow: It concerns the case of non-critical instructions. It is commonly used for instructions that guide the user to continue without any change, for example, "Continue straight".
- TransitFlow: it concerns the case of instructions relevant to the Public Means of Transport.
- Summary: It concerns the instructions relevant to informing the user of the major navigational events along the route to the destination. This information is the first instruction

issued by the application before starting the navigation. Finally, examples of the real-time scheduler’s operation are the following:

- The voice instruction “the bus will arrive in 3 min” is not issued when the time has elapsed.
- The voice instruction “Continue straight on” is not issued after a critical change voice instruction that prompts the user to return to the correct navigational path due to deviating from the navigation vector.
- When the voice instruction remains the same for a long period, for example “Continue straight on” in the case of a long straight, the scheduler limits the frequency by which it is selected for emission in order to prevent the user from being overwhelmed by instructions void of utility.

### 9.3.5. Great Accuracy and Tracking Density

The following section presents the higher location accuracy and density, as well as the significantly smaller error of the reported user position of the external GPS receiver in comparison to the one integrated into the smartphone. The figures below are excerpts from a trial during the pilot stage.

Firstly, as it can be seen from Figure 9.4, the external GPS receiver, represented by the satellite icon, has better user location accuracy than the phone’s integrated GPS, represented by the phone icon. The proposed system can achieve centimeter position accuracy by utilizing, on one hand, three systems in parallel choosing between GPS/QZSS, GLONASS, GALILEO and BEIDU and, on the other hand, the large surface of the external GPS receiver antenna that cannot be integrated on smartphone devices. Their combination produces much better accuracy for the actual position of the user while the phone’s GPS falsely reports the user even being on top of buildings. Secondly, there is a significant difference in the density of the points reported from the two GPS receivers. Specifically, as it can be observed from the above figure: nine points of the external GPS receiver against three points of the phone’s GPS (Figure 9.4—left), thirteen points of the external GPS receiver against four points of the phone’s GPS (Figure 9.4—right). Thirdly, with the help of the small scale located at the bottom right, the difference in the error between the two GPS receivers is evident. There are cases where the reported user location given by the smartphone’s GPS receiver is 10 m away from what the external GPS receiver reports. Lastly, the error of the latter receiver is found to be less than 1 m.

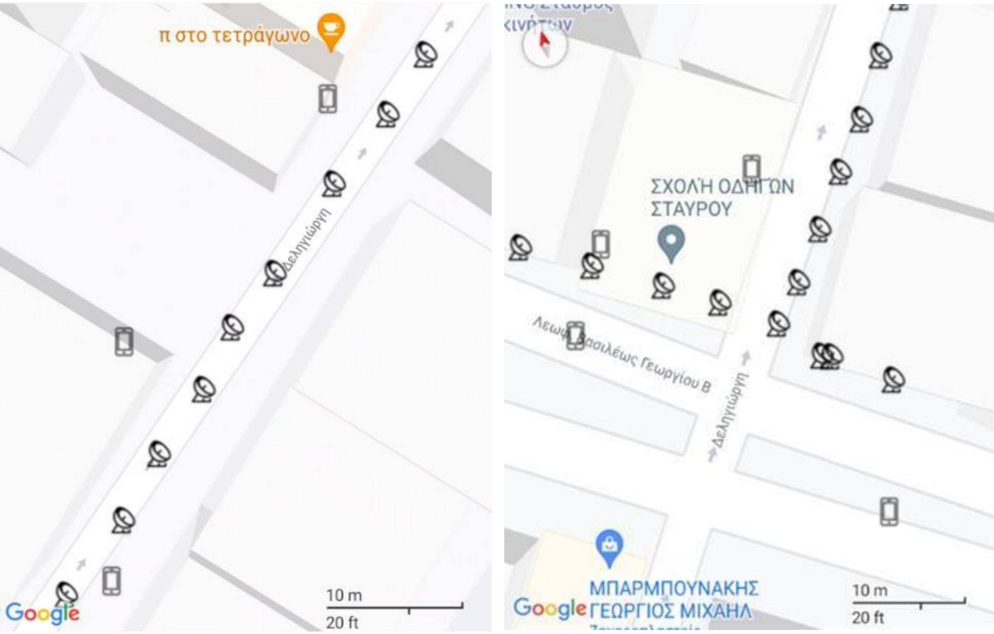


*Figure 9.4. (right and left). Great accuracy and tracking density.*

## 9.3.6 Navigation Route Combined with Public Means of Transport (Buses)

This section presents the case of selecting to include public buses as part of the navigation route. As a primary source of information about the location of the stops and the arrival time of the buses, the application utilizes the OASA Telematics service, a Greek public service that supports real-time information for buses. In the case that the latter service is unavailable, the application has designated the Google Maps service as a backup mechanism, which provides the required information, albeit, with reduced accuracy. The trials during the pilot evaluation phase of this feature's functionality were conducted with the aid of blind subjects. Both the route and voice instructions issued from the moment of entering to the moment of exiting the bus were recorded. The following example is an excerpt from a trial in the field where the user chose Makrigianni Square in the district of Dafni as the destination and the nearest stop to Ymittos Square in the district of Ymittos as the starting point.

The figures below (Figures 9.5 and 9.6) show the application's functionality that issues notifications about the intermediate stops through which the user passes until reaching the destination. At each stop, shortly before arrival, a notification is issued and, unless it is the terminal stop, it alerts about the next stop.

Πλησιάζετε στην στάση ΠΛ.Υμηττού

*Figure 9.5 The application issues the instruction “Approaching Ymittos bus stop”.*

Πλησιάζετε στην στάση Εικονοστάση

*Figure 9.6. The application issues the instruction “Approaching Eikonostasi bus stop”.*

Finally, when the blind user has reached the intended destination, the app alerts him/her to exit the bus (see Figure 9.7).

Φτάσατε στην στάση Πλ.Μακρυγιαννη, όπου αποβιβάζεστε

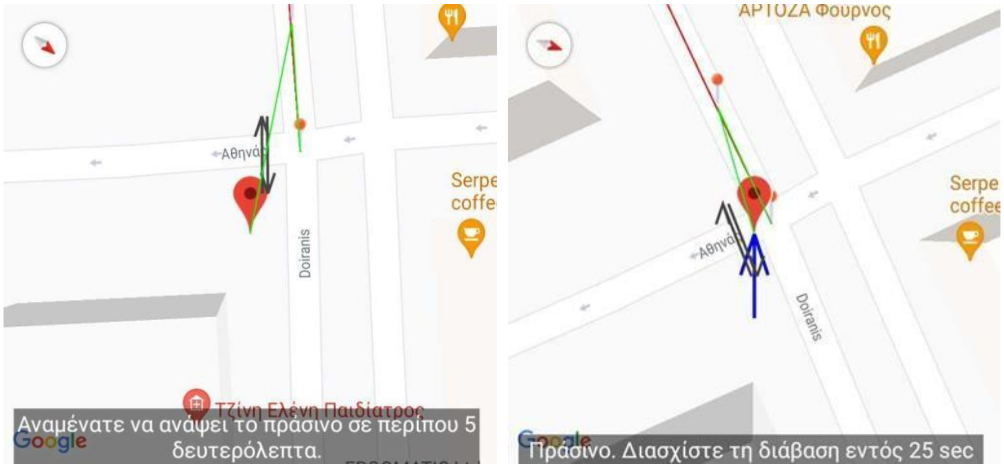
*Figure 9.7. The application issues the instruction "You reached Makrygianni Square stop—Exit the bus".*

### 9.3.7. Passing Traffic Lights Crossings with Safety

This section presents the case of passing traffic lights crossings with the aid of a second external waterproof (IP66) device mounted on every traffic light. The device sends to multiple Android smartphones, having BlindRouteVision installed, information about the status of the traffic lights (Green/Red) and the remaining time until the next status change occurs. The latter information, along with the information retrieved from a database, during the initialization of the application, includes the geographical position and other characteristics of traffic lights, such as the starting and ending point of the crossing, the direction of the vehicles and the number of the crossings, are used as inputs to help the user pass a crossing successfully. The pilot trial, the result of which is presented below, has been conducted on the marked crossing next to the traffic light of Doiranis and Athinas in Kallithea. The following figures are recorded from the smartphone device and present the user's position, the vector of the user's direction along the path and the corresponding voice instruction issued by the application.

As can be seen in Figure 9.8 (left), when the user arrives at the crossing, the application detects the traffic light status and informs the blind user about the red status, prompting him/her to wait for five seconds until the status changes to green. When the level of the traffic light becomes green, the application informs the user of the time remaining to pass the crossing with safety (Figure 9.8—right).

During the execution of the trial routes, the trainer’s responsibility was to observe the procedure and to provide continuously constructive feedback. The following route is an excerpt of the available routes for training. In particular, Figure 9.8 depicts the blind user traversing outside the Lighthouse for the Blind of Greece in the region of Kallithea. The route starts and ends at the entrance of the Lighthouse for the Blind of Greece, Athinas 17. This procedure (trial) is repeated several times depending on the user’s capability and perception of the environment.



Αναμένατε να ανάψει το πράσινο σε περίπου 5 δευτερόλεπτα.

Πράσινο. Διασχίστε τη διάβαση εντός 25 sec

*Figure 9.8. (Right and left). Passing traffic lights crossings with safety—text in left figure: “Five seconds remaining for the traffic light to turn green”; Text in right figure: “Traffic light turned green. 25 s remaining to cross”.*

## 9.4 Materials and Methods

### 9.4.1 Usability—User Experience (UX) Methodology

One of the primary targets of this chapter is to quantify the Usability and User Experience (UX) of the application and validate the system design in those terms. The reason for evaluating these two measures can be attributed to the great need to know the extent to which a system can be easily learned, its usage efficiency, the error rate, as well as the degree to which a user can swiftly recall how to use it [66]. Towards that direction, we reviewed the literature on the available methods to assess them. According to ISO/IEC 25,010 2011 [67], usability is defined as “the degree to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. In particular, the 3 main components measure the following:

1. Effectiveness—measures the degree to which users can complete a task.
2. Efficiency—measures the time it takes users to complete a task.
3. Satisfaction—measures, subjectively, the quality of interaction with the application.

On the other hand, UX is a term that is broadly used by many researchers and practitioners to include different concepts [68]. Thus, it is an umbrella term for a range of dynamic concepts, such as traditional usability, and it also includes affective, emotional, hedonic, experiential, and esthetic dimensions. According to ISO 9241-210:2019 [69], UX includes users’ emotions, beliefs, physical and psychological responses and it is also the result of brand image, presentation, system performance, the user’s internal and physical state resulting from prior experiences, attitudes, skills and personality, among others.

Therefore, instead of using more typical usability questionnaires such as System Usability Scale (SUS), Post-Study System Usability Questionnaire (PSSUQ) and others, we opted for UX questionnaires since this concept is more general and captures usability more broadly [70] as it includes other aspects such as user perceptions and responses both from the use and anticipated use of a product [69]. These characteristics of UX and the ones described above make clearer the fact that it is the appropriate measure for assessing the component of satisfaction as described in the definition of usability in [67].

According to Dvaz-Oreiro et al. [71], there are three most used standardized questionnaires for user experience evaluation. In particular, these are AttrakDiff, UEQ and meCUE. This is also indicated in studies such as those given by Lallemand et al. [72], Baumgartner et al. [73], Forster et al. [74] and Klammer et al. [75]. The number of questions including AttrakDiff, UEQ and meCUE, as well as the scales they employ and the theoretical models on which they are based, are listed in [72]. The authors note that AttrakDiff has been the most popular option since it was firstly introduced in 2003, while UEQ surpassed it in 2017 and 2018. On the other hand, with meCUE being a relative newcomer, it has a substantially smaller usage rate.

These approaches are frequently supplemented with others and, according to DvazOreiro et al. [71], over 60% of the cases utilized between one and five additional methods. For example, a widely used standardized usability questionnaire is the SUS that is found both in academia and in business. Hedonistic and pragmatic aspects of UX are found both on AttrakDiff [76], meCUE [77] and UEQ+. While meCUE considers the emotional component as well, thus providing greater insight into acceptance-related problems, its usage rate is comparatively lower, diminishing the value of the results when it comes to reaching safe conclusions.

### 9.4.2. Usability—Metrics for Effectiveness and Efficiency

The user study aimed to evaluate the usability of the developed prototype both for blind and visually impaired people, in terms of effectiveness and efficiency, and receive feedback from experts involved in this study. In search of finding appropriate statistical metrics for measuring effectiveness, we conducted a literature review where we found that among the most common ones are the following: Completion, Errors and Error Rate. Their simplicity makes it easy to understand them and, thus, they are widely used in many studies. Completion rate counts, either as a pure number or as a percentage, the successfully completed tasks while Errors count the errors made by a user, as its name suggests. Error rate reports the number of errors per user. Common cases of errors include, among others, mental errors, for example, when a user cannot comprehend a system option [78], and undesired results as a consequence of either poor interaction with the system's interface or lack of the provided information resolution.

For the evaluation of completion, error and error rates, the research team defined three tasks:

- First task: completion of a pedestrian navigation route—this task demands the user to successfully complete both known and unknown itineraries that do not include the use of public means of transport or passing traffic lights crossings.
- Second task: combining pedestrian navigation with public means of transport (entering and exiting the bus)—this task demands that the user successfully complete the following steps:
    a. arriving at the bus stop
    b. leveraging the information emitted for being aware when the bus arrives

    c. entering the bus
    d. activating the public means of transport mode of operation by pressing the given interface element
    e. exiting the bus at the correct stop

- Third task: passing marked crossings near traffic lights—this task demands from the user to pass a traffic light marked crossing in time.

For each of the above tasks, the definition of completion and error is defined as follows:

- First task:
    a. Completion: successful termination of the navigation despite any errors made during the trial.
    b. Error: the user giving up the attempt or asking for help from the research team counts as an error.
- Second task:
    a. Completion: successfully completing the steps described above.
    b. Error: if one of the steps described above is completed with the help of the research team or the user gives up, then it counts as an error.
- Third task:
    a. Completion: successfully passing a marked crossing close to a traffic light.
    b. Error: if the user gives up or asks for assistance from a member of the research team, then it counts as an error.

Finally, the completion rate is calculated by the following equation:

$$Effectiveness = \frac{total\ \#\ of\ tasks\ successfully\ completed}{total\ \#\ of\ tasks\ undertaken} = \frac{\sum_{l=1}^{U}\sum_{i=1}^{M} task_{li}}{U * M}$$

where *U* = # *of participants*, *M* = # *of tasks per participant* and $task_{li}$ = *i − th task of the l − th user*.

Furthermore, $task_{li}$ takes the value 1 if the task is successfully completed and 0 otherwise.

Efficiency is closely related to effectiveness as it considers the time (in seconds and/or minutes) involved in successfully completing a task. A common way to measure effectiveness is with the help of the following formula:

$$Efficiency = \frac{\sum_{j=1}^{U}\sum_{i=1}^{M} tasks_{ij} t_{ij}}{\sum_{j=1}^{U}\sum_{i=1}^{M} t_{ij}} \times 100\% \quad (2)$$

where $t_{ij} = EndTime_{ij} - StartTime_{ij}$, for which, in turn, $EndTime_{ij}$ is defined as the time required for the *i − th task of the j − th user* to be completed successfully or the time until the user quits.

Errors will be measured as simply the sum of each participant's total number of errors:

$$Error = \sum_{i=1}^{N} e_i \quad (3)$$

where $N$ = the total number of the participants, while the error rate is calculated by the following equation:

$$Error\ rate = \frac{Error}{P} \quad (4)$$

where *Error* = # *of total errors* and *P* = # *of total participants*.

Last but not least, an added benefit of the above metrics is their deployment flexibility as their required input can be collected during any stage of development.

### 9.4.3 UEQ+ Standardized Questionnaire

To the best of our knowledge, there are no questionnaires available that evaluate the user experience of blind and visually impaired individuals. One of the drawbacks of the existing questionnaires is the lack of specificity in the features they assess. In response to this inflexibility, the UX questionnaire framework UEQ+ was selected.

The latter is a modular extension of the very well-known user experience assessment tool UEQ that provides results consisting of easily processed quantitative data and which has proven to be appropriate in evaluating new technologies regardless of gender, age group, level of education and technological proficiency [79]. Specifically, the UEQ+ is a set of scales that are combined to form a concrete UX questionnaire. Therefore, it is possible to create a questionnaire that is custom made to fit exactly the features of the proposed application which is under evaluation. Each scale is decomposed into 4 items that measure the impression of the user towards the UX aspect under consideration and a single item that measures the relevance or importance of the scale for the user. The items are scored on a seven-point Likert psychometric scale. The rating is configured to look at opposite pairs of the app's properties. Users, according to the evaluation instructions, always choose an answer, even when they are not sure about the evaluation of a pair of terms or even when they think that it does not relate to the product perfectly. Finally, the user states how important each scale is for the overall impression of the product.

The UEQ+ framework currently offers several UX scales. After careful consideration of the challenges, of the results of the user requirements elicitation stage [61,80], by which the blind and visually impaired users become part of the process of defining the evaluation criteria, and of the importance ratings given by the blind users to a preselected set of scales, we concluded that the following scales best describe the UX impression for the features that are deemed to have a higher value. Based on the available categories of UEQ+, the following were selected particularly for our case:

- Efficiency: this scale evaluates the user's subjective impression as to whether he/she must put in the minimum effort required to achieve the desired goal as well as how quickly the application reacts to the user's actions.
- Perspicuity: this scale evaluates the ease with which users become familiar with the application and how easily they can learn it (educability).
- Dependability: This scale evaluates the subjective impression that the user has on the predictability and consistency of the system's response concerning its instructions and actions. In other words, it examines whether the user controls the interaction with the application.
- Adaptability: this scale evaluates whether the application can be adapted to the personal preferences of the user as well as how easily and quickly this adjustment process is done.
- Usefulness: this scale evaluates the advantages that the user perceives in terms of achieving his goals, how much time he/she saves and whether it increases his/her efficiency.

- Trustworthiness of content: this scale evaluates whether the content of the instructions provided by the application is of good quality and reliable.
- Response behavior: this scale evaluates whether the response from the voice assistant is friendly and pleasant to the user.

### 9.4.4 Semi-Structured Questionnaires

We have designed a seven-point Likert scale questionnaire similar in scope to the UEQ and UEQ+. The format of semi-structured interviews was preferred over other options due to its flexibility, and despite the limitations that affect statistical analysis, it ensures that the views of the blind and visually impaired are underlined. Undoubtedly, this feature is one of the key factors of this technique's success as the increased flexibility provides the required degrees of freedom in the design and refinement phase of the interviews' questions. Simultaneously, this type of interview allows for both the research team and the interviewees to further clarify their thinking about the challenges and the desired functionality. On the other hand, an unforeseen implication that pleasantly surprised us was the eagerness and willingness of some of the participants to engage in the refinement process of the interviews, expressing at the same time a depth of feeling about the issues that were raised. In this way, the blind and visually impaired get to express their views and expertise as well as provide feedback both on how to better formulate the interview questions in greater depth and to highlight areas of improvement for the application's supplied functionality. Finally, during the semi-structured interviews, a goal of high priority was for the participants to remain impartial to the interviewers' expectations and create a safe environment where the participants could express their opinion openly without the fear of being criticized.

### 9.4.5 Description of the Evaluation Setup and the Interview Participants

This section presents the evaluation setup of both Usability and UX, as well as their respective results. In more detail, it will present the findings of the application's usability, measured in terms of effectiveness and efficiency, along with the results from the application's UX evaluation, assessing user satisfaction, combined with the lessons learned from semi-structured interviews to better understand the user experience evaluation score. The trials were conducted at the premises of the Lighthouse for the Blind of Greece, which is the main non-profit organization for the education and assistance of the blind and visually impaired in Athens. Specifically, the pilot phase was instrumented with the following data collection tools.

#### 9.4.4.1 Personal Characteristics Questionnaire

This questionnaire, filled in by the interviewees, aimed at learning various personal characteristics of the participants. In more detail, they were asked to fill in details related to their gender, age, degree of visual impairment, cause of vision loss and digital sophistication.

#### 9.4.4.2 Exploration of the Application

The functionality of the application's characteristics was presented in the Orientation and Mobility (O&M) lessons with the aid of instructors. In this way, the interaction between instructors and trainees is encouraged, thus expediting the learning process via a more personalized and elaborate exchange of information. As a result, the benefits of this phase are twofold. At the same time, trainees ask freely for clarifications without having any feelings of inadequacy and instructors receive feedback from the trainees assessing both the comprehension progress and the rising opportunities that could potentially improve the learning process in the future.

#### 9.4.4.3 Pedestrian Navigation Tasks

Following the exploration phase of the application's functionality, trainees were asked to perform pedestrian navigation tasks (see Section 2.2). These include both known and unknown routes that also incorporate public transportation (buses) and passing marked crossings near traffic lights, the details of which are described in Section 1.2.7. These tasks also include the utilization of the obstacle detection and avoidance subsystem that is based on the external sonar-like device.

#### 9.4.4.4. Usability, UEQ+ and Semi-Structured Interviews

After the tasks were performed, the research team proceeded with the user evaluation aspect of the study. The research team measured effectiveness and efficiency (see Section 2.2), the UEQ+ questionnaire was used to assess user experience (see Section 2.3) and semi-structured interviews (see Section 2.4) were held for assessing functionality using both prearranged questions and encouraging the interviewees to share anything they thought was relevant. All the above data collection tools were used to find potential areas of improvement to further refine the functionality of the application. The format of the semi-structured interviews was particularly helpful in that direction.

#### 9.4.4.5 Recording of Trials

Throughout the pilot stage, the research team diligently recorded, in video format, every phase described above to avoid misinterpretations and guarantee the validity of the results. The recordings were made after receiving permission respecting any privacy concerns raised by the trainees.

#### 9.4.4.6 Evaluation Process

For the evaluation process, 30 male and female members of the community of the blind and visually impaired participated by executing a number of tasks and filling out a set of questionnaires. The subjects were between the ages of 30 and 60 and they ranged from having severe to complete blindness due to various causes. Most of the interviewees had low digital sophistication, which highlighted the requirement to provide special training sessions customized to their needs. These sessions were held in the vicinity of the Blindhouse of Greece. Although we acknowledge that the number of participants is not representative enough and does not help to draw strong conclusions, the results of both Usability and UX evaluation can be used to make assertions about the behavior of the application. Finally, the sample that was provided is representative of the beneficiaries of the Blindhouse of Greece concerning age, gender, age of vision loss and ability to use digital devices.

To assess the Usability aspect of the application, the research team evaluated a few tasks (see Section 2.2) during O&M training sessions held at the BlindHouse of Greece. In particular, the users for the case of pedestrian navigation were tasked to execute two known and two unknown test routes. The known routes include a route that starts from the entrance of the Blindhouse of Greece and cycles back to it and another one that starts again from the entrance of the Blindhouse of Greece navigating toward the Stavros Niarchos Foundation Cultural Center (SNFCC). For the unknown routes, we met the users at the entrance of the Blindhouse of Greece, and we escorted them to two locations undisclosed to them (a local market store and the Onassis Cardiac Surgery Center) that were designated as the starting point with the task to return to the Blindhouse of Greece.

For the case of pedestrian navigation where a user selects the option to include Public Means of Transport, the users executed two test scenarios starting from the nearest bus stop and heading to Piraeus using the bus lines 040 and 229. Last but not least, in the case of passing traffic light crossings, the users conducted one trial on the traffic light of Doiranis and Athinas in Kallithea. According to Section 2.5.4, the research team that conducted the UX evaluations used two UX questionnaires. The first questionnaire, distributed via Google Forms, followed the format of a standardized one. For a UX evaluation questionnaire to be considered standardized it must contain a constant number of questions found in the same order by the participants and answered independently. An important feature of the standardized questionnaires that makes their usage quite extended is their cost-effective nature and simplicity since all it takes is for the user to complete it after having experienced the product or service in question. Finally, another attractive feature of these UX questionnaires, is that they are considered dependable and valid [81]. The visually impaired users had the opportunity to complete the Google Form questionnaire either with the aid of the personnel at the Lighthouse for the Blind of Greece or at their own time and place. The second questionnaire, which followed a semi-structured interviews format, concerned also issues of UX. On average, the first questionnaire required 20 min while the semistructured interviews required 30 min. The descriptive characteristics of the interviewees are presented in Table 9.1.

Table 9.1. Participants' Characteristics.

| | Gender | Age | Degree of Visual Impairment | Cause of Vision Loss | Digital Sophistication |
|---|---|---|---|---|---|
| P1 | Male | 55 | Complete | By birth | High |
| P2 | Female | 35 | Severe | By birth | Average |
| P3 | Male | 36 | Complete | Diabetes | High |
| P4 | Male | 40 | Almost complete (95%) | By birth | Low |
| P5 | Male | 40 | Almost complete (95%) | By birth | Low |
| P6 | Female | 55 | Complete | Retinopathy (28 years old) | Low |
| P7 | Male | 40 | Almost complete (90–95%) | By birth | Low |
| P8 | Male | 40 | Complete | Cancer (7 years old) | Low |
| P9 | Male | 35 | Almost complete (>95%) | Benign tumor (15 years old) | Low |
| P10 | Male | 60 | Complete | By birth | High |
| P11 | Male | 30 | Complete | By birth | High |
| P12 | Male | 40 | Complete | By birth | High |
| P13 | Male | 38 | Almost complete (90–95%) | Craniocerebral injuries at 23 | High |
| P14 | Male | 54 | Complete | By birth | High |
| P15 | Female | 39 | Severe | By birth | Average |
| P16 | Male | 36 | Complete | Diabetes | High |
| P17 | Male | 46 | Almost complete (95%) | By birth | High |
| P18 | Male | 44 | Almost complete (95%) | By birth | Low |
| P19 | Female | 52 | Complete | Retinopathy (23 years old) | Low |

**Table 9.1.** *Cont.*

|  | Gender | Age | Degree of Visual Impairment | Cause of Vision Loss | Digital Sophistication |
|---|---|---|---|---|---|
| P20 | Male | 50 | Almost complete (90–95%) | By birth | Low |
| P21 | Male | 40 | Complete | Cancer (15 years old) | Low |
| P22 | Male | 35 | Almost complete (>95%) | Benign tumor (6 years old) | Low |
| P23 | Female | 60 | Complete | By birth | Low |
| P24 | Male | 47 | Complete | By birth | Low |
| P25 | Male | 49 | Complete | By birth | Low |
| P26 | Female | 38 | Almost complete (90–95%) | By birth | Average |
| P27 | Female | 65 | Complete | By birth | Average |
| P28 | Female | 39 | Complete | By birth | Average |
| P29 | Female | 37 | Complete | By birth | Average |
| P30 | Female | 40 | Almost complete (90–95%) | Diabetes | Low |

## 9.5. Results

### 9.5.1 Completion Rate during Evaluation Activities

Table 9.2 presents the number of successfully completed tasks during the evaluation phase per user for each case scenario. According to Equation (1) from Section 2.2, in order to calculate effectiveness, we need to first know the number of successfully completed tasks and the total number of tasks undertaken [78]. The total number of tasks consists of those tasks for which the result of execution was either a success or a failure, while the number of tasks successfully completed is the sum of each individual classification shown in the Table 9.2. Finally, by utilizing the table data, we calculate effectiveness as follows:

- Total # of tasks completed successfully = # of tasks “Completion of a route” + # of tasks “entering and exiting the bus” + # of tasks “Passing crossing with traffic lights” = 162.
- Total # of tasks undertaken = #number of tasks per user * #of participants = 7 × 30 = 210.

Hence,

$$Effectiveness = \frac{162}{210} \times 100\% = 77.14\%$$

The complementary metric of the completion rate (failure rate) is calculated as FAILURE RATE = Total # of failed tasks/Total # of tasks undertaken, where Total # of failed tasks = Total # of tasks undertaken—Total # of tasks completed successfully. Therefore, FAILURE RATE = (48/210) × 100% = 22.85%.

### 9.5.2. Errors—Error Rate during Evaluation Activities

In order to gain an understanding of the participants’ ability to navigate using the application, during the evaluation phase, the research team recorded the errors, both recoverable and unrecoverable, while the users made attempts to use the full functionality of the application. These are pedestrian navigation with or without the use of public means of transport and passing traffic light crossings. The identified errors for the exclusive pedestrian navigation case were classified as follows:

1. Collision with obstacles: records the cases where users collided with an obstacle.
2. Veering: Records the cases where users deviate from the designated path and veer off to one side or the other. This also pertains to the conventional methods of a white-cane and/or guide dogs.
3. External factor: records the cases where users are affected by an external factor such as another person on the path or the application glitches.

4. Missed turn: records the cases where users either react too early or too late and miss the correct turn.
5. Over-turn: records the cases where users over-turned and missed the correct navigational path.
6. Issued instructions: records the cases where users request further clarification about instructions from the research team.

Table 9.2. Completion Rate.

| Participant | Completion of a Route | Entering and Exiting the Bus | Passing Crossing with a Traffic Light |
|---|---|---|---|
| P1 | 3 | 1 | 0 |
| P2 | 3 | 1 | 1 |
| P3 | 3 | 1 | 0 |
| P4 | 4 | 2 | 1 |
| P5 | 2 | 2 | 0 |
| P6 | 3 | 1 | 1 |
| P7 | 3 | 2 | 0 |
| P8 | 2 | 1 | 1 |
| P9 | 3 | 2 | 1 |
| P10 | 3 | 2 | 1 |
| P11 | 3 | 2 | 0 |
| P12 | 4 | 1 | 1 |
| P13 | 3 | 2 | 0 |
| P14 | 3 | 1 | 1 |
| P15 | 4 | 1 | 1 |
| P16 | 3 | 1 | 1 |
| P17 | 3 | 1 | 0 |
| P18 | 3 | 2 | 1 |
| P19 | 3 | 2 | 0 |
| P20 | 4 | 2 | 1 |
| P21 | 3 | 1 | 1 |
| P22 | 3 | 2 | 1 |
| P23 | 4 | 2 | 0 |
| P24 | 3 | 2 | 1 |
| P25 | 3 | 1 | 1 |
| P26 | 3 | 2 | 1 |
| P27 | 4 | 1 | 1 |
| P28 | 3 | 2 | 1 |
| P29 | 3 | 1 | 1 |
| P30 | 4 | 2 | 1 |

Table 9.3 presents the number of navigation errors made during the execution of pedestrian navigation tasks following the above classifications after the users completed their training sessions. The column ‘Assisted’ contains the number of unrecoverable errors where users required external assistance from the research team or the instructor and, thus, failed to successfully complete the task at hand. This means that those tasks are not taken into consideration when estimating the completion rate metric. The rest of the columns present the errors made by the user; however, they were able to recover by themselves and, thus, contribute to the completion rate metric. In total, we identified 166 errors where the users

recovered on their own, while 24 required external assistance. The most commonly occurring error (44 out of 166) was the users colliding with obstacles. Although we have managed to deliver a functional version of the obstacle detection system, there are still scenarios, such as balconies or short trees, that need to be improved in the future. The second most often occurring error (28 out of 166) was the inability to always recover from an overturn back to the correct navigational path due to different cognitive capabilities, shaped attitudes, beliefs and preferences. The overturns were mainly either the result of the irregularities of some building blocks and other parts of the trial routes or the result of any other external factor that leads to an over-turn. The latter event is not taken into consideration when determining the errors caused by external factors, hence, securing that those errors are not double counted.

Table 9.3 Pedestrian Navigation Errors.

| Participant | Collision with Obstacles | Veering | External Factor | Missed Turn | Over-Turn | Issued Instructions | Assisted |
|---|---|---|---|---|---|---|---|
| P1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| P2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 |
| P3 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| P4 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| P5 | 2 | 0 | 1 | 1 | 0 | 0 | 2 |
| P6 | 3 | 1 | 1 | 0 | 1 | 1 | 1 |
| P7 | 2 | 1 | 0 | 0 | 1 | 1 | 1 |
| P8 | 2 | 0 | 0 | 1 | 0 | 0 | 1 |
| P9 | 1 | 3 | 2 | 1 | 0 | 1 | 1 |
| P10 | 0 | 0 | 1 | 2 | 1 | 1 | 1 |
| P11 | 3 | 0 | 1 | 1 | 1 | 1 | 1 |
| P12 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| P13 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| P14 | 1 | 2 | 1 | 0 | 1 | 1 | 1 |
| P15 | 1 | 2 | 1 | 1 | 2 | 0 | 0 |
| P16 | 2 | 3 | 1 | 0 | 2 | 1 | 1 |
| P17 | 3 | 1 | 0 | 1 | 2 | 1 | 1 |
| P18 | 2 | 1 | 0 | 0 | 1 | 1 | 1 |
| P19 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| P20 | 1 | 0 | 1 | 1 | 3 | 0 | 0 |
| P21 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| P22 | 0 | 3 | 1 | 0 | 1 | 1 | 1 |
| P23 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| P24 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| P25 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| P26 | 2 | 0 | 1 | 0 | 0 | 1 | 1 |
| P27 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| P28 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| P29 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| P30 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |

It is worth mentioning that the most common error requesting assistance from the research team was from the category of obstacle collision and whenever the user had to deal with multiple obstacles in close proximity that had different shapes, awkward angles and were made of materials that could not be properly identified by the selected ultra-sonic sensor technology. For this case, the error rate (Equation (4)) is 166/30 = 5.53 recoverable errors per user on average.

Likewise, the identified errors for the case of utilizing the Public Means of Transport and for the case of passing traffic lights crossings were classified as follows: Public Means of Transport

- Boarding button: this category records the cases of activating the public means of transport mode of operation.
- Boarding on the bus: this category records the cases where the blind and the visually impaired user enters the bus.
- Exiting the bus: this category records the cases where the blind and visually impaired user exits at the correct bus stop. Traffic Lights Crossings
- Veering: this category records the cases where the blind and visually impaired user deviates from the straight line of the user's vector path.
- Reaction time to the status change notifications: this category records the cases where the blind and visually impaired user reacts to the traffic lights status change notification.

Table 9.4 presents the number of errors made by the users for each category after they completed their training sessions both in the case of pedestrian navigation combined with public means of transport and in the case of passing traffic light crossings. Similar to the above case, the columns 'Assisted' for each category contain the number of unrecoverable errors where users required external assistance from the research team or the instructor and, thus, failed to successfully complete the task at hand. This means that those tasks are not taken into consideration when estimating the completion rate metric. The rest of the columns present the errors made by the user; however, they were able to recover by themselves and, thus, contribute to the completion rate metric. In total, for the case of pedestrian navigation combined with public means of transport, we identified 70 errors where the users recovered on their own, while 16 required external assistance. The most often occurring error (44 out of 70) concerned the users forgetting to activate the Public Means of Transport mode of operation. We plan to address this issue in the future by providing both haptic and audio feedback as a reminder to the user. For this case, the error rate (Equation (4)) is 70/30 = 2.33 recoverable errors per user on average. Likewise, for the case of passing traffic light crossings, in total, we identified thirty-one errors where the users recovered on their own, while nine required external assistance. Both classifications of errors for this case were equally identified (15 and 16 out of 31) by the research team. We plan to address this issue in the future by providing both haptic and audio feedback in order to correct the user. For this case, the error rate (Equation (4)) is 31/30 = 1.033 recoverable errors per user on average.

### 9.5.3. Efficiency

This section presents the results of the measured efficiency. In contrast to the previous presentation on effectiveness, not all cases are considered. Since efficiency takes the time a user needs to complete a task as the input, it seems reasonable to exclude the ones for which their time completion is dependent on external factors besides the user's actions. This implies that both the tasks that include the use of Public Means of Transport and passing traffic light crossings will not be measured in terms of efficiency, thus leaving the pedestrian navigation as the only category that will be studied. Specifically, in the case of pedestrian navigation combined with Public Means of Transport, the task's completion time depends on the bus' time of arrival as well as the traffic conditions. Likewise, for the case of passing traffic light crossings, the task's completion time is upper bounded by the time a traffic light is set to change its status.

In particular, the efficiency of pedestrian navigation is measured by utilizing Equation (2) on the successfully completed routes (see Section 2.5.6 for more details). The first known route was completed on an average time of ten minutes and a standard deviation of two minutes while the second known route had an average of five minutes and a standard deviation of one minute. The first unknown route was completed on an average time of five minutes and a standard deviation of three minutes while the second had an average time of ten minutes and a standard deviation of two minutes. Taking into consideration Equation (2) and the above data, we measured the efficiency to be 74%.

### 9.5.4. Questionnaires, Interviews and Group Discussions Findings (UEQ+)

This section presents the statistical results from the evaluation of the pilot phase. These include the mean value and standard deviation for every scale, the consistency of the questionnaire, the importance ratings for the selected scales and a Key Performance Indicator (KPI). The latter is provided by the UEQ+ tool and allows for the overall evaluation of the UX impression. For the calculation of the KPI, the UEQ+ tool collects each scale rating for four items and one rating for the overall importance of the scale. Next, the relative importance of the scale and the scale mean per participant are calculated. Finally, the KPI is then simply the mean over all participants.

### *9.5.5. Mean Value and Standard Deviation for Every Scale*

This section’s scope is to present various statistics, including the mean value, for every scale of the questionnaire, as well as for each of the items in which they are decomposed, the corresponding standard deviation and, finally, the relevant confidence intervals. (Remark: The mean value ranges from −3 to +3 instead of 1 to 7. The latter transformation is a result of trying to conform with the range values of the initial version of the UEQ questionnaire.)

Table 9.5 summarizes the average value, the standard deviation and the computed 95% confidence interval level.

Table 9.4. Traffic lights crossings and public means of Transport Navigation Errors.

| | **Public Means of Transport** | | | | **Traffic Lights Crossings** | | |
|---|---|---|---|---|---|---|---|
| **Participant** | **Boarding Button** | **Boarding** | **Exiting** | **Assisted** | **Veering** | **Reaction Time *** | **Assisted** |
| P1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| P2 | 2 | 0 | 0 | 1 | 1 | 1 | 0 |
| P3 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| P4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| P5 | 2 | 1 | 0 | 0 | 1 | 1 | 1 |
| P6 | 3 | 0 | 1 | 1 | 0 | 0 | 0 |
| P7 | 2 | 0 | 0 | 1 | 1 | 1 | 1 |
| P8 | 2 | 0 | 1 | 1 | 1 | 0 | 0 |
| P9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| P10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P11 | 3 | 0 | 0 | 0 | 1 | 1 | 1 |
| P12 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| P13 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| P14 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| P15 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| P16 | 2 | 1 | 1 | 1 | 0 | 1 | 0 |
| P17 | 3 | 0 | 0 | 1 | 1 | 1 | 1 |
| P18 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| P19 | 2 | 1 | 1 | 0 | 0 | 0 | 1 |
| P20 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| P21 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| P22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P24 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| P25 | 2 | 1 | 0 | 1 | 1 | 0 | 0 |
| P26 | 2 | 1 | 1 | 1 | 0 | 1 | 0 |
| P27 | 2 | 1 | 1 | 1 | 1 | 1 | 0 |
| P28 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| P29 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |

| Scale | Mean Value | Standard Deviation | Confidence | Confidence Intervals | |
|---|---|---|---|---|---|
| Efficiency | 1.36 | 1.37 | 0.49 | 0.87 | 1.85 |
| Perspicuity | 1.25 | 1.22 | 0.44 | 0.81 | 1.68 |
| Dependability | 1.38 | 1.25 | 0.45 | 0.94 | 1.83 |
| Personalization | 1.00 | 1.13 | 0.41 | 0.59 | 1.41 |
| Usefulness | 1.39 | 1.32 | 0.47 | 0.92 | 1.86 |
| Trustworthiness of Content | 1.34 | 1.00 | 0.36 | 0.99 | 1.70 |
| Response Behavior | 1.18 | 1.30 | 0.46 | 0.72 | 1.65 |

*Table 9.5 Mean value per scale*

Subsequently, the above table is depicted also graphically in Figures 9.9 and 9.10.

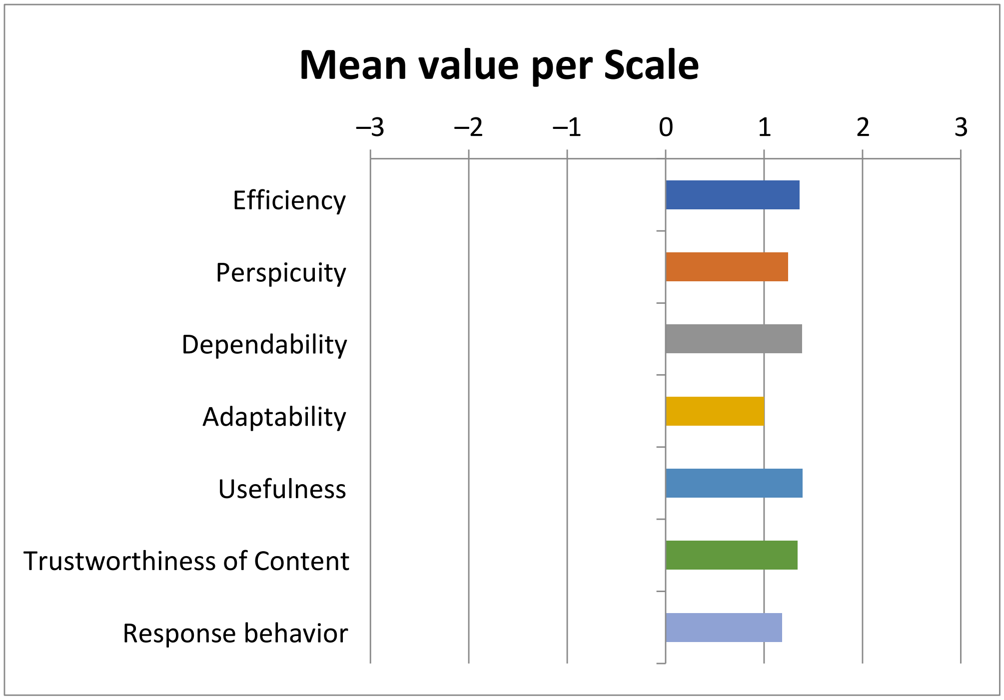


*Figure 9.9. Mean value per Scale*

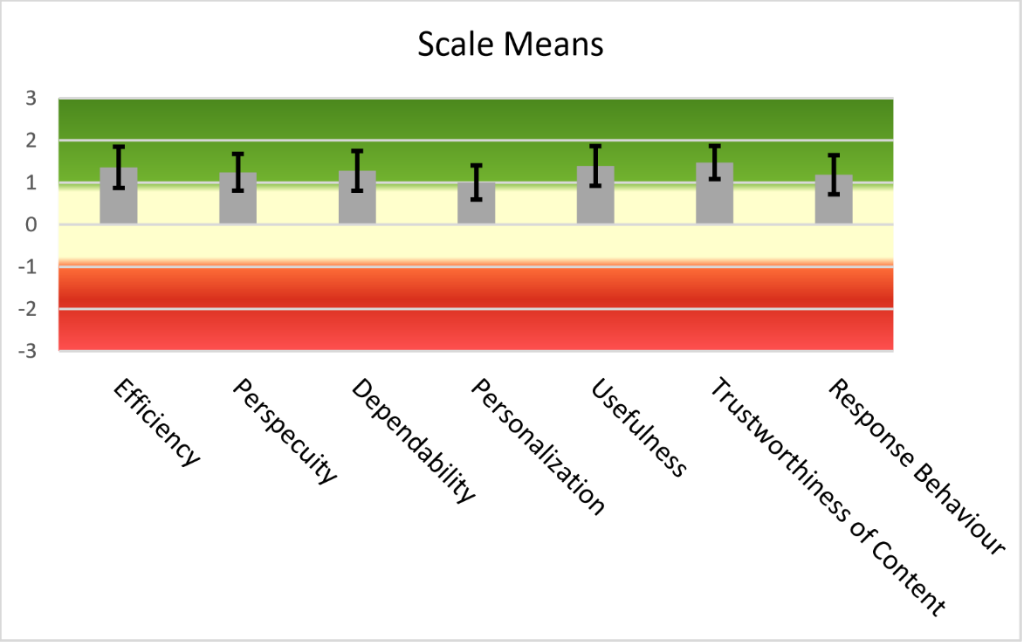


**Figure 10.** Scale Means and Standard Deviation.

*Figure 9.10. Scale Means and Standard Deviation*

Next, the above scales are then analyzed into their constituent items, four per scale, in order to highlight, in greater detail, the above observations. The order of the exposition for the individual items mirrors the order the scales are presented.

For the scale of Efficiency (1.36), users judged that the application was found to be primarily very organized (1.53), practical (1.33), fast (1.30) and that it was very efficient (1.27). Users stated that they do not have to perform unnecessary actions and they do not have to wait too long for the application to respond.

For the scale of Perspicuity (1.25), users found the app understandable (1.53), easy to learn (1.27), easy to use (1.13) and having a clear structure (1.10). Specifically, users were satisfied with the interface as it follows practices already known to blind people that are also compatible with the widely used TALKBACK service. Additionally, they reported that the available functions were well organized. Moreover, the majority stated that the training version, although it could be improved, created the necessary conditions for learning to use the application properly, firstly, by eliminating external distractions and, secondly, by minimizing users' doubts about the risks that arise while navigating in a dynamic environment with obstacles. Another feature that makes it easier to use the app is that it does not add any further cognitive load to users. This is due to lifting the burden of having the user memorize detailed information about their pedestrian navigation, such as constructing cognitive maps of the entire route and tracking in real-time the current position in it. Finally, they noted that the user manual is quite explanatory and helps in learning how to use the application, especially if it is demonstrated by someone trained in this assistive technology. This is also true even for digitally sophisticated blind individuals which are approximately a third of the participants.

For the scale of Dependability (1.38), users found that the application's functions were predictable (1.47), supported their navigation activities (1.43), met their expectations (1.27) and gave them a high sense of security (1.37). Specifically, they commented on the accuracy of the app and the precision of the instructions given that the app is in the pilot testing phase. Additionally, they were satisfied with the snap response of the application when the user made mistakes during the navigation as well as with the issued instructions that redirected the user back to the correct route. The functionality that integrates Public Means of Transport (buses) with pedestrian navigation was found satisfactory, while passing marked crossings near traffic lights was much safer according to users. Last but not least, users found the shake functionality that reminds them of their current position extremely helpful even if the user is inside a speedy bus.

For the scale of Adaptability, users stated that the application's reading speed capability can be adjusted (0.97) according to their needs, through the utilization of the Talkback service, while at the same time they were somewhat satisfied with the provided flexibility (0.73) to choose between different styles of navigation instructions, either in a rectangular or clockwise style. The instructions issued in the former style follow a more discrete approach that exclusively includes perpendicular moves (right, left, behind, straight), while the latter includes instructions that are issued in degrees based on the hands of the clock. However, the users found the lack of a wider range of virtual assistants somewhat restricting as the application currently supports only Melissa, thus justifying the lower score on this feature. Finally, users found that adjusting the settings was neither difficult (1.1) nor slow to characterize as useless (1.2).

Specifically, from Figure 9.11, it is evident that for the scale of Usefulness (1.39), the application was found to be very helpful (1.70), beneficial (1.47), useful (1.37) and sufficiently rewarding (1.03) since it significantly facilitated the navigation of blind people outdoors. Furthermore, to this end, another factor of contribution was the fact that users found the ability to switch between different applications while running the outdoor navigation application (BlindRouteVision) particularly useful.

For the scale of the Trustworthiness of Content (1.34), users found that the app provides trustworthy voice guidance content (1.43). It was also useful (1.23), plausible (1.43) and accurate (1.27). Users stated that the voice instructions were tailored to the specific requirements and needs of the blind and visually impaired and their frequency of repetition was within reasonable limits facilitated by the custom-made scheduler. Users also stated that they were satisfied with the battery consumption and the level notification rate.

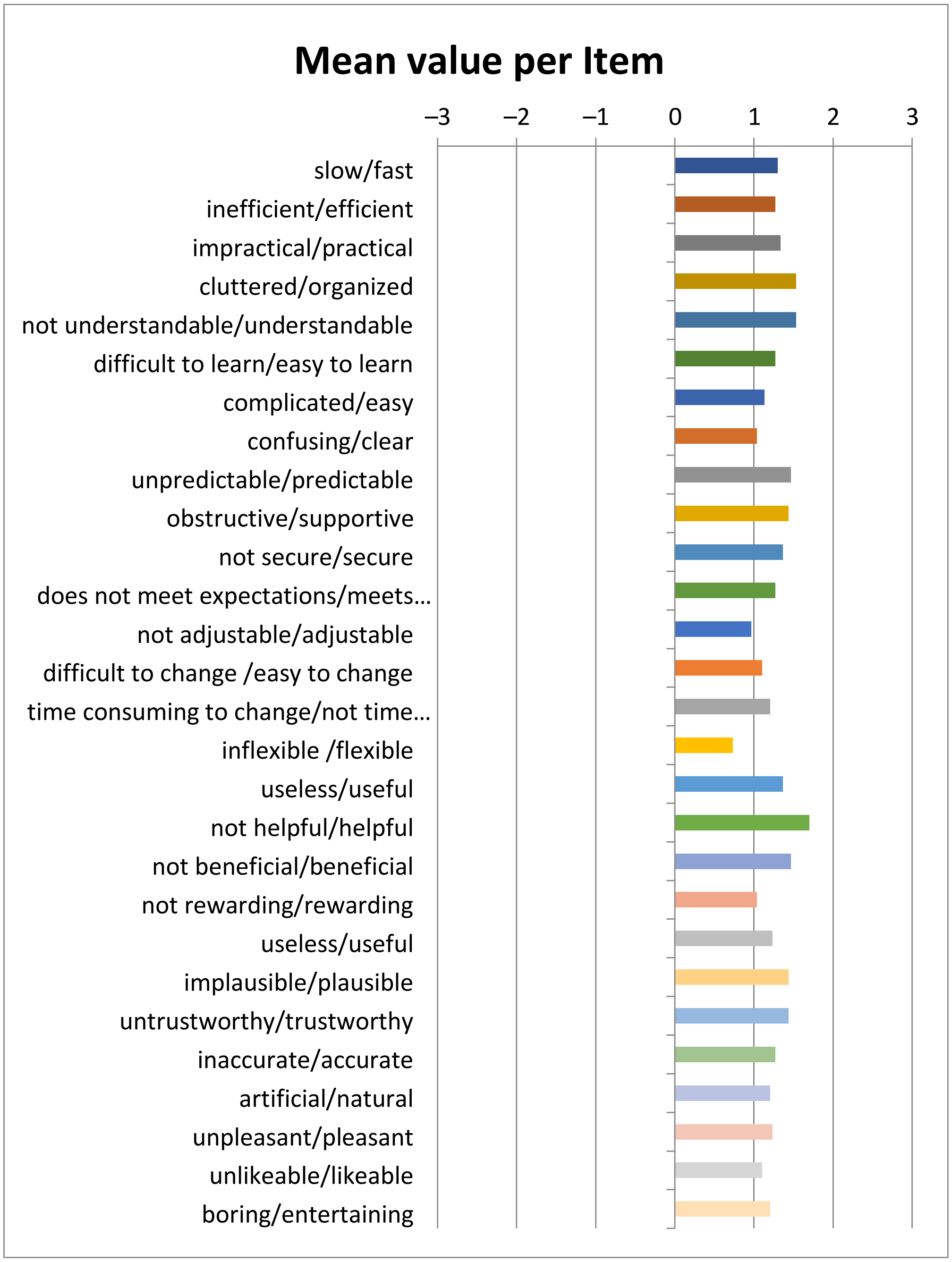


*Figure 9.11. Mean value per Item*

For the scale of the Response Behavior (1.18), users judged that the application's response is produced at a relatively satisfactory rate and is pleasant (1.23), natural (1.20), likeable (1.10) and entertaining (1.20).

Additionally, many users noted that the instructions could be improved despite being already satisfactorily natural.

### 9.5.6. Distribution of Responses by Scale

Next, Figure 9.12 depicts the distribution of responses for each scale. Given the above analysis, it is evident that the overall rating was positive, with the majority of the responses having a score above five. On average, 77.8% of the responses had a score of at least five, while the scales of Adaptability and Response Behavior scored the lowest.

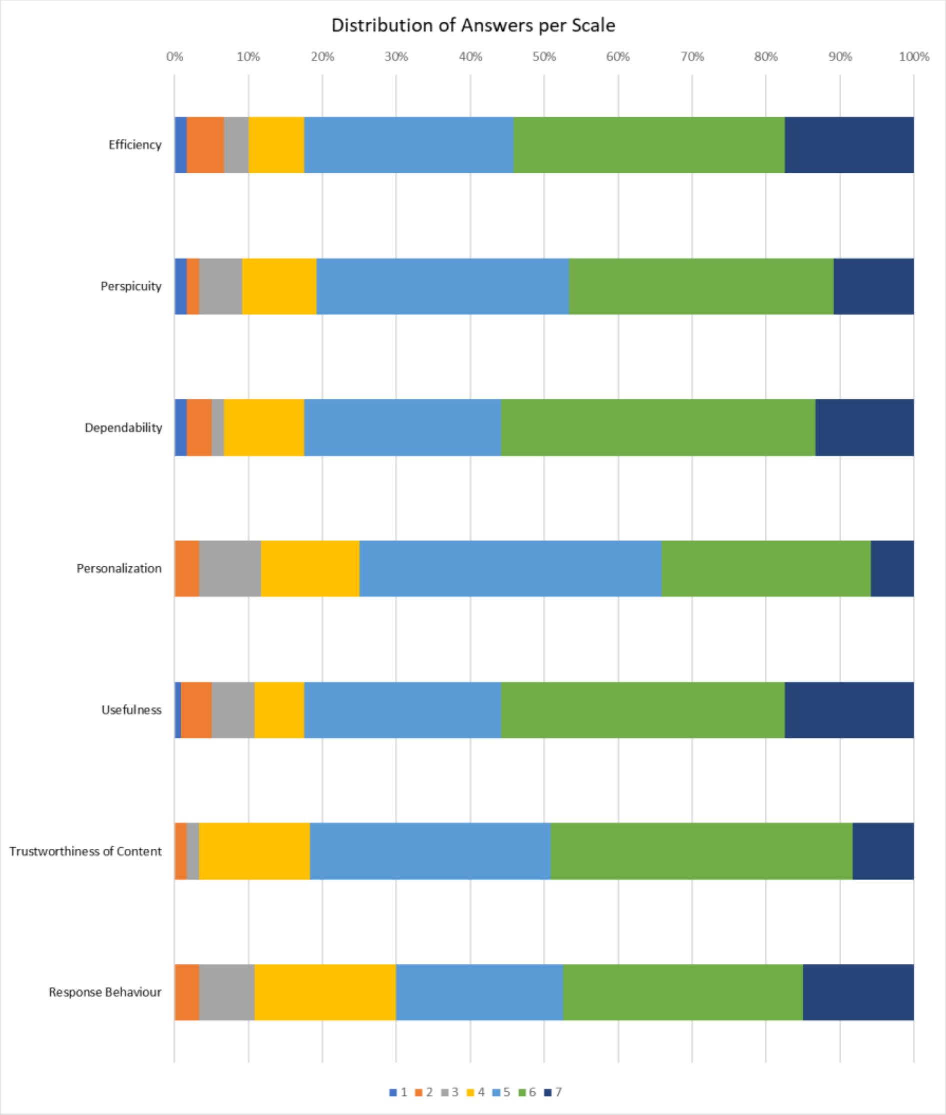


*Figure 9.12. Standard Deviation of scales.*

Overall, user experience was positively evaluated by all participants, with the scale of Adaptability being the exception. This scale, which describes the capability of customization to the user's personal preferences, received the lowest score (1.00). On the contrary, the scales of Usefulness (1.39) and Dependability (1.38) received the highest scores as users found that the app removes restrictions concerning pedestrian navigation, while, at the same time, the app's operations were found to be reliable and predictable, respectively. The scales that are close enough are the scale of Efficiency (1.36), as users found that their goals can be achieved both quickly and efficiently, and the scale of Trustworthiness of Content (1.34) that emphasizes the quality of the information provided during navigation. The scale of Perspicuity (1.24) received a score that indicates there is room for improvement on how easy it is for the users to familiarize themselves with the application as well as to learn its operation, followed by the scale of Response Behavior (1.18) that shows the desire of users for somewhat better-quality characteristics regarding the app's issued instructions. Finally, as already mentioned above, the UEQ+ tool provides a Key Performance Indicator (KPI) for the overall evaluation of the UX impression. It received a score of 1.48, which is considered a positive result given that the scale ranges between [−3, 3]. Figure 9.13 describes the importance ratings as given by the blind participants about the selected scales.

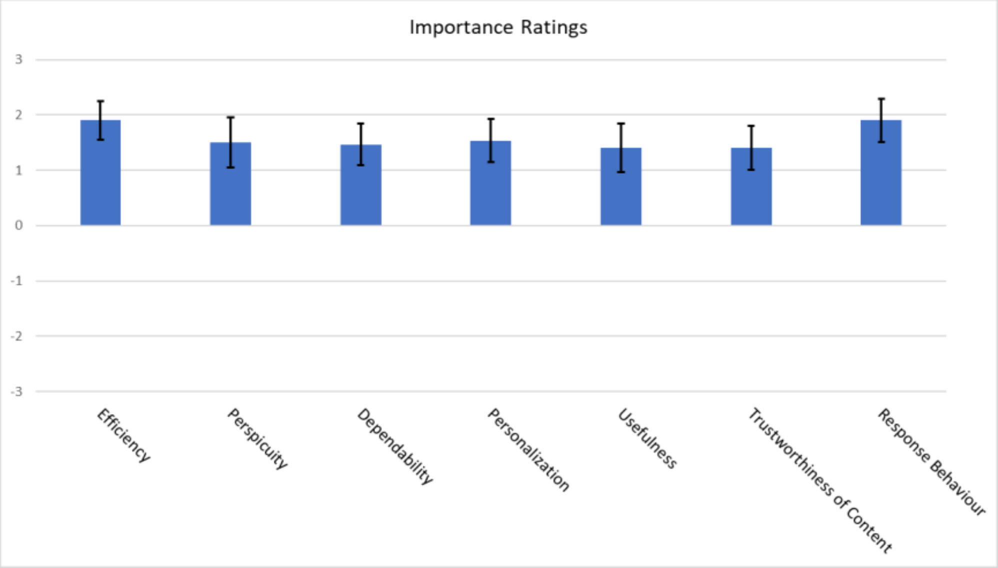


*Figure 9.13. Importance ratings of scales.*

### 9.5.7 Consistency of the Evaluation Categories

Finally, we used Cronbach's alpha coefficient to determine the reliability of the results based on user responses. There is no generally accepted rule of thumb on how large the value of the coefficient should be, however, in practice, a value greater than 0.7 is sufficient to qualify the results as reliable. Specifically, the table below (Table 9.6) details the Cronbach's coefficient values broken down by scale. The observed values indicate that the results are reliable. Figure 9.14 depicts Table 9.6 as a bar graph.

Table 9.6. Cronbach per scale.

| | |
|---|---|
| Efficiency | 0.9 |
| Perspicuity | 0.9 |
| Dependability | 0.9 |
| Adaptability | 0.85 |
| Usefulness | 0.92 |
| Trustworthiness of Content | 0.72 |
| Response Behavior | 0.77 |

## 9.5.8. Comparative Evaluation

### 9.5.8.1. Advancing the State-of-the-Art

In contrast to our approach, none of the state-of-the-art solutions (Section 1.1) underline the necessity of introducing specialized training courses as part of an evaluation framework for Usability and UX aimed at blind and visually impaired individuals, if they even consider assessing them at all. The benefit of this activity is that we can further solidify the validity of the findings. Our framework also emphasizes user participation into the process of defining the evaluation criteria by incorporating needs, beliefs, opinions, characteristics, personality and attitudes that were the result of the user requirements' elicitation stage [61,80]. In addition, it includes user-centered courses incorporated in the existing O&M courses of the Lighthouse for the Blind of Greece with the cooperation of the instructors. Finally, with the aid of a custom-made training tool, the blind individuals were able to become familiar with the application in simulated conditions and scenarios, avoiding external hazards and guaranteeing their safety.

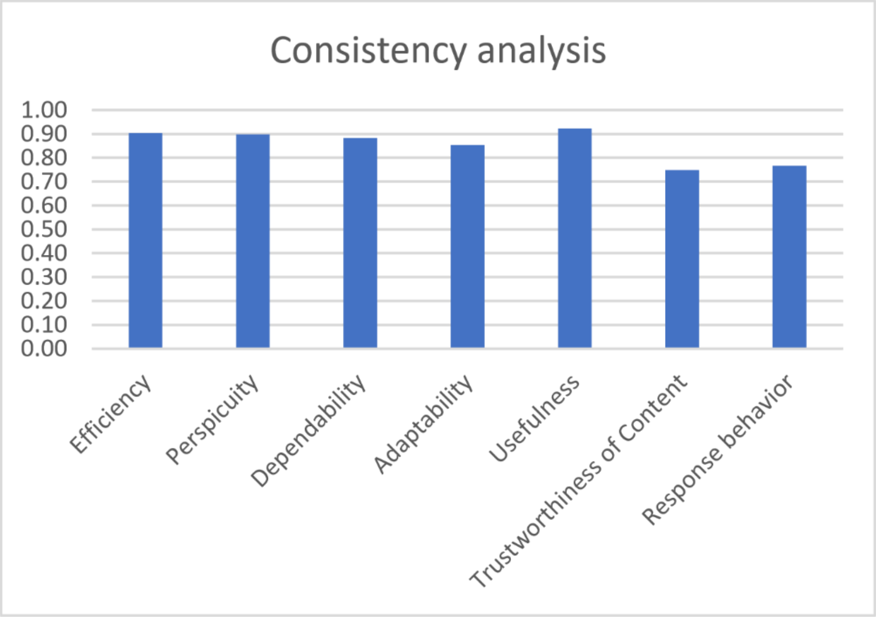


**Figure 14.** Consistency Analysis.

*Figure 9.14 Consistency Analysis*

The major motivations for the proposed approach of obstacle recognition against the limitations of the related work is the sophistication of the proposed method regarding the detection of object size and near-field moving-object tracking and the subsequent short oral warnings for avoidance.

Our proposed solution for passing traffic lights crossings has the advantage of being non-invasive and not imposing the requirement of interaction with the traffic light management system. To guarantee the user's safe crossing, the system, via a patent-pending algorithm allowing the connection of the application with the traffic light device, emits critical information with high accuracy, including the traffic light's current status and its transitions, the time remaining to traverse the crossing as well as the directionality of the passing vehicles. It provides true low latency guarantees as it is not affected by network connectivity issues that cloud-based solutions must deal with. Furthermore, neither light nor weather conditions play a role as they do in computer-vision-based systems. In contrast to our short-range server system, other beacon-based solutions face the limitations of not being able to transmit accurate timing information in real-time, while they need to solve the problem of recognizing the ID of the receiving passive signal among a multitude of almost identical signals from multiple intersections.

Another advantage of the proposed solution in comparison to the existing state of the art is the high accuracy and density of the users' tracked location, achieved by the combination of the external device with the application that enables accurate navigation. The application, also, provides:

a. accurate instructions for recovering back to the navigation path when the user diverges from it;
b. route selection confirmation
c. navigation to bus stops, safely boarding them, upcoming bus stop notifications and instructions to exit the bus.

The power consumption of the proposed solution can be distinguished in two separate cases, one involving the sonar-based detection system and one without it. The experimental results show that the external device, having a 3500 mAh battery installed, can demonstrate constant operation exceeding 12 h before recharging in the most demanding navigation scenario involving sending dense high precision GPS data to the smartphone application every 1 s. For the case with the sonar module active, the system exceeds 4 h of operation before recharging is required, mainly due to the servomotor dominating the power budget of the external device. In fact, had we swapped the servomotor with two sensors placed at both sides of the central sensor, then we could have achieved more than a 90% reduction in power consumption. However, the servomotor mechanism is indispensable for the configuration of the system utilizing the narrow/pencil-beam sensors due to the smaller required rotation step. For more details regarding the power consumption as well the CPU utilization of the impulse noise filtering software, the reader is advised to refer to [59]. Although a comparison between the power consumption characteristics of the existing hardware solutions would be of great interest, nonetheless, the majority of the literature do not include relevant experimentation sections.

Finally, not one of all these efforts is an integral part of a holistic modern state-of-the-art reliable high-precision wearable navigation system relying on a smartphone.

### 9.5.8.2. Commercial Navigation Applications

The BlindSquare application is a proven solution that combines existing technologies to help blind and partially sighted people in their daily life. Specifically, it helps the user to perceive the surrounding environment with the help of voice instructions. It works solely on Apple-related devices. The BlindSquare app uses both the GPS sensor and the compass of the smartphone and gathers information about the surrounding environment from FourSquare. By utilizing unique filtering algorithms, the Blindsquare app can decide what information is most relevant and reports back to the user the results via high-quality speech synthesis.

Lazarillo is a specialized GPS application that integrates mobility tools for the blind. Using audio messages, Lazarillo informs about nearby places, streets, intersections and so on. The GPS sensor is used even if the app is in the background. This allows the user to continue using the app without actively using the screen, even when the phone is in a pocket or when other apps are used. The goal of the app is to help every blind person reach the selected destination simply by giving voice notifications of nearby locations, institutions and shops, thus allowing the user to interact more actively within the city.

InMoBS is an application that aims to keep users on the correct path, describe the surrounding area and inform them about the dangers they may face in it, as well as to support them during passing crossings.

To support all the above, an appropriate networkbased system was developed where the user interacted with the service either through an application for smartphones ("InMoBS mobile") or, alternatively, through an application based on web technologies ("InMoBS Home"). With the support of the central service provider node, the above applications achieve the desired objective of ensuring the correct navigation. To ensure a higher degree of accuracy of the users' reported location during external navigation, a high-precision external GPS receiver connected via Bluetooth is used, while, with the support of WiFi-capable devices placed at traffic lights, the integrity of users is ensured when passing crossings.

In comparison to the Blindsquare application, BlindRouteVision follows the same general principles and shares a common set of functionalities. Despite this overlap, BlindRouteVision is superior in the following features. First, the BlindRouteVision app has a higher accuracy and localization density during the user's outdoor navigation, significantly outperforming Blindsquare, which uses the smartphone's GPS receiver. Specifically, according to the data measurements, the accuracy of the GPS receivers integrated into smartphones is less than 10 m, which leads to inaccurately reported locations, while the use of an external high-precision receiver by BlindRouteVision helps to achieve an error of less than 1 m.

In addition to the high density and accuracy of tracking, BlindRouteVision features an innovative navigation algorithm that continuously tracks the user's gait with great precision along the route, constantly knowing the distance from the route, and corrects the user in real-time when he/she deviates. In addition, the resolution of the reference points of the route path is at least three times denser (from two to five times) than the reference points used by the Google Maps navigator. For example, the Google Maps navigator will report "Move straight to 23 Thivon Avenue", while the Blind RouteVision app utilizes the set of reference points yielding a more descriptive route: "Move along Ethnikis Antistaseos Street. Turn right on Thivon Avenue. Continue straight on 23 Thevon Avenue". In this way, it ensures that the user's actual path and the path planned by the application are in close proximity and parallel to each other. Therefore, as it is evident from the above, the real-time tracking of BlindRouteVision surpasses Blindsquare's corresponding functionality.

Another point of differentiation is the BlindRouteVision algorithm's change of direction instructions, which are extremely precise with an error of less than a meter, unlike the navigation instructions of classic navigators that do not have specialized instructions for the blind. For example, a classical navigator in the corresponding case would issue the instruction "in 600 m turn right" followed by the instruction "turn right", e.g., 100 m before the turn, even though at that point there may be no turn or there may be a vertical road with an opposite direction of vehicle flow, as the driver can only turn right at the next alley. In addition, the Blind RouteVision application very effectively integrates Public Means of Transport.

Furthermore, it can guide the user very accurately to the bus stop, much more efficiently than other applications. It then gives them real-time information about the bus arrival time. Inside the bus, the user receives notifications about the next stops and when to get off. After the user gets off the bus, the application automatically continues the pedestrian navigation. Regarding crossings, the application knows precisely with zero latency the red–green status of all traffic lights of a traffic junction that the user is approaching and accurately selects the correct crossing. It also knows with zero latency the remaining time of the traffic lights status, the number of crossings and the direction of the vehicles at each crossing. The application guides the blind or the visually impaired user very precisely to pass the crossing safely. However, the correct operation of this feature depends on whether the traffic light has a second external device installed. Finally, the other applications do not support this feature.

## 9.6. Discussion

The successful completion of the evaluation phase marked the end of the MANTO project. Throughout this period, the team obtained valuable experience around issues concerning the navigation of the blind and visually impaired and how these translate to the design, implementation and validation process of relevant apps, as well as how to administrate such projects. Additionally, the lessons learned from this process, being of paramount importance, include the following:

1. The importance of having a guiding application that allows blind users to complete all their activities.
2. The necessity to adopt a design process that involves the blind and visually impaired users for enabling the development of an application where users can recognize the functionality of the cognitive processes used during their navigation.
3. The necessity to design and implement an organized training framework for increasing the adoption and learning rate of the application.
4. The importance of blending the design process of both the educational framework and the technical capabilities of the system to get a better and more robust result.

### 9.6.1. Technical Limitations and Future Work of BlindRouteVision

We recognize that a limitation of the original design is a lack of sufficiently distinguishing the specific needs of blind and low-vision users. Although it is the common case to conduct a detailed analysis of the needs of blind individuals, it has become clear from interacting with users at various stages of the development and pilot phases that blind and low-vision users have substantially different needs and have access to a set of different cognitive processes and experiences affecting, differently, the navigation requirements and the assistance that should be provided to them. A similar problem is identified for people with congenital and late-onset visual impairment.

During the pilot phase, it became evident that the current implementation of the external sonar device cannot distinguish obstacles with the desired degree of reliability when used in dense urban environments, while some transient false readings affecting the accuracy of obstacle detection need to be eliminated. The latter is due to the combination of the sensitivity of the ultrasonic sensor and the periodic change in its direction caused by the servo motor. In addition, the current form factor of the external device does not satisfy all users in terms of portability and a portion of them prefer to carry only the high-accuracy external GPS receiver due to its smaller size. In the near future, we will address the above limitations by evaluating the characteristics of a wider range of sensors. From our experience, we found that, in practice, their operation diverges both from the nominal viewing angle and the beam pattern listed on the accompanying specifications and even produces different results depending on the features of the object. Additionally, the existing noise removal filter will be further optimized in order to improve the application’s behavior in scenarios involving frequently detected obstacles that are part of the blind route, such as walls or cars parked along the road. On the other hand, addressing the portability constraints will be the subject of longer-term research as factors not exclusively related to the technical dimensions of the problem need to be weighed. While several solutions have been proposed and evaluated by blind and visually impaired participants, no final solution has been accepted.

Concerning the external device mounted on traffic lights, some recognized limitations of the current implementation are, on one hand, the distance at which the application can detect the traffic lights and, on the other hand, the maximum supported number of concurrent users that can be connected to this device. Although the current number is satisfactory, based also on the evaluation, the aim is to increase this number.

Besides further improvements to existing features, part of the strategy to strengthen the value of the app as a blind person's assistant is the incorporation of free travel functionality. By choosing this form of navigation, the user, without having to choose a specific destination, will be able to be informed about various points of interest such as shops, museums, retail stores and so on as they walk. This information is emitted in two approaches; either the user requests the information from the app (pull-based interaction) or the app gives the information to the user at its own pace (push-based interaction). Part of the future work will include the following:

- The app should provide additional feedback to the user to recover in the case of over-turning.
- Participants would like for the app to provide the capability to control how much information is given to them (push interaction). Furthermore, the participants requested for both push- and pull-based interactions to be adjusted in order to better match their personal style of preference.
- Search based on shop names and general categories—it will be possible to constrain the search results returned to the user based on the selected coverage radius. It will also be possible to search either via shop names or via more general categories.
- Integration of the application with social networks—instant connection and presentation of news related to points of interest that were the result of a search.
- Use of other navigation map services such as TomTom, Navigon and Apple Maps.
- Support for a wider range of Public Means of Transport besides buses, including trains, subways and taxis.
- As it is common for the task performance to vary amongst users, or even for the same user, a method for adjusting to the user's abilities is required to facilitate an efficient interface between the blind or visually impaired user and the navigation system. Currently, the interface is designed and fine-tuned exclusively for blind users, but we intend to experiment with high-contrast visual interfaces for partially sighted users as well.
- Providing the capability to repeat an issued instruction in the case where the user was unable to hear it due to external factors such as environmental noise or other distractions.
- Adding the capability to adjust the speed by which the overall brief description of the navigation route and the subsequent navigation instructions are issued.
- Allowing the user to flexibly change the destination without having to start the process all over again.
- Providing in-app updates. At the time of writing of this chapter, the application is made available to download from an external link found in the bulletin board system of the Lighthouse for the Blind of Greece where manual installation is required.
- Multimodal sensory interface for traffic lights information by combining vibration and acoustic feedback. The above achieves safer and more accurate guidance for the user while passing traffic light crossings.

### 9.6.2. Limitations and Future Work for User Evaluation

We also acknowledge that the findings obtained from the Usability and UX evaluation of our application do not aid in generalizing as the participants are only from Greece and are few. Various factors contributed to the latter, with the main ones being the difficulty in finding and recruiting for the interviews many people with severe visual impairment due to the COVID-19 pandemic and other challenges related to mobility issues. Recruiting participants around the globe, which could be facilitated through World Wide Web communities, would certainly lead to more general and sound conclusions and is a future endeavor. In addition, as part of the above effort, the participant pool will expand and be diversified in key areas such as age, gender, ethnicity, living environment and previous experiences with the regular white cane and other assistive technologies. This will provide an adequate basis for developing a better appreciation of the needs and requirements of a wider part of the blind and visually impaired global population. Finally, this will create opportunities to enhance and improve the acceptance and usage of the proposed and other related technologies by creating an extended version of the TAM model. Nonetheless, all is not for naught as the requirements gathered during interviews can form a useful basis for researchers in the field and for developers of related applications even though they express personal preferences, opinions and suggestions from this local group. This can be based on the assertion that the core effects of vision loss on any blind person, regardless of their origin and region, are common, and therefore, it is reasonable to assume that their preferences, along with the solutions they choose to overcome them, overlap to some extent.

Another concern that emerged as a result of the evaluations was the issue of participant response bias, which is known to significantly affect the preferences about technological artefacts displayed in participants' responses [82] and is often not taken into account when conducting field experiments with blind participants. Specifically, response bias is attributed to the perceived, by the participants, socio-economic characteristics of the person conducting the interview and the potential preferences of that person with respect to the subject of the study. In the interviews conducted as part of the project, the interviewer was a member of the research team which potentially may have contributed to increasing the bias in the responses. To avoid this situation, the part of the semi-structured interviews that requests feedback could be given in Braille so those blind users could have the opportunity to read the questions and assess the applications themselves during the evaluation phase. Furthermore, the UX questionnaire, which is accessible via Google Forms, will be handed out in Braille format as well so that participants with low digital sophistication will be included.

As part of our future work, we intend to fine-tune the existing version of the simulation app, which is developed as an interactive virtual navigation software solution that supports both Android smartphones and PCs. The end goal is to ease the engagement with this type of technology and increase the effectiveness of its usage since spatial information can be obtained indirectly (prior to navigation). The details of this simulation app will be described in depth in a future research work. Furthermore, we are considering designing, implementing and validating a VR application that hopefully will improve the trainability of the blind and visually impaired.

### 9.6.3. Future Work for Ameliorating the General Trend on Adoption Rates Usage

Last but not least, the requirements/expectations identified regarding the usability, functionality and trainability can be used for the creation of a framework that extends the Technology Acceptance Model to blind or visually impaired individuals. Such an extension will have to address the following two factors:

a. the increased sensitivity of the target group to needs related to their disability, and
b. the corresponding psychological patterns that stem from the insecurity caused by their disability.

The development of such a model is of paramount importance as it will make it possible to understand what creates positive anticipation. The latter plays a critical role in enhancing acceptance and continuing the usage of assistive technologies, otherwise blind users most often resist trying anything new until it is required.

This behavior inhibits assistive technology adoption, and, in a future work, there will be a demonstration of how these limiting factors can be reduced by appropriate user-centered training models. The focus will be to provide a thorough description of the training models regarding the use of applications and how these produce guidelines that contribute to the creation of a revised version of TAM targeting the difficulties that affect the blind and visually impaired people. Furthermore, we will present, in the context of our newly proposed extension, a comparative evaluation of several various navigation methods that include both our application and other traditional methods, such as the use of a white cane with or without an accompanying guide dog. Finally, part of the presentation will be the evaluation of other existing applications currently favored by most blind users in terms of our proposed extended TAM model.

## 9.7. Conclusions

This chapter has outlined the development and the extended Usability and UX evaluation of a specialized mobile outdoor pedestrian navigation system for people that are blind and visually impaired. The system was developed on the Android platform following a cognitive design process that incorporated extended interviews with blind users who had expertise in assistive technologies, as well as blind users with low digital sophistication, and resulted in a detailed requirements elicitation. Our functional prototype system, besides the Android device, comprises a high-accuracy GPS tracking sensor, an ultrasonic sensor for the detection of near-field obstacles along the route and a second external device mounted on traffic lights that monitors their status. The system interacts in real-time with the environment and issues navigational and object detection instructions, as well as traffic light crossing instructions. The content of the orientation instructions is customized to the special needs of our target group and are the same ones that are being taught in the O&M courses.

Overall, user experience was positively evaluated by all participants, however, they expressed an expectation for the system to improve its adaptability by providing more customizable options that suit better the users' personal preferences. These include the available virtual assistants, more settings for the Talkback service and the voice interface with the Android device. Further enhancing its adaptability will, subsequently, improve the positively evaluated usefulness of our application. The users already report benefits in their lives as the application removes restrictions concerning pedestrian navigation. A consequence of the changes applied to the Adaptability features of our application will create the need for horizontal changes in the learning process. The system was found both dependable, due to the reliable and predictable nature of the app's operations, and trustworthy, due to the quality of the information provided during navigation. The users also found the system to be efficient, as it enables them to swiftly complete their tasks, while they had, on one hand, mixed feelings about how explicit and straightforward it was to learn the application and, on the other, about the non-functional characteristics of the issued instructions that could potentially improve the perceived quality of service.

The data collected from the usability evaluation showed a high completion rate and a small number of cases where the participants could not successfully complete the given task. Nonetheless, throughout this process, we discovered some of the limitations of our current implementation that could potentially be improved. Although we have managed to deliver a functional version of the obstacle detection system

[59], there are still scenarios, such as balconies or short trees, that need to be improved in the future. Furthermore, users quite often forgot to activate the public means of transport mode of operation that tracks the route on the bus. Another issue that became apparent was the fact that sometimes users would not react to the audio feedback related to traffic light crossings due to noise from the environment. Both of the last two cases will be addressed in the future by providing suitable haptic and audio feedback.

In response to the crucial requirement for trainability concerning the use of our proposed app, we developed a supplementary training version, identical in functionality to the main application, that familiarizes the user with the various features. The great need for trainability is due, on the one hand, to the fact that the skills, ease of learning and familiarity with digital platforms differ greatly between users and, on the other hand, the challenges that arise as a result of the interaction with a dynamic and unpredictable environment are more demanding for the blind people. The most effective way of solving the above difficulties is via the simulation of navigation routes utilizing familiar equipment that enables the users to experimentally navigate by replaying routes at their pace and place. Additionally, it is made to be convenient for the users as they are not required to carry all the standard equipment for regular navigation.

Intending to create an effective training tool, we identified the gaps that arise when people learn about the routes and their surroundings by reviewing the literature. In practice, various in situ navigation aids, tactile (and interactive) maps, as well as virtual navigation solutions that require special equipment, are used as means of training. These methods entail time-consuming and costly processes that our training version tool avoids. Furthermore, it allows for the combination of the positive aspects of the field and lab tests as it protects the users from the hazards of trials in real scenarios. Additionally, after the completion of the pilot tests, users were asked to evaluate their experience with the application in combination with the educational process. In general, most of the users evaluated the above process positively. Specifically, in a short time, they became familiar with the application environment.

Finally, our gained experience from the validation and evaluation of the proposed system set a starting point to surpass barriers that society imposes on people with disabilities, according to the Social Model of Disability [83].

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# Chapter 10 (Content partially published in #8)

## An extended usability and UX evaluation of a mobile application for the navigation of individuals with blindness and visual impairments indoors: An evaluation approach combined with training sessions

**Keywords**: Android, assistive application, blind accessibility, blind and visually impaired, blind indoor navigation, indoor positioning system, smartphone navigation, Tactual Museum, usability evaluation, User Experience

## 10.1 Introduction

Loss of eyesight ranks third among disabilities globally. [1] report that the number of blind people will increase to 38.5 million by 2020 and 115 million by 2050. For the next three decades, it is projected that individuals with moderate and severe visual impairments (MSVI) will rise to more than 550 million, a significant increase from the approximately 200 million individuals in 2020 [2]. Furthermore, the World Health Organization [3] reports that most of these individuals live in low-income areas, which raises the challenges of daily life even more due to the serious social and economic issues these regions face.

Despite technological progress, individuals with blindness and visual impairments are still excluded from social events hosted in indoor spaces. These are usually related to entertainment venues and educational institutions among others. The most prominent limiting factor for this target group is the lack of spatial awareness, thus restricting their independent mobility. While cutting-edge solutions exist for the indoor navigation of individuals with blindness and visual impairments, they are not being utilized in real scenarios and thus, have no impact at all. In this article, we present a blind navigation system developed as part of the MANTO project [4 -6], called BlindMuseumTourer, which enables users to safely navigate in indoor spaces, along with the system's usability and user experience (UX) evaluation. Specifically, in section 'Background', we present a survey of the available indoor navigation solutions found in the literature highlighting the progress throughout the past decade as well as the different approaches and their limitations. In section 'System design', we present the system design, a high-level overview of the main components comprising the application along with the software design pattern of choice for the implementation. Section 'Usability and UX evaluation' presents the methodology followed to assess the usability and UX of the application after the users had completed special training sessions, along with the findings of the analysis that could be used as guidelines by other researchers and developers in the field. In section 'Discussion – Limitations – Future actions', we present a thorough discussion including the lessons learned, limitations, and future work addressing the existing challenges. Finally, section 'Conclusion' concludes the article by summarizing the main points of this work.

## 10.2 Background

A first step in implementing effective solutions for indoor blind navigation is the recognition of the basic requirements of this specific target group [7 - 9]. The available literature is focused on blind user's requirements analysis for indoor navigation and independent mobility in central public buildings. Specifically, the authors in [10], after a thorough analysis of interviews held with experts and blind participants, describe the needs and challenges of the target group when navigating in indoor spaces. Furthermore, [11] recommend a set of technical criteria for setting a baseline for navigation devices.

These include location accuracy, robustness, flexibility, adaptability to indoor environments, and the quality of the issued instructions. This framework has been widely used to assess compliance with a minimum set of features in a non-quantifiable way concerning navigation applications for individuals with blindness and visual impairments identifying, simultaneously, unresolved issues and areas of potential improvement. Finally, these efforts made it clear that many of the unresolved issues could be solved by incorporating into the design process the blind users themselves as well as their challenges considered in the broader social context.

Miao et al. in [12] proceed with a thorough analysis of user requirements for multimodal mobile applications, conducted with blind users, while [13] identify several research issues that could facilitate the extensive development of indoor navigation systems. In [14], the authors describe some of the navigation technologies supporting independent travel available to blind people. The primary focus here is on large-scale blind navigation in both unfamiliar and familiar environments. [15] present a comparative survey between handheld/wearable obstacle detection/avoidance systems regarding the provided functionality of these systems and how these solutions advance the state of the art of assistive technologies for visually impaired people.

Guidelines for future research related to indoor navigation and destination-finding tools for assisting people with blindness and visual impairments are discussed in [10]. These include localization techniques that utilize a variety of sensors and crowdsourcing, customized user interfaces, point of interest lists, accessibility instructions, floor plan representations, and path planning. As key enablers of the broader vision of effective navigation solutions, they recognize the enhancement of the existing urban infrastructure, including the construction of smart cities and the introduction of ubiquitous assistive robotics technology solutions, among others. Finally, smartphones and other mobile devices will be the main way to provide navigation capabilities to people that are blind and visually impaired.

### 10.2.1 Surveys

A lot of surveys exist in the literature with each one reviewing different aspects of the proposed systems and reporting the new advances in the area. In [16], the authors review recent innovative assistive technologies and present the advantages and disadvantages of existing solutions in the fields of computer vision, embedded systems, and mobile devices. In particular, the recognized challenges for systems based on ultrasonic sensors are mostly their limited detection range (200– 400cm) and their vulnerability to environmental factors. Systems based on infrared (IR) technologies can demonstrate degraded performance due to ultraviolet sensitivity, especially during the daytime. Next, for the case of computer vision-based systems, the authors highlight their reduced performance due to factors such as hard-to-identify objects, perspective, low obstacles visibility, and bad lighting conditions, among others. Last but not least, smartphone-based solutions can have poor audio feedback that can be lost in a noisy environment, and many people with blindness and visual impairment experience difficulty when utilizing smartphones. Therefore, based on these observations, the authors recognize areas requiring further improvements and lay out a plan for future work. Finally, they conclude with a set of rules that every assistive solution should satisfy to be effective. This set includes (1) simplicity in design so that no extra external devices are required, (2) low cost, (3) low weight, (4) reliability and dependability, and (5) coverage of both indoor and outdoor scenarios.

The authors of [17] provide an overview of the methods used by navigation systems to locate staircases using computer vision. Most systems achieve a very high accuracy rate in recognizing static and horizontal stairs, but not spiral stairs. Although several systems have been developed, there is room for further improvement. Similar to [16], by doing this comparative review, the authors provide a comprehensive list of available systems that will help future researchers in their efforts to advance the field.

In [18] the authors make a comparative review of indoor localization solutions based on smartphone devices leveraging radio frequency technologies. Fingerprinting localization is very often used for this kind of application as it demonstrates good localization accuracy; however, its requirement for offline training significantly reduces its practicality. Specifically, the review focuses on practical indoor positioning systems that consist of a smartphone and Wi-Fi/Bluetooth low energy (BLE) beacons. Furthermore, the authors provide details about the challenges of practical indoor positioning systems, the available solutions, and a comprehensive performance comparison. Finally, the paper presents some future trends in indoor positioning systems development. This includes the design of hybrid systems that combine many methods and alternative technologies, an effective mechanism for learning radio signals, and deep learning algorithms, as well as solutions that make it easier to acquire data. Last but not least, [19] presents a holistic review of indoor and outdoor navigation solutions for people with blindness and visual impairments aiming at bringing up to date developers about the state of the art. Specifically, they present solutions from early research on sensory substitution and indoor/outdoor positioning to recent systems based on computer vision. They address issues related to the design approaches of previous efforts as well as highlight the technological achievements of state-of-the-art solutions. Finally, based on their findings, they pro- pose future directions.

### 10.2.2 Radio-frequency identification/near-field communication systems/multimodal RFID systems/BLE

The 'Ways4all' project [20] uses passive radio-frequency identification (RFID) tags as the main driver of their tactile guidance system for indoor route navigation and detection of obstacles. At all strategic points of a building (the entrance, platforms, and intersections) passive RFID tags are placed and their location along with other relevant information are stored as pairs in a database. These tags transmit a unique code received by the user's smartphone with the help of an RFID reader. The system calculates the optimal route based on their proposed algorithm (Gerwei-Method) that takes as input the location, the moving direction, and the user profile. Finally, the routing information is issued in real-time to the user via the smartphone's acoustic channels. The paper provides a cost estimation of the system demonstrating its relatively high cost. Among the limitations of the system are the utilization of short-range RFID tags as well as the fact that not all RFID tag readers work equally the same.

The PERCEPT system [21] enhances indoor environment perception at public health facilities such as clinics, hospitals, and wellness centres, using carefully placed passive RFID tags, a customized handheld unit, a smartphone held by the user, and a server that generates and stores information about the building and the available RFID tags. The PERCEPT system directs the user to the destination combining information found at predefined kiosk locations,accessible via a custom-made glove, and points of interest ([POIs] e.g., rooms and elevators). The extension of the above tracking system [22] allows the user to carry only a smartphone and exploit near-field communication (NFC) tags on existing signage and POIs in the environment (e.g., doors, stairs, and elevators). Users receive audio navigation instructions when they touch the NFC tags using their phones. In [23] the authors propose yet another system extension (Percept V) that provides to people with blindness and visually impairments real time spatial perception during navigation in large public spaces. It also enhances the accuracy and functionality of the PERCEPT indoor navigation system by incorporating a sensing framework that utilizes low-power Bluetooth technology. In particular, the latter is leveraged from the smartphone application to find the user's location, estimate the direction of their movement, and theirproximity to existing POIs. Real-life test scenarios of the system show that it can provide sufficient information for the navigation, although its accuracy is not very high. Furthermore, some aspects of the sensing framework are not ready for real-life scenarios.

The authors in [24] present a sophisticated system that accurately tracks the indoor location of an individual through a combination of inertial navigation (INS) techniques with active RFID technology. The integrated INS and RFID methodology results in a typical localization error along the walking path (regardless of its length) of approximately 1.5m. The main limitations of the system concern the low accuracy of the user's actual location as well as the accumulation of location error that remains uncorrected when the user is moving upstairs or downstairs, on a ramp, opening a door, is in an elevator, on a moving escalator or conveyor belt. In [25] the authors propose a system comprised of a mobile application with a server that utilizes BLE beacons and a framework based on augmented reality (AR) to provide wayfinding instructions in a storytelling format emulating the behaviour of a sighted person escorting them. Besides having highly precise positioning and navigational capabilities enabling traverse of cluttered indoor environments, it also enables the user to find door handles, Braille signs, or elevator buttons. Furthermore, the proposed solution utilizes environmental annotations that greatly help the user to have a better grasp of the current environment's static characteristics. The user interfaces with the application via either touch or voice input. It also provides a customized experience by varying the level of impact. One limitation of the system is that it remains an experimental attempt and is not yet a fully functional product.

### 10.2.3 Magnetic systems

The authors in [26] describe the development and evaluation of a navigation system leveraging magnetic fields information. It consists of a wireless magnetometer mounted on the users' hip and a smartphone that algorithmically processes the received stream of magnetic readings. Human trials were conducted to evaluate the effectiveness of the system by studying the performance of providing real-time guidance to blind and visually impaired people while executing several route scenarios. However, it is well established that environments with steel frame structures are the cause of significant magnetic distortions. Many of these distortions have sufficient intensity and spatial characteristics and are persistent, thus limiting the possibility of adopting this type of technology as the basis for positioning technology.

In [27] they collected an extensive dataset of 2000 data points using a mobile phone device with an embedded magnetometer. Leveraging these magnetic fields, they can signify POIs and provide guidelines, distinguish rooms and corridors, and be used as a reference for generating magnetic maps of floors. Despite the successful demonstration of the solution's effectiveness, the proposed system has poor results in tracking turns when the compass heading is fluctuating, its measurement process needs to better address human error, and finally, the robustness and performance of the selected classification techniques need to be improved for the cases of rooms and corridors.

### 10.2.4 Three-dimensional sensor and AR systems

In [28] the author presents a system that detects changes in a three-dimensional (3D) space based on a combination of range data and image data obtained from cameras, creating a 3D representation of the surrounding space. The latter and the detection of dynamic changes in the space are mapped onto a two-dimensional (2D) vibration array mounted on the chest of the blind user. The degree of vibration aids the user’s perception of the 3D space and its changes.

[29] introduces a new approach to using building floor plans to create semantic maps. Room numbers, doors, and the like serve as points of reference to infer the waypoints in each room. This article demonstrates the potential of AR as an interface for blind users to perceive the physical constraints of the real world. The proposed solution uses haptic and vocal feedback to emit critical information. The haptic belt vibrates as the user moves towards the travel destination based on positioning metrics. In addition, voice guidance instructions about the travel route are issued to the user by accurately estimating the user’s location and confirming it by extracting POIs. The results show that it is feasible to safely and independently navigate a blind user by informing about the environmental constraints through AR. The system’s main limitation, however, is that it fails to provide increased safety in real-world situations.

In [30] the authors present a novel RGBD (Red, Green, Blue, and Depth) camera-based wearable navigation system. It consists of a smartphone, a glass-mounted RGBD camera device, a real-time navigation algorithm, and a haptic feedback system. To extract the orientation information, the navigation algorithm performs in real-time six-degree-of-freedom (6-DOF) feature-based optical odometry from the input of the RGBD camera. The navigation algorithm also generates a 3D voxel map of the environment and analyses its traversability, while the path planner generates a safe and efficient path to a reference point. The haptic feedback system, consisting of four microvibration motors, is designed to guide the visually impaired user along the computed path and minimize the cognitive load. The main limitations of the proposed system include occasional inaccurate visual odometry results caused by rapid head rotations as well as accumulated errors upon revisiting the same place repeatedly. Finally, the system has not been tested with real blind users.

In [31] proposes an ego-motion tracking method that uses visual–inertial Google Glass sensors for wearable blind navigation. The authors introduce a visual sanity check that compares the visually estimated rotation with the rotation measurement from a gyroscope. The motion trajectory is generated by adaptively fusing the visual estimations and inertial measurements. The use of a multiple extended Kalman filter as the method of fusion solves the problem of the frame rate difference between visual and inertial sensors. The proposed solution was tested in different indoor environments according to the authors, demonstrating its effectiveness and accuracy. Nonetheless, the proposed system still needs to address robustness issues as well as its real-time performance.

The authors in [32] present an embedded navigation system that is used as an audio aid for individuals who are blind or visually impaired based on visual marker recognition and ultrasonic obstacle perception. The visual markers correspond to POIs in the user’s environment. These points are depicted on a map that indicates the distance and direction between the various points of approach, thus creating a virtual path. The proposed system is based on wearable glasses equipped with sensors including an RGB camera, magnetometer, ultrasound, gyroscope, and accelerometer sensors to greatly improve the amount and quality of the information. The user can freely navigate the environment via the identification of location markers. The calculation of the path to the next marker uses either the origin point or the location point information along with the value returned by the gyroscope sensor. The users interact with the system via audio utilizing simple known instructions to indicate with accuracy the desired route and obstacles in it. The experimental results demonstrate rates of about 94.92% successful marker recognition using only 26 frames/s and 98.33% of ultrasonic obstacles perception at a distance between 0.50 and 4.0 m. The system’s main weaknesses concern quality limitations in indoor navigation as well as reduced confidence in the presence of low-light conditions.

The Horizon 2020 Sound of Vision project [33] is implementing a non-invasive hardware and software system that creates and conveys to a blind person an acoustic representation of the environment (indoor/outdoor), continuously, and in real-time, without requiring tags/sensors located in the environment. The main objective of the project is to design and implement optimal algorithms for creating 3D environment models and for rendering these using spatial audio signals. In [34], the 3D acquisition module is enhanced to support both indoor and outdoor spaces in various illuminating conditions by employing data fusion from multiple sensors. Specifically, it fuses data from a stereo RGB camera, a structured light sensor, and an inertial measurement unit (IMU) device to deliver consistent data to image processing algorithms in non-typical conditions to normal CMOS sensors. The system is implemented as a wearable device mounted on the user’s head. Preliminary experimentation, carried out in modelled indoor environments, demonstrated its feasibility as blind and visually impaired volunteers were able to perform simple navigation tasks and avoid cardboard box obstacles. Among the weaknesses of the system are the lack of thorough experimentation and the weight aspect of the wearable device as after prolonged use the headgear can cause a feeling of discomfort and fatigue.

[35] is another sophisticated navigation system with displays that allow a user to easily launch and deploy indoor navigation services on a smartphone, without requiring either a full indoor tracking system or available floor maps. Travi-Navi captures highquality images during a guider’s walk on navigation routes, collects a rich set of sensor readings, and groups them into a navigation trace. The followers track the navigation trace and receive instant visual instructions and image tips as well as alerts when they deviate from the correct route. Travi-Navi also finds shortcuts whenever possible. The evaluation results demonstrate the capabilities of the system to track and navigate users with timely instructions, typically detecting deviation events. The authors provide the battery consumption of the application on three different devices averaging a capacity of 2150 mA that achieve on average a runtime of 3.6 hr in Guider Mode and 4.29 hr in Follower Mode. Among the weaknesses of the system are the increased number of steps required to detect deviation events as well as the rather high-power consumption.

[36] presents an indoor navigation system that utilizes a smartphone device, mounted on the user’s body, and exploits the capabilities of Google ARCore to acquire robust computer visionbased localization without requiring Global Positioning System (GPS) and wireless beacons. It also utilizes an adaptive artificial potential field-based path planning component to help guide users away from obstacles. The system, besides the smartphone device, consists of headphones and gloves with haptic sensors that provide a two-channel human–machine interaction mechanism for continuous guidance. Specifically, the haptic interface creates situational awareness while the audio interface helps to avoid obstacles. Compared with conventional visual odometry systems, the system achieves better mapping and positioning. Among the limitations of the system is the fact that it requires users to wear custom-made equipment covering a large portion of their bodies.

### 10.2.5 Map matching

The authors in [37] use another approach to develop indoor navigation systems for people that are blind and visually impaired by modelling building information. It provides rich semantic information about all building elements, objects, and users located in the building and allows information about the topology of a specific part of the building to be extracted. This information is subsequently used by an algorithm to improve route finding accuracy. The proposed system can help to solve the existing problems in the field of indoor navigation for people that are blind and visually impaired.

### 10.2.6 Wi-Fi multimodal system

In [38] the authors present an indoor navigation assistance system that combines visual information and Wi-Fi to detect and locate people on the move. This combination offers some advantages over single-technology systems, such as installation cost, computational time, and accuracy. The interface of the application with users is via voice synthesis and recognition. Experimental results demonstrate the suitability of the proposed technologies for navigation assistance. However, so far, the accuracy of the localization solution (1.71 m with 90% reliability) is insufficient for real applications and the supported language is limited to Vietnamese.

### 10.2.7 Dead-reckoning systems

The authors in [39] describe the construction and evaluation of an inertial dead reckoning navigation system providing real-time acoustic guidance along mapped routes. It uses information from the mapped route to reduce the accumulation of errors inherent in traditional dead reckoning approaches. The prototype system consists of a wireless inertial sensor module mounted on the users' hip, which transmits readings to a smartphone executing a navigation algorithm. Experimental tests were conducted with the aid of test subjects to evaluate the effectiveness of the system by studying the performance following British Virgin Islands (BVI) routes while using the real-time guided navigation system. The main weakness of the system is the requirement to place the module on the user's hip.

The proposed system in [40] is based on an inertial measurement unit requiring no infrastructural support. The navigation algorithm consists of two parts that include, on one hand, the positioning process and, on the other hand, the orientation process. The positioning process is concerned with estimating the current location based on multiple inertial inputs while the orientation process generates ideal paths from the current position to the destination. In this article, the kinematic characteristics of walking are investigated to develop a step frequency detection algorithm and a step length estimation method. In addition, an efficient position correction algorithm is proposed to improve tracking accuracy. The experimentation demonstrates the accuracy of positioning to be on average off a few centimetres from the actual position.

## 10.3 System design

### 10.3.1 System architecture

The proposed system aims at enabling individuals with blindness and visual impairments to accurately and safely navigate in indoor spaces. Its basis lies in the combination of a newly proposed pedestrian dead reckoning (PDR) algorithm with surface tactile ground indicator guides, the gyroscope sensor found on smartphone devices, and last but not least, BLE technology radio beacons that are used to correct the accumulated error of the PDR method. The first version of the developed application, called BlindMuseumTourer, revolves around the provision of navigational capabilities inside the spaces of the Tactual Museum of Athens organized into thematic tours that correspond to the available exhibition rooms. The proposed PDR algorithm accurately computes the user's position and the travelled distance minimizing the associated error. The application provides its capabilities to users via a voice-command-based interface that is configurable to their preferences. In case of an emergency, it can guide the users to dedicated places inside the museum as well as provide the functionality to make emergency calls either to family members or public services. Finally, a part of the system is a companion web application specifically targeted at the employees of the museum that allows the creation and modification of the internal spaces mappings required by the application.

Figure 10.1 depicts the architecture of the application at a high level. The implementation follows the model-view-controller (MVC) architectural design pattern. Specifically, the model manages the logic, the data, and the rules of the application; the View component provides the user interface; while the Controller component accepts input and converts it to commands for either the model or the view component.

Following that, Figure 10.2 presents the subsystems comprising the BlindMuseumTourer Android application. As it can be seen, the functionality is decomposed into a motion, a location, and a navigation subsystem as well as an Android BLE beacon library that in the future will be used to receive BLE beacon readings and fuse that input into the application's algorithm as well.

## 10.3.2 PDR

The core of this application is centred around an innovative PDR algorithm that leverages the three-axes acceleration sensor of smartphone devices and, furthermore, embeds into its model the particularities and special characteristics of the user's gait. The latter is achieved by requesting users to perform a trial walk on a special surface tactile ground indicator guide at a predefined location before starting a touring experience. The PDR model iteratively calculates the new position of the user in the space having as a point of reference the previously mentioned initial starting location. As with every PDR method, it consists of three operations: step detection, walking distance estimation, and heading estimation. Compared with the state of the art, the proposed PDR solution achieves a more accurate walking distance estimation even at speeds lower than 0.5 m/s, it works in real-time since it has a very small processing delay, has a low computational cost, and has linear complexity in the number of time intervals. The technical details of the proposed PDR algorithm are beyond the scope of this article and will be presented in the near future.

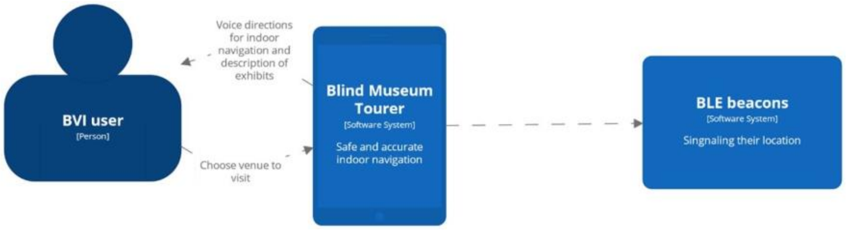


*Figure 10.1 Architectural diagram of the application*

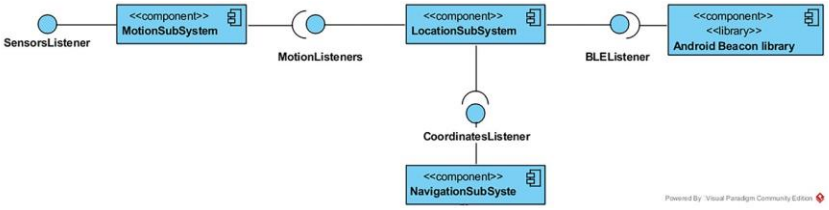


*Figure10.2 UML diagrams of subsystems*

### 10.3.3 BlindMuseumTourer’s User Interface

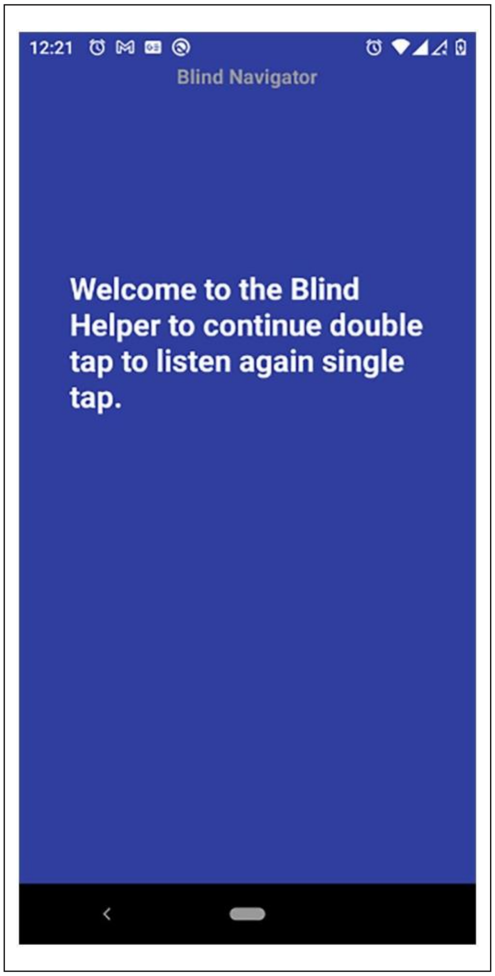
In addition to the voice-command-based interface, the application provides a graphical user interface (GUI) to address the needs of people that do not suffer from complete blindness but still face moderate to severe visual impairments. To support the range of possible users, the application’s windows are compliant with the available screen readers.

Upon opening the application, users are welcomed by the screen shown in Figure 10.3, informing them, via voice instructions, about the existence of two possibilities. Either tap twice on the screen to continue to the next window or tap once to replay again the current message. When users continue, a screen presenting the available thematic routes from which to choose is shown in Figure 10.4.

Next, users are required to take a mandatory trial walk the output of which is shown in Figure 10.5. Finally, while navigating the exhibition rooms, the application provides a graphical representation of the exhibit’s configuration along with the path of the user (Figure 10.6).

### 10.3.4 Map administration subsystem

Crucial to the success of BlindMuseumTourer is the provision of correct and accurate mappings of indoor spaces. For this reason, alongside the main application, there exists a companion tool provided in the form of a web application that allows the museum’s staff to either add or remove:



Welcome to the Blind Helper to continue double tap to listen again single tap.

*Figure 10.3 Welcoming screen*

- Information about spaces and, in particular, the associated name and coordinates of various POIs such as helpdesks, exits, facilities, and the like as well as sizing information including length and width.
- Entrance and exit points that include doors and hallways along with related information such as coordinates, their length, and the like.
- Information about POIs such as brief descriptions, dimensions, length, height, and location coordinates among others. Typically, these include museum exhibits, helpdesks, facilities, and the like.

Finally, Figure 10.7 presents a sample UI page of the web administration tool concerning the insertion of a new surface tactile ground indicator guide.

*Figure 10.4. Main screen consisting of three windows: (a) emergency call (top part in red), (b) routes selection (middle part in white), and (c) exit (bottom part blue).*

## 10.4 Usability and UX evaluation

This article's main goal is to assess the proposed application's Usability and UX and subsequently validate, in those terms, the system design. This is a significant but often neglected aspect of a system as an improved UX combined with a low learning curve, besides decreasing the error rate, can make the application more appealing to the user and, thus, increase the, especially low for this type of applications, adoption rate among the individuals that are blind and visually impaired [42, 43]. Previous research has shown a variety of factors responsible for assistive technology (AT) adoption, the subsequent low rate of adoption and technology acceptance and, finally, abandonment [43]. Such factors include a lack of consideration for user opinion, ease of device procurement, poor device performance, adaptability to new requirements or priorities, errors such as misrecognized building features, wrong representation of the exhibits' configuration and other POIs, as well as the social/environmental setting [44]. The process of evaluating usability and UX will provide the opportunity to better understand these issues and, subsequently, lead to more effective heuristic solutions, thus decreasing the negative impact of the technical difficulties or even impossibilities that plague current assistive technologies for indoor navigation.

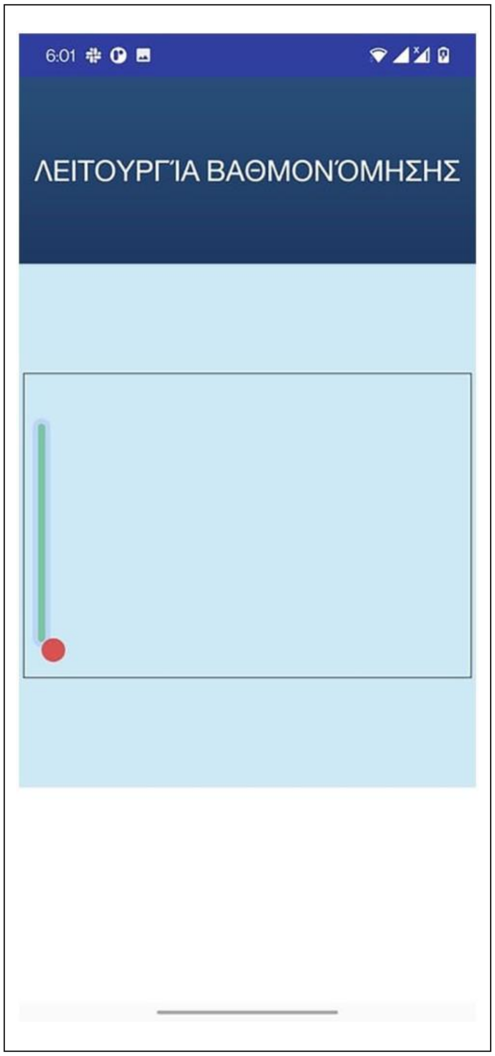


*Figure 10.5 Calibration window depicting the mandatory trial walk.*

## 10.4.1 Methodology

The literature review revealed various available methods to conduct the assessment. The most prominent methodology comes from the ISO/IEC 25010:2011 [45] standard that defines usability as ‘the degree to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use’. In particular, the three components measure the following:

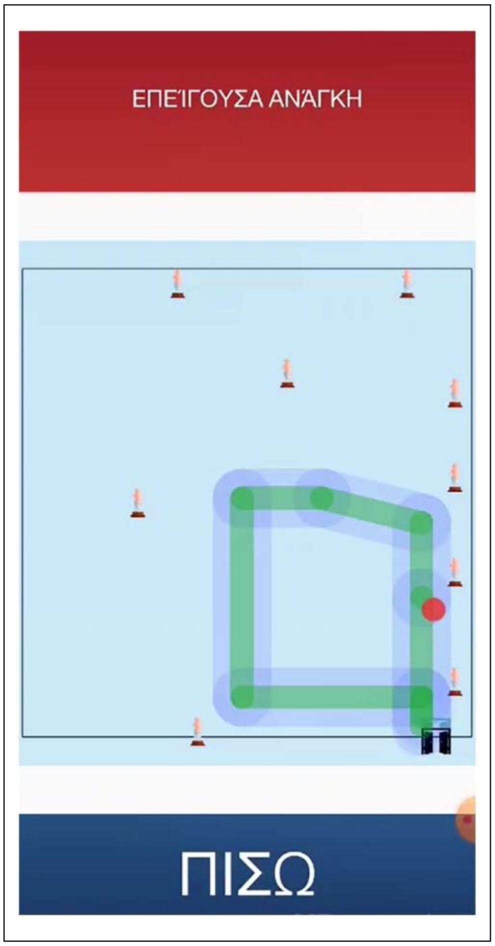
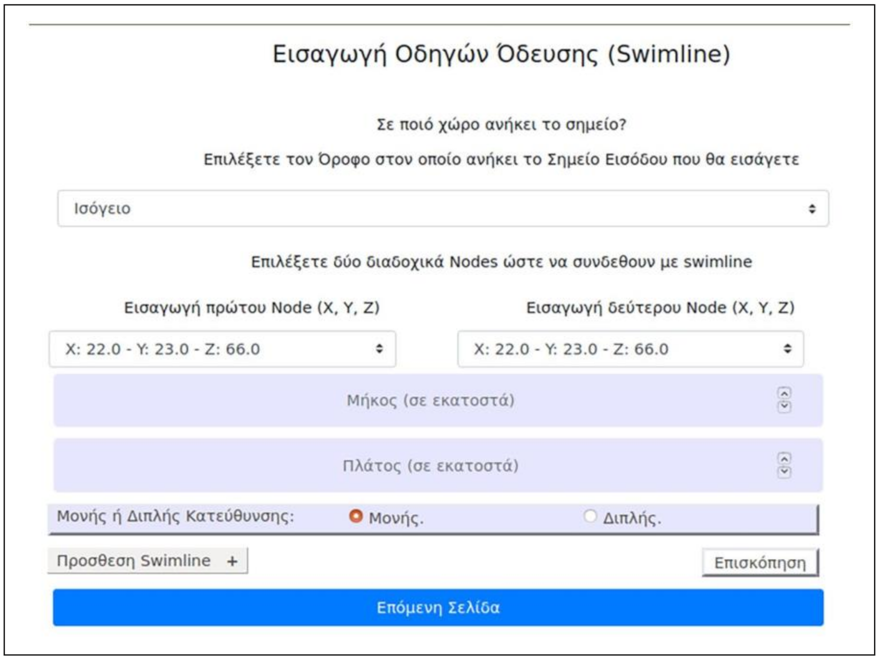


*Figure 10.6. Exhibits location and user path while navigating an exhibition room.*

1. Effectiveness – measures the degree to which users can complete a task;
2. Efficiency – measures the time it takes users to complete a task;
3. Satisfaction – measures subjectively the quality of interaction with the application.

On the contrary, UX is a term that is broadly used by many researchers and practitioners to include different concepts [46] quite often overlapping with the concept of usability. The range of dynamic concepts associated with UX include affective, emotional (see e.g, [47], [48]), hedonic (see e.g., [49], [50]), experiential (see, for example [51], [46]), and aesthetic dimensions (see, for example [52]). According to the ISO 9241-210:2019 [53] standard, UX includes users’ emotions, beliefs, physical, and psychological responses, and it is also the result of brand image, presentation, system performance, the user’s internal and physical state resulting



Εισαγωγή Οδηγών Όδευσης (Swimline)

Σε ποιό χώρο ανήκει το σημείο?

Επιλέξετε τον Όροφο στον οποίο ανήκει το Σημείο Εισόδου που θα εισάγετε

Ισόγειο

Επιλέξετε δύο διαδοχικά Nodes ώστε να συνδεθουν με swimline

Εισαγωγή πρώτου Node (X, Y, Z): X: 22.0 - Y: 23.0 - Z: 66.0

Εισαγωγή δεύτερου Node (X, Y, Z): X: 22.0 - Y: 23.0 - Z: 66.0

Μήκος (σε εκατοστά)

Πλάτος (σε εκατοστά)

Μονής ή Διπλής Κατεύθυνσης: ● Μονής. ○ Διπλής.

***Figure 10.7. Web administration tool inserting surface tactile ground indicator guides – fields: floor selection, inserting coordinates of two points (nodes) that will be connected via swimline – inserting width and length, selecting directionality one-way or two-way.***

from prior experiences, attitudes, skills, and personality, among others. These characteristics of UX and the ones described in a more detailed fashion in [54] justify the selection of this measure for assessing the component of satisfaction as described in the definition of usability in ISO/IEC 25010:2011 [45]. Thus, in our view, UX is a part of usability.

The assessment of both usability and UX following the above-described methodology took place at the Tactual Museum of the Lighthouse for the Blind of Greece, located in Kallithea, where 30 blind and visually impaired users navigated around the premises with the help of the BlindMuseumTourer application. Prior to starting each user evaluation, the team responsible for conducting those tests gave, in the context of special training sessions, accurate and clear instructions to the blind users regarding the use of both the application's features and the tactile ground surface indicators located near the museum entrance. The guides, besides signaling the start of the tour, are also used for calibrating the application's pedometer model to match the user's characteristics. The users had to complete two test scenarios each broken into two parts, the details of which are described in section 'Methodology', to quantitatively measure effectiveness and efficiency.

Satisfaction was measured with two UX questionnaires. The first one, distributed via Google Forms, followed the format of a standardized format the details of which are described in section 'Questionnaire for measuring satisfaction/UX'. The visually impaired users had the opportunity to complete the Google Form questionnaire either with the aid of the personnel at the Lighthouse for the Blind of Greece or at their own time and place. The second questionnaire, which followed a semi-structured interview format, also concerned issues of UX. The details of the semi-structured questionnaires are described in [54]. On average, the first questionnaire required 20 min while the semi-structured interviews required 30 min.

The exhibition rooms had no tactile ground surface indicators installed as the museum staff expressed concerns about the required interventions that could negatively affect, on one hand, the accessibility of people with mobility disabilities and, on the other hand, the maintainability of the spaces. Also, BLE beacons were not mounted on the exhibits as, after some preliminary testing, it was found that the characteristics of the museum's spaces nullified any gains made with the help of readings from those. This was due to the small dimensions of the rooms as (1) the received power readings from the radio beacons were affected by reflection-generated noise and (2) the linear motion mechanisms of our proposed algorithm when combined with input from the gyroscope sensor gave excellent results. The latter was possible due to the users being aligned to the correct route path at the beginning of the museum tour with the aid of the initial tactile ground surface indicators, and due to the application's features that prevent the user from veering.

## 10.4.2 Metrics for effectiveness and efficiency

A literature review on finding statistical metrics for measuring effectiveness revealed that among the most common ones include the following: Completion rate, Errors, and Error rate [55]. Their simplicity makes them appealing and, thus they are widely used in many studies. Completion rate counts the successfully completed tasks and it is either a pure number or a percentage while Errors count the errors made by a user, as its name suggests. Error rate reports the number of errors per user. Common causes of errors include, among others, mental errors, for example, when a user cannot comprehend a system option, and undesired results as a consequence of either poor interaction with the system's interface or limitations of the provided information resolution.

For the evaluation of completion rate, error and error rate, the research team defined the following test scenarios for the users to perform:

- Completion of thematic routes – users have to complete two thematic routes one of which is known to them, while the other unknown and have no prior knowledge of it. The known case involved the exhibition room of Hermes where the application's capabilities were first showcased to the users. Its location on the ground floor and the small size made it a good fit for conducting special training sessions facilitated by a customized training version of the BlindMuseumTourer. In contrast, the Poseidon exhibition room was the choice for the unknown case.
- Assessing guidance to special POIs – users are requested to stop the thematic route and use the application to guide them to POIs. For the evaluation, the users had to guide themselves to the helpdesk and the toilet facilities (WC).

In total four tasks were evaluated, two for each case. For each of the above test scenarios the successful completion and error conditions were defined as follows:

(a) Completion: successfully completing the goal of the task at hand. For the first test scenario, the users must complete the thematic route in its entirety, while for the second the users must find the requested POIs.

(b) Error: in either case, if the user gives up the attempt or asks for help from the research team counts as an error.

Finally, following the task definition is the mathematical formulation of these metrics. The equation used for the completion rate is calculated as follows

$$Effectiveness = \frac{total\ \#\ of\ tasks\ successfully\ completed}{total\ \#\ of\ tasks\ undertaken} = \frac{\sum_{l=1}^{U}\sum_{i=1}^{M} task_{li}}{U * M} \quad (1)$$

where $U = \#\ of\ participants$, $M = of\ tasks\ per\ participant$, and $task_{li} = i - th\ task\ of\ the\ l - th\ user$.

Furthermore, $task_{li}$ takes the value 1 if the task is successfully completed and 0 otherwise.

Efficiency is closely related to effectiveness as it considers the time (in seconds and/or minutes) involved in successfully completing a task. A common way to measure effectiveness is with the help of the following formula

$$Efficiency = \frac{\sum_{j=1}^{U}\sum_{i=1}^{M} tasks_{ij} t_{ij}}{\sum_{j=1}^{U}\sum_{i=1}^{M} t_{ij}} \times 100\% \quad (2)$$

where $t_{ij} = EndTime_{ij} - StartTime_{ij}$, which in turn, $EndTime_{ij}$ is defined as the time required for the $i - th$ $task\ of\ the\ j - th\ user$ to be completed successfully or the time until the user quits.

Errors will be measured as simply the sum of each participant's total number of errors

$$Error = \sum_{i=1}^{N} e_i \quad (3)$$

where $N$ = the total number of participants, while the error rate is calculated by the following equation

$$Error\ rate = \frac{Error}{P} \quad (4)$$

where $Error = \#\ of\ total\ errors$ and $P = \#\ of\ total\ participants$

Last but not least, an added benefit of the above metrics is their deployment flexibility as their required input can be collected, besides the final stage of evaluation, during early stages of the development cycle as well to receive quick feedback.

### 10.4.3 Questionnaire for measuring satisfaction/UX.

The main methodology followed for the study of Satisfaction predominantly consists of questionnaires. According to [56], AttrakDiff, UEQ, and meCUE are the three most commonly used standardized questionnaires for UX evaluation. The number of questions, the scales they employ, along with the theoretical models on which they are based, are listed in [57]. Out of the three, the authors note that AttrakDiff is the most popular option since it was first introduced in 2003, while UEQ surpassed it in 2017 and 2018. On the contrary, meCUE being a relative newcomer has a substantially smaller usage rate. Frequently, these approaches are supplemented with other methods where over 60% of the cases utilized between one and five additional methods [56].

Hedonistic and pragmatic aspects of UX are found in AttrakDiff [58], meCUE [59] and UEQ+. To the best of our knowledge, there are no questionnaires available that evaluate the UX of blind and visually impaired individuals. In addition, one of the most common limitations of the existing questionnaires is the absence of customization for the features they assess. To alleviate that, the UX questionnaire framework UEQ+ was selected.

This framework adds modularity to the original UEQ assessment tool. Its suitability and effectiveness have been demonstrated by evaluating new technologies regardless of sex, age, level of education, and level of technological knowledge [60], [61]. Also, the ready-to-be-used tools for processing quantitative data add to the appeal of the tool. Specifically, the UEQ+ [62] is a set of scales that the authors can selectively combine to form a concrete UX questionnaire that better matches the features of the application under evaluation. Each scale is decomposed into five items, four of which contribute to the score of the scale and a single item that measures the relevance or importance of the scale itself. The items are measured on a seven-point Likert-type psychometric scale and the rating of the latter is configured to quantify opposing pairs of the application's features. According to the evaluation instructions, users always choose to rank the scale according to their preference, even when they are unsure about their evaluation or even when they think that the scale is not appropriate for the product. Last but not least, users rate the importance of each scale according to their view, aggregating them into a score that represents the overall impression of the product.

From our point of view, the following scales best assess the UX of the individuals who are blind and visually impaired utilizing our application:

- Efficiency: this scale measures the users' subjective impression of the effort required to achieve the desired goals as well as the application's responsiveness to their actions.
- Perspicuity: this scale measures the degree to which the users find the application's functionality familiar and easy to learn.
- Dependability: This scale measures the subjective impression of whether the user is in control of the application in terms of the predictability and consistency of the systems' issued instructions and actions.
- Personalization: this scale measures how well the application adapts to the personal preferences of the user along with how promptly this process is completed.
- Usefulness: this scale measures the users' perception on achieving goals, the amount of time saved and the resulting efficiency.
- Trustworthiness of content: this scale measures the quality and reliability of the instructions' content.
- Response behaviour: this scale measures the friendliness of the voice assistant [61].

Analogous to the scope of the above framework, we have designed a seven-point Likert-type scale questionnaire. The format of semi-structured interviews was preferred as it is flexible and ensures that the views of the blind and visually impaired are highlighted, despite the decreased amenability to statistical analysis.

Finally, a goal of paramount importance was for the participants to remain unbiased to the interviewers' expectations. For a more elaborate description of the format and the benefits of the semistructured questionnaires, readers can refer to [54].

## 10.4.4 Usability and UX results

In this section, we present the results and conclusions drawn from the participation of 30 blind users during the evaluation process that assessed the completion of the above-mentioned tasks as well as gathered input from the questionnaires to quantify in a subjective time the perceived UX. We acknowledge that the number of participants is not representative enough and does not help to draw strong results; however, they can be used to understand the applications in this pilot stage.

Finally, these results were also examined in the context of the information gathered during free interviews using a second questionnaire in an attempt to better understand the UX evaluation score.

### 10.4.4.1 Effectiveness

Table 10.1 presents the number of successfully completed tasks per user for each test scenario. Equation (1) from section 'Metrics for effectiveness and efficiency' takes as input the number of successfully completed tasks and the total number of tasks undertaken [55]. The latter consists of those tasks for which the result of execution was either a success or a failure, while the former is the sum of each individual's successfully completed tasks, as shown in Table 10.1. Finally, by utilizing the table data, we calculate effectiveness as follows:

*Total # of tasks completed successfully = # of tasks 'Completion of a thematic route' + # of tasks 'Navigation to POIs' = 45 + 49 = 94*

*Total # of tasks undertaken = #number of tasks per user × #of participants = 4 × 30 = 120*

Hence

$$Effectiveness = \frac{94}{120} * 100\% = 78.33\%$$

The complementary metric of completion rate, failure rate, is calculated as follows *total # of*

$$Failure\ rate = \frac{total\ \#\ of\ failed\ tasks}{total\ \#\ of\ tasks}$$

where the numerator total # of failed tasks is calculated as the difference between the total # of tasks undertaken – the total # of tasks completed successfully. Therefore, failure rate = (26/120) × 100% = 21.67%.

### 10.4.4.2 Efficiency

In particular, the efficiency measured by utilizing equation (2) takes into consideration both the tasks of successfully completing the thematic routes and those of assessing the navigation of the user to the selected POIs (see Section 'Metrics for effectiveness and efficiency' for more details). The first thematic route, known to the user, was completed at an average time of 18 min with an $SD$ of 2.1 min while the second route, this time unknown to the user, had an average of 58 min with an $SD$ of 5.4 min. For the second task, the attempt to navigate the user to the helpdesk took an average of 8 min with an $SD$ of 2.1 min while for the case of navigation to the WC facilities, it was completed in 10 min with an $SD$ of 2.2 min. Taking into consideration equation (2) and the above data (Table 10.1), we measured the efficiency to be 67.3%

$$Efficiency = \frac{\sum_{j=1}^{U}\sum_{i=1}^{M} tasks_{ij} t_{ij}}{\sum_{j=1}^{U}\sum_{i=1}^{M} t_{ij}} \times 100\%$$

#### 10.4.4.3 Errors and error rate

Besides recording information about the completion of the thematic routes, the research team also recorded data regarding the errors committed by the users. They were classified into two types: recoverable and unrecoverable. The former considers errors where the users, despite making them, managed to successfully complete the assigned task, while the latter, considers errors where users could not address the challenge and decided either to quit their attempt or could not complete the task without the help of the research team, thus characterizing this attempt as a failure. During the evaluation, the research team identified the following errors:

Table 10.1 Completion rate.

| Participant | Completion of the thematic routes | Navigation to POIs |
|---|---|---|
| P1 | 2 | 2 |
| P2 | 2 | 1 |
| P3 | 1 | 2 |
| P4 | 2 | 1 |
| P5 | 1 | 2 |
| P6 | 2 | 2 |
| P7 | 2 | 1 |
| P8 | 2 | 2 |
| P9 | 1 | 1 |
| P10 | 1 | 2 |
| P11 | 1 | 1 |
| P12 | 2 | 2 |
| P13 | 1 | 2 |
| P14 | 1 | 2 |
| P15 | 2 | 2 |
| P16 | 1 | 0 |
| P17 | 2 | 1 |
| P18 | 1 | 2 |
| P19 | 2 | 2 |
| P20 | 2 | 1 |
| P21 | 1 | 2 |
| P22 | 1 | 1 |
| P23 | 2 | 2 |
| P24 | 2 | 2 |
| P25 | 1 | 2 |
| P26 | 1 | 1 |
| P27 | 2 | 2 |
| P28 | 1 | 2 |
| P29 | 1 | 2 |
| P30 | 2 | 2 |

POIs: points of interest.

- Collision with the museum exhibits: counts the occasions of users colliding with an exhibit of the museum;
- Veering: counts the occasions of users deviating from the designated path and veering off to one side or the other;
- Over-turn: counts the occasions of users turning more or less, thus, creating a wrong angle with the correct navigational path;
- Issued instructions: counts the occasions of users feeling confused about the issued instructions.

Table 10.2 presents the number of navigation errors made during the execution of the indoor navigation tasks described in section 'Metrics for effectiveness and efficiency' and after the training sessions

***Table 10.2 Errors***

| Participant | Collision with exhibits | Veering | Over-turn | Issued instructions | Assisted | Assisted II |
|---|---|---|---|---|---|---|
| P1 | 2 | 2 | 4 | 2 | 0 | 0 |
| P2 | 1 | 3 | 7 | 3 | 0 | 1 |
| P3 | 3 | 0 | 6 | 2 | 1 | 0 |
| P4 | 2 | 3 | 5 | 2 | 0 | 1 |
| P5 | 5 | 4 | 5 | 3 | 1 | 0 |
| P6 | 4 | 2 | 8 | 2 | 0 | 0 |
| P7 | 4 | 3 | 4 | 3 | 0 | 1 |
| P8 | 3 | 5 | 5 | 2 | 0 | 0 |
| P9 | 5 | 2 | 6 | 2 | 1 | 1 |
| P10 | 4 | 5 | 5 | 1 | 1 | 0 |
| P11 | 6 | 4 | 6 | 3 | 1 | 1 |
| P12 | 4 | 5 | 4 | 2 | 0 | 0 |
| P13 | 5 | 3 | 5 | 2 | 1 | 0 |
| P14 | 3 | 2 | 6 | 1 | 1 | 0 |
| P15 | 6 | 5 | 3 | 3 | 0 | 0 |
| P16 | 4 | 3 | 2 | 2 | 1 | 2 |
| P17 | 6 | 4 | 2 | 1 | 0 | 1 |
| P18 | 4 | 4 | 6 | 1 | 1 | 0 |
| P19 | 5 | 2 | 5 | 2 | 0 | 0 |
| P20 | 3 | 3 | 6 | 3 | 0 | 1 |
| P21 | 3 | 3 | 6 | 2 | 1 | 0 |
| P22 | 2 | 3 | 7 | 3 | 1 | 1 |
| P23 | 2 | 2 | 7 | 2 | 0 | 0 |
| P24 | 6 | 1 | 6 | 3 | 0 | 0 |
| P25 | 5 | 1 | 5 | 3 | 1 | 0 |
| P26 | 3 | 0 | 4 | 2 | 1 | 1 |
| P27 | 4 | 2 | 6 | 3 | 0 | 0 |
| P28 | 2 | 0 | 7 | 4 | 1 | 0 |
| P29 | 2 | 2 | 5 | 2 | 1 | 0 |
| P30 | 2 | 1 | 7 | 1 | 0 | 0 |

were completed. The ‘Assisted’ and ‘Assisted II’ columns contain the number of unrecoverable errors where users failed to successfully complete the first and second task, respectively, according to the criteria described above. The tasks with these kinds of errors are not considered when calculating the completion rate metric. In contrast, the rest of the columns report the recoverable errors, thus contributing to the calculation of the completion rate metric.

In total, we identified 416 errors where the users recovered on their own, while 15 and 11 of them required external assistance corresponding to the first and second task, respectively. The most commonly occurring error (160 out of 416) concerned the case where the users rotated more or less than required, thus creating a wrong angle with the correct navigational path. This is the most demanding action blind users have to perform since it greatly depends on spatial awareness, a skill that not all of them possess, especially the ones who were born that way. To address this issue, the application monitors the rotation of the user informing about when to stop or in the case of an error made by the user to restart the action.

The second most-often occurring error (110 out of 166) concerned minor collisions with the exhibits. This mainly concerned cases of statues where an arm or a leg was extended outwards. For those cases, the application specifically informs the users to be extra cautious. The rest of the cases concerned either the case of veering off the navigational path or clarifications regarding an instruction. Finally, the overall error rate (equation 4) was measured to be 416/30 = 13.8 recoverable errors per user on average.

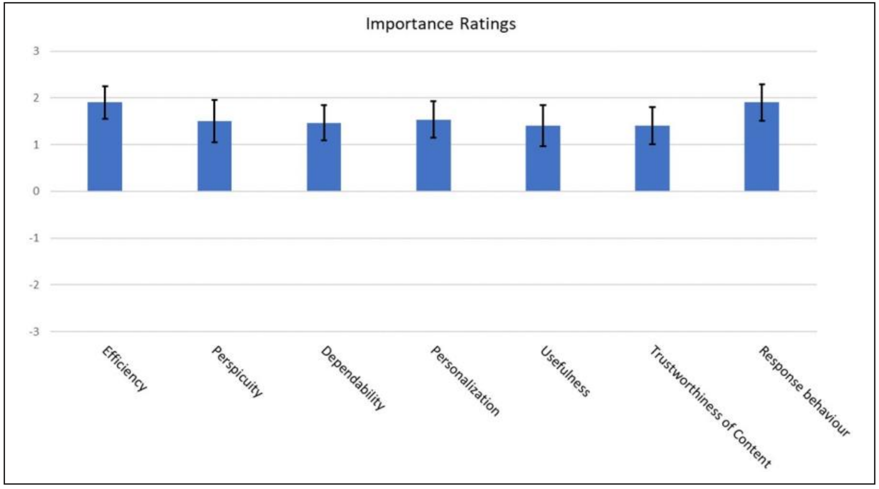


***Figure 10.8*** Mean value per scale.

Table 10.3 Mean value, standard deviation, confidence, and confidence intervals of the selected scales. The possible values range between −3 and 3.

| Category | *M* | *SD* | Confidence | Confidence interval | |
|---|---|---|---|---|---|
| Efficiency | 1.58 | 1.15 | 0.45 | 1.13 | 2.03 |
| Perspicuity | 1.45 | 0.98 | 0.39 | 1.06 | 1.84 |
| Dependability | 1.51 | 0.99 | 0.39 | 1.12 | 1.90 |
| Personalization | −0.01 | 0.79 | 0.31 | −0.32 | 0.30 |
| Usefulness | 1.59 | 1.01 | 0.40 | 1.19 | 1.99 |
| Trustworthiness of content | 1.48 | 0.69 | 0.27 | 1.21 | 1.75 |
| Response behaviour | −0.15 | 0.78 | 0.31 | −0.46 | 0.16 |

### 10.4.4.4 UEQ+ questionnaire results

This section presents the statistical findings based on the data collected via the questionnaires. Namely, these include the mean value and standard deviation for every scale, the consistency results and the importance ratings for the selected scales, the distribution of answers, as well as a key performance indicator (KPI) to assess the overall UX impression.

### 10.4.4.5 Mean and standard deviation by category.

This section reports the mean value, the standard deviation, and the corresponding confidence intervals for every scale as well as for each of the items, in which the scales are decomposed, their mean value. To preserve compatibility with the original version, UEQ + statistical tools rescale the results of mean value and standard deviation back to the range of −3 to 3 from the range of 1 to 7. The scales were chosen after considering the importance ratings given by the users and they are presented in Figure 10.8.

Table 10.3 shows in detail the mean, standard deviation, and 95% confidence interval level.

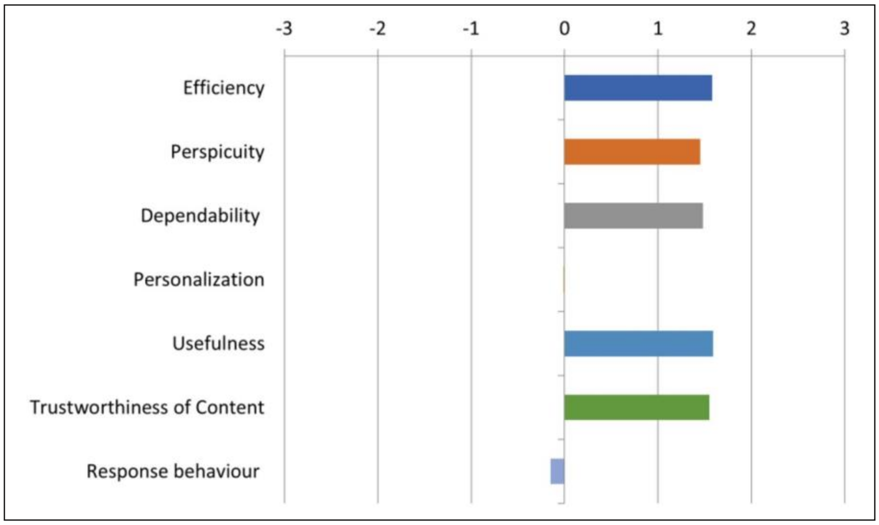


*Figure 10.9. Mean value per scale*

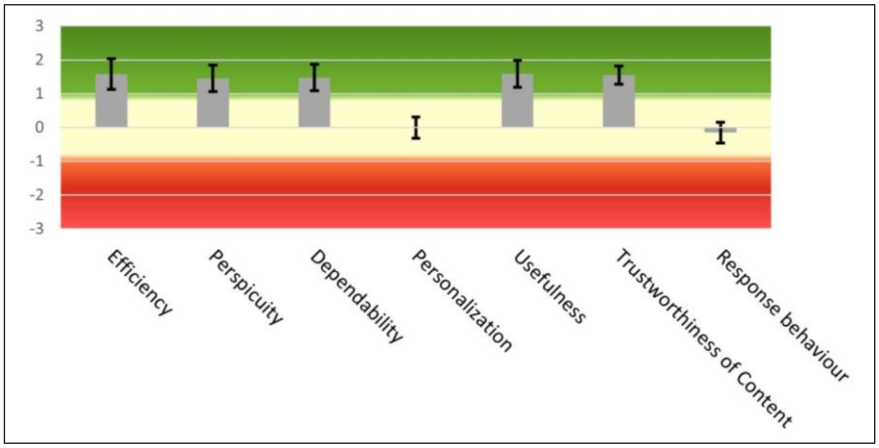


*Figure 10.10. Scale means and standard deviation*

Figures 10.9 and 10.10 depict graphically the data from Table 10.3. The former highlights the mean value while the latter, besides depicting the mean value as well, highlights the standard deviation.

Overall, as it can be seen from the above results, UX has been rated quite positively by all users; however, both the scales of Personalization (−0.01), which measure the ability to adapt to the user's personal preferences and the scale of Response Behaviour (−0.15), which describes the qualitative characteristics of the voice assistant and highlights the opinion of the users for the issued instructions to have somewhat better quality, received average ratings. In contrast, Usefulness (1.59) and Efficiency (1.58) scored the highest among the scales as users found that they can quickly and efficiently complete their navigation in the museum. The scale followed is Dependability (1.51), as users feel they can freely navigate around the premises of the museum since the predictability of the application makes it easier to rely on it. Trustworthiness of Content (1.48) comes next, highlighting a complementary aspect of dependability concerning the quality of information transmitted via the instructions given during the blind navigation, while Perspicuity (1.45) highlights the fact that users are more or less satisfied with the ease with which they familiarize themselves and learn the provided functionality. Nonetheless, progress can still be made in this aspect as well. For the overall evaluation of the UX, the UEQ + tool provides the KPI value whose range is between −3 for the lowest possible evaluation and 3 for the best possible evaluation. Our application receives a score of 1.20, which can be interpreted as a positive evaluation.

To further elaborate the results of the scales, they are decomposed into their constituent items, four in number for each, and are presented in Figure 10.11. They adhere to the same range of values as their encompassing scale. Specifically, Usefulness (1.59) was judged as very helpful (1.88), beneficial (1.68), useful (1.48), and sufficiently rewarding (1.32) since it significantly facilitates the navigation of people with blindness and visual impairments in the thematic routes of the Tactual Museum of Athens. For the scale of Efficiency (1.58), users found the application to be very organized (1.76), practical (1.48), fast (1.60), and as a whole very efficient (1.48). Users stated that they do not have to perform unnecessary actions and that the application has a snappy response time. For the scale of Dependability (1.51), users noted that the provided functionality was predictable (1.60), supported their navigation in the museum (1.44), met their expectations (1.52), and made them feel more secure (1.48). Specifically, they praised the accuracy of the navigation given that the application was still in a relatively early stage. Overall, they were highly satisfied with the sense of security provided to them as they were less anxious about damaging the exhibits.

Trustworthiness of Content (1.48) shows that users found the voice guidance content trustworthy to follow (1.48), useful (1.44), plausible (1.56), and accurate (1.44). The users stated that the content of the issued instructions was accurate enough to help them successfully complete their navigation in the museum. Finally, they emphasized the effectiveness of the special instruction that helps the users realign themselves back to the correct path direction when they fail to comply with the instruction ‘Rotate’.

Next, the scale of Perspicuity (1.45) was rated as understandable (1.76), easy to learn (1.24), easy to use (1.40), and having a clean structure (1.40). Specifically, users mentioned that they found it easy to use the interface since it follows practices already known to people that are blind and visually impaired, while the available functionalities were well-organized. Another feature mentioned by the users that greatly improves the usability of the application is that it does not require them to recall past information about their navigation, thus decreasing the cognitive load strain. Moreover, the majority gave positive feedback about the accompanying training version as it encouraged them to move more freely and with confidence when using the application, reducing the stress levels they had regarding either damaging the exhibitions or hurting themselves in the process. Finally, the user manual was quite explanatory according to the users; however, they did find the demonstration by someone trained in this application more reassuring. This is also true even for digitally sophisticated blind individuals which are approximately a third of the participants.

For the scale of Response Behaviour (1.18), users had mixed feelings concerning the rate by which the application responds (–0.16). They found it slightly unpleasant (−0.28), not sufficiently natural (−0.08), and not entertaining enough (−0.08). Many of the users noted that they prefer the response behaviour to be more natural and they recommended that many instructions with short duration be substituted by instructions with larger duration. For example, the following instructions are typically issued in succession:

1. Stop; 2. Turn right;
3. Move on.

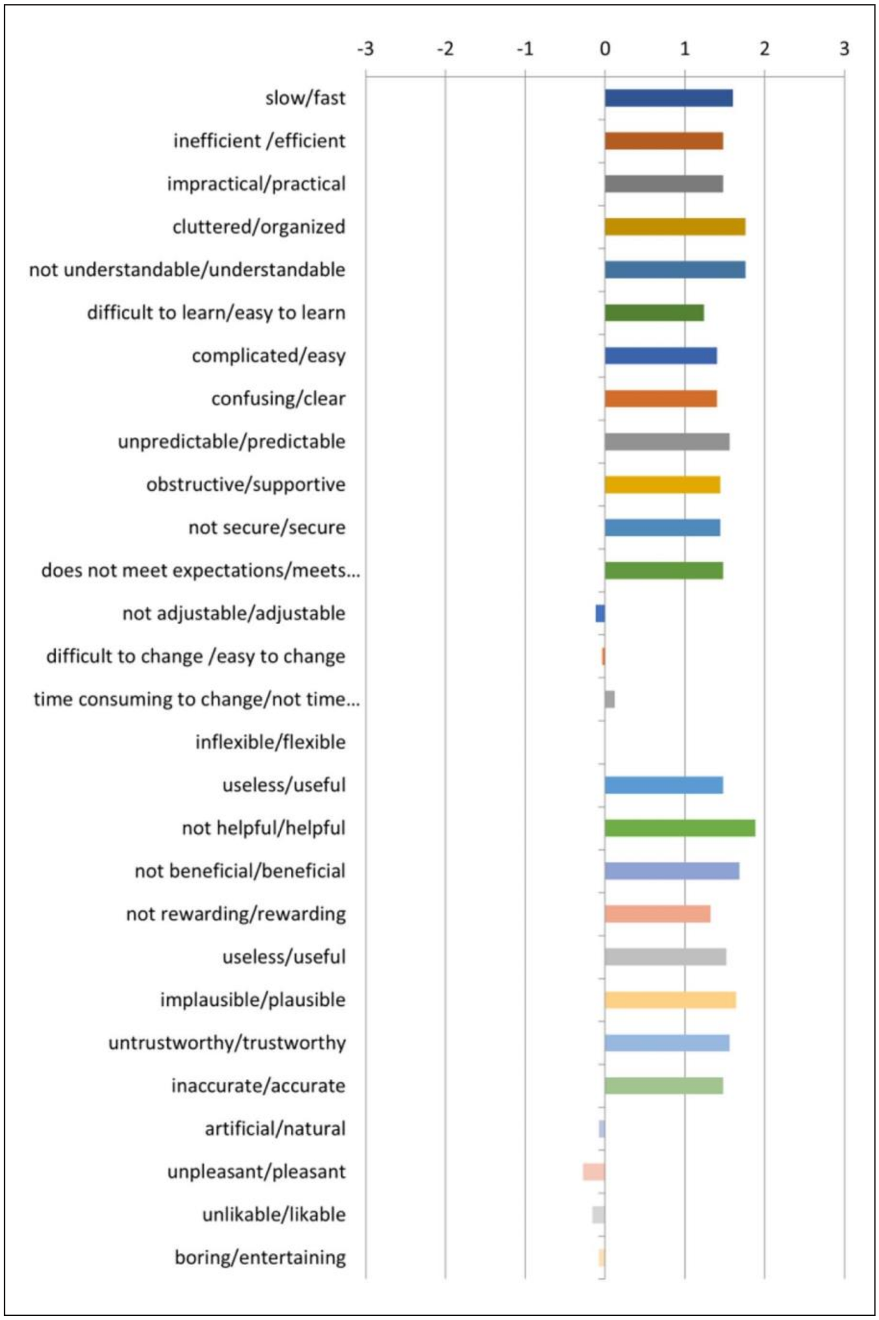


*Figure10.11 Mean value per item*

Should be changed to the following instruction:

1. Stop, then turn right and then move on.

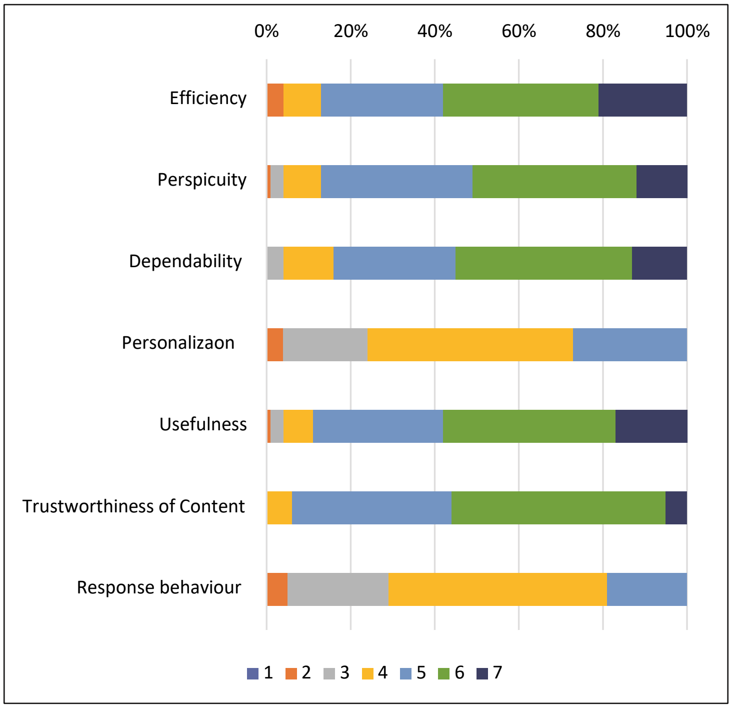


*Figure 10.12. Distribution of answers per scale.*

Finally, the majority of the users, taking into consideration both the educational and entertaining aspects of a museum, suggested that the content of instructions should not be structured in an imperative voice.

The score of the Personalization scale (−0.01) highlights the need to provide more customizability regarding the speed by which the instructions are issued, the available voice assistants as well as the speed by which the exhibits are described (−0.12). In addition, the users stated that changing the current configuration options is neither easy nor difficult (−0.04) and does not slow them down significantly (0.12). Finally, users without complete vision loss and differentiated cases of visual impairments as well as users that have their escorts would prefer the application to have the capability to choose to simply tour an exhibition room without the application issuing navigation instructions. The lack of this feature thereof results in negatively impacting the rating about the flexibility of the application (0.00).

### 10.4.4.6 Distribution of responses by scale

Next, Figures 10.12 and 10.13 depict the distribution of responses for each scale and per item, respectively, in the range of 1–7. Most of the responses had a score above 5 with the only exceptions that the scales of personalization and response behaviour were their highest scores topped at 5. On average, 50.5% of the responses of these two scales scored a 4 while 22% of them scored a 3. Overall, 77% of responses are lower than 4. The rest of the scales received higher scores closer to 6, thus boosting the average.

#### 10.4.4.7 Consistency of the scales

Finally, to assert the consistency of our results, we applied Cronbach’s alpha coefficient to user responses. Despite the lack of a generally accepted rule of thumb about the value of the coefficient, in practice, a value greater than 0.7 is sufficient to qualify the results as reliable. Table 10.4 contains the results of consistency for every scale where we can observe that the results are indeed reliable. Figure 10.14 depicts Table 10.4 as a bar graph.

### 10.4.5 Real-life demonstration

In this section, we demonstrate the application’s functionality as it is being used by a blind individual for navigating inside the exhibition rooms of the Tactual Museum of Athens. In this scenario, the blind user has selected to navigate the rooms of the thematic route including the exhibition room of Hermes, and Poseidon, situated on the ground and first floor, respectively. Besides Poseidon, the first floor has three additional exhibition rooms. After selecting the thematic route via the provided voice interface, the user must stabilize the smartphone device on a part of his body. The following instruction ‘Please, hold the phone and stay still’ is issued. In this case, the user chose to place the smartphone device in the front pocket of his shirt. As soon as this is completed, the application requests the user to perform a trial walk on a special surface tactile ground indicator guide located at the entrance of the museum serving as the starting point for every thematic route. The purpose of the latter is to allow for the calibration of the application’s model to the particularities of the user’s unique gait. The following sequence of snapshots (Figure 10.15) depicts the previously described process. The first three snapshots from left to right show the user traversing from one end of the special surface tactile ground indicator guide to the other completing the stage of calibration. For this case, the following sequence of instructions is issued: ‘Please, after the distinctive sound, walk down the initial tactile ground surface indicator’ followed by ‘You have reached the end of the route, calibration completed’.

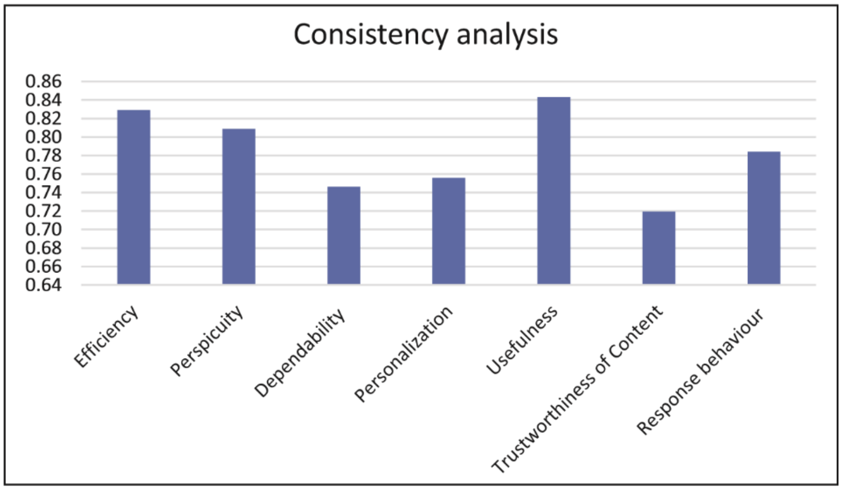


*Figure 10.14 Bar graphic of Cronbach per scale.*

Table 10.4 Cronbach per scale.

| | |
|---|---|
| Efficiency | 0.83 |
| Perspicuity | 0.81 |
| Dependability | 0.75 |
| Personalization | 0.76 |
| Usefulness | 0.84 |
| Trustworthiness of content | 0.72 |
| Response behaviour | 0.78 |

Next, the application requested the user to make a 180° turn issuing the instruction: “Make a 180 degree turn until you hear the distinctive sound’. In the fourth figure, the user is depicted midway through this turn. As soon as the turn is complete, the application issues the ‘Please stop’ instruction. Subsequently, it issues navigation instructions for the exhibition room of Hermes. Next, the application issues the instruction ‘Please continue moving straight ahead’. The fifth figure depicts the user navigating to the door of the Hermes exhibition room located on his right side approximately at the middle section of the surface tactile ground indicator guide. When the user reaches the entrance, the following instructions are issued ‘Please stop’ and ‘Please make a sharp right turn until you hear the distinctive sound”.

At the entrance of the Hermes exhibition room and after being properly aligned with the help of the special surface tactile ground indicator guide, the application instructs the user to perform a single step to enter the room. For every exhibit, the application guides the user up to the corresponding location followed by an instruction to make a right or a left turn to properly align the user with the exhibit. To avoid overturns, the application has special instruction that informs the user when to stop. The first three snapshots from left to right (Figure 10.16) show a sample of the exhibits found in the Hermes exhibition room. The last figure depicts the user following the issued instructions to exit the room and continue the exhibition to the next room. Generally, the instructions issued for the navigation are of the following form: ‘Please make a sharp right/left turn until you hear the distinctive sound’, ‘Stop’, ‘Please continue straight ahead’, ‘The exhibit can be found at

*Figure 10.15 Step 1: Calibrating the application’s model to the user’s gait.*

*Figure 10.16* *Step 2: Inside the exhibition room of Hermes*.

the height of your shoulder – Exhibit description', "Would you like the short or full description, yes or no? '

To approach the Poseidon exhibition room, the blind user has to use the staircases that are on the opposite side of the Hermes exhibition room. With the help of the special surface tactile ground indicator guide the user is realigned and becomes ready to use the stairs (Figure 10.17, first). Special instructions are used to caution the user while using the staircase (Figure 10.17, second). 'Please go up the stairs carefully following the handrail on your right, when you go up the stairs, press your screen twice to continue the tour".

When the user reaches the first floor, another set of special surface tactile ground indicator guides are used to align the user to the correct route.

Analogous to the first exhibition room, the application issues the appropriate instructions to navigate the user to the substantially larger Poseidon exhibition room. The following snapshots present a sample of the available exhibits (Figure 10.18).

At some point during the navigation, the user makes an error and overturns. The application tries to realign the user back to the correct path direction by issuing special instructions that inform him when to stop. In the following snapshots, the user can be seen trying to realign himself after his error (Figure 10.19). He makes multiple attempts to correct himself (first three snapshots from left to right) before finally succeeding (fourth snapshot). The typical instructions for this scenario are the following: 'Please make a sharp right/left turn until you hear the distinctive sound', 'Stop' and in case of overturn 'You turned less/more than needed'.

When the exhibition of the Poseidon room finishes the application returns the user to the ground floor of the museum where the employees and volunteers take back the smartphone device.

*Figure 10.17 Step 3: Staircase leading to the Poseidon exhibition room on the first floor.*

*Figure 10.18. Step 4: Inside the Poseidon room*

*Figure 10.19 Step 5: Correcting accidental overturn*

## 10.5 Discussion – limitations – future actions

In contrast to the case of external navigation which uses both the GPS to dynamically calculate the user's position and the available map services, such as Google Maps, Apple Maps, and other related services, to navigate the user, there is no universally accepted solution for the case of indoor navigation. Also, there is neither an abundance of research results nor available commercial solutions found for the case of internal navigation [19]. The difficulties associated with indoor navigation applications relate, on one hand, to the limited accuracy in positioning that can often deviate significantly from the actual position, creating problems for individuals with blindness and visual impairments, and on the other hand, to the resources and time costs involved in the process of mapping indoor spaces as it is separately performed for each case.

Although there are enough solutions available to track the location of individuals in indoor environments with a fairly high degree of accuracy, most of them require the use of special equipment (e.g., RFID readers, special cameras, and others) that, first, impose costs on individuals with visual impairments and blindness, second, significantly slow down the adoption rate and, third, many of these solutions perform computations that require high processing power (e.g., 3D space representation systems, AR systems, and the like). The consolidation of the use of smartphone devices in indoor navigation applications, with their comparatively lower cost and the integration of powerful computational capabilities, multiple sensors and augmented interfaces in a handheld device, is undoubtedly the best candidate for blind indoor navigation applications.

Taking into consideration the aforementioned and the strong requirement concerning ease of use of indoor navigation applications, we implemented and evaluated a competitive indoor navigation system that has several advantages over the available state-of-the-art solutions. First, the proposed system demonstrates excellent indoor positioning accuracy via the combination of surface tactile ground indicator guides, which follow the ISO 23599:2012 [63] standard, and of the PDR method. Despite the initial design and implementation of the application including the utilization of BLE beacons for the minimization of positioning errors, the small rooms of the Tactual Museum created challenges (as described in section 'Methodology') that prohibited the adoption of this solution. Nonetheless, preliminary trials in bigger spaces suggest the effectiveness of incorporating BLE beacons as proximity sensors of POIs for indoor environments. Second, the adoption of surface tactile ground indicator guides further increases the sense of safety and confidence that is crucial for individuals that are blind and visually impaired. Third, the proposed solution has a low cost facilitated by the adoption of BLE technology radio beacons instead of passive RFID tags for marking the location of POIs. This allows for the formation of one-to-many active-passive relationships between the users and indoor spaces. The alternative solution would instead form one-to-many passive– active relationships between the indoor space and the users, thus, involving a significantly higher cost as it is proportional to the number of users (e.g., one RFID tag reader for each user).

Next, our work highlights the central role of smartphone devices as enablers of indoor blind navigation applications that allow the interaction with POIs facilitated by BLE beacons without requiring additional special equipment to realize such applications. Despite the success of our application, the only limitation concerns the placement of the smartphone device on the user. However, during the testing stages at the Tactual Museum of Athens, the users did not seem to raise any serious concerns about that issue. Moreover, the fact that there is no other similar application in scope available to them reinforces a positive attitude towards our application. Another benefit of our proposed solution, besides satisfying the critical requirement for high accuracy in positioning and system reliability, is that it highlights the importance of another decisive factor for the adoption of such applications by users that are blind and visually impaired. This pertains to the ease of use via proper auditory and tactile interfaces. Unfortunately, many cutting-edge technologies do not focus enough on this important issue as any indoor navigation application should be easy to use. Finally, the successful implementation of an indoor blind navigation application requires mapping the indoor environment. Our system resolves the typical dilemma between the complexity of high positioning accuracy and the cost of the manual indoor navigation mapping process by choosing to simplify the latter without, though, compromising on the accuracy and reliability of the positioning system.

Although the proposed system has been successfully implemented and the results demonstrate a fully functional product, the current implementation does not address the possibility of having multiple users sharing a large indoor space where they can bump into each other. In the near future, we plan to resolve this limitation by adopting one of the following solutions or a combination of them. Either we can leverage the obstacle detection subsystem of BlindRouteVision, our outdoor blind navigation system ([64], [54]) and integrate into BlindMuseumTourer appropriate voice instructions, or we could develop a companion service running on a server that would extend the basic version of BlindMuseumTourer by transmitting in realtime the position of the users navigating in the same place. With that service available, the application could detect and send a collision-avoidance message in the case of an imminent collision.

Moreover, in the near future, we intend to further leverage the information provided by the BLE beacons to even eliminate the requirement for surface tactile ground indicator guides, to further optimize the PDR mechanism and improve the voice interface. Furthermore, we plan to run more extensive pilot trials in a multitude of different venues requiring extensions to the current version of BlindMuseumTourer. These include larger museums as well as public spaces such as hospitals, airports, shopping malls, and the like. At the time of the writing, we have formally requested and received responses expressing the intent to participate in trials from the National Archaeological Museum, the Acropolis Museum, the Goulandris Museum, the National Historical Museum, the Stavros Niarchos Foundation Cultural Center (SNFCC), Attiko Metro, the shopping centre 'The Mall', the Rea Maternity Hospital, and the Evangelismos Hospital where a preliminary mapping of the Emergency Room (ER) section has already been made.

Recognized limitations of our usability and UX evaluation study are both the insufficient number of test subjects and the lack of the sample's geographical heterogeneity, since the pool comes only from Greece. Subsequently, these affect our ability to make generally applicable statements and their emergence can be attributed to various factors. Among the ones that influenced the most the effort to find a large sample of individuals with blindness and visual impairments are the mobility challenges they face and the unfortunate occurrence of the COVID-19 pandemic. To address these challenges, we intend to recruit participants from around the globe, with the help of World Wide Web communities. In this way, the enriched sample will solidify our effort to reach conclusions that have greater statistical significance. In addition, as part of the above effort, we will try to diversify the sample in key areas such as age, gender, living environment, as well as previous experiences with the conventional white cane and other assistive technologies. Ultimately, this will provide a firm basis for developing more widely acceptable tools due to having a better grasp of the needs and requirements of a wider part of the blind and visually impaired global population.

Nonetheless, all this effort is not fruitless. Although the local group expresses personal preferences, opinions, and suggestions, the gathered requirements during interviews can be leveraged by other researchers in the field as well as from developers of similar applications. This can be argued on the basis that it is reasonable to assume that preferences along with the solutions blind individuals choose to overcome the challenges they face, overlap to some extent regardless of their origin and region.

Response bias was another issue that concerned us during the evaluation phase as it can happen without noticing it. The causes of this issue can be attributed to the influence exerted on the participants by the socio-economic characteristics of the person conducting the interview as well as the potential preferences of that person with respect to the subject of the study [65]. Given that in our case the interviewer was a member of the research team, we cannot rule out the possibility of having response bias. To address this issue, we intend for the upcoming evaluation with a larger and more diverse sample to provide the semi-structured interviews in Braille form as well, so that blind users can have the opportunity to assess the application completely on their own. Following the same line of thought, the accessible via Google Forms UX questionnaire will be handed out in Braille format as well to include participants with low digital sophistication.

As part of our future work, we intend to further optimize the existing training (simulation) version of the app. It is developed as an interactive virtual navigation software solution for Android smartphones with the end goal to ease engagement with this type of technology and increase the effectiveness of its usage since spatial information can be obtained indirectly (before navigation). Moreover, we consider that the design, implementation, and validation of a relevant virtual reality (VR) application can significantly enhance the trainability of the blind and visually impaired.

One of the outcomes of our involvement with the MANTO project for indoor navigation was the realization of the importance of the participation of the users that are blind and visually impaired during both the design and the validation phase. This was achieved via a cognitive design framework and the conduct of usability and performance studies. The former promotes a set of principles-criteria that include safety, reliability, reinforcement, and preferences and emphasizes the inclusion of the immediate beneficiaries in the design process as well. The latter allowed for the research team to gather information related to adding new features, fixing bugs, improving the application’s performance, and learning about the usability and UX aspects of the proposed system. It is within the deep convictions of the research team that this information was indispensable in the process of designing and validating an indoor navigation application that best serves the interests of the blind and the visually impaired.

Finally, the creation of an extended version of the technology acceptance model (TAM) model is of paramount importance for the goal of improving the acceptance and usage of the proposed and other related technologies. To the best of our knowledge, we are not aware of a TAM-based model that focuses on the individual characteristics of this particular target group.

## 10.6 Conclusion

This article presented the extended usability and UX evaluation of a smartphone-based indoor navigation application for people that are blind and visually impaired named BlindMuseumTourer. Prior to conducting the evaluation, the research team ensured that the users familiarized themselves with the functionality of the application during special training sessions. Next, a survey of the available literature highlighted the progress made and the limitations of the various attempts during the past decade. Following, a high-level description of the proposed solution was also included for reasons of completeness the design of which was the result of a cognitive-driven process that incorporated extended interviews with blind users who had expertise in assistive technologies as well as those with low digital sophistication. The proposed solution combines a PDR algorithm with in-premise surface tactile ground indicator guides, the smartphone’s gyroscope sensor, and BLE technology radio beacons, which were not utilized in the current version of the app. The algorithm computes with high accuracy the user’s position and the travelled distance minimizing the associated error, thus allowing the successful navigation of the user around the premises of the museum. Furthermore, the findings of this work confirm that the design process and the selected equipment satisfy the user requirements. Specifically, the results from the usability and UX assessment demonstrate that the current version of the system is both dependable and useful while the overall results from the trials in the museum predict the effectiveness of the system on a larger scale as well. Despite a few limitations described in section ‘Discussion – limitations – future actions’, the application was well-received, its user base is increasing according to the statistics gathered by the Tactual Museum of Athens, and as reported, it created anticipation for future versions that will extend the number and type of supported spaces.

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# Chapter 11 (Content partially published #9)

## Challenges in Acceptance of Smartphone-based Assistive Technologies - Extending the UTAUT Model for People with Blindness and Visual Impairments

**Keywords:** Technology Acceptance, UTAUT, Usability, User Experience, Mobile Application, EFA, CFA, SEM

## 11.1 Introduction

Worldwide, there are 295 million people who have moderate to severe vision impairments, while 43 million are completely blind, most living in low to middle-income living environments. Interacting with individuals suffering from any form of visual impairment reveals the challenges they face in their daily functioning, social inclusion, communication, and work. Further complicating these challenges was the COVID-19 pandemic as it posed new restrictions and, simultaneously, decelerated the development rate of innovative assistive technologies (ATs) (Senjam et al., 2021).

Over the last decades, solutions have been proposed for both indoor and outdoor navigation. Specifically, indoor navigation solutions are based on inertial odometry (Ren et al., 2021), sensor-based pedestrian dead reckoning (Huang et al., 2019), indoor localization utilizing computer vision and deep learning on camera-based input or beacons readings (Koutris et al., 2022; Viset et al., 2022) as well as methods for reliably evaluating the adaptability of these solutions (Schyga et al., 2022). Likewise, outdoor navigation employs approaches incorporating both the smartphone sensors and external higher accuracy GPS receivers coupled with patent-pending novel routing algorithms (Theodorou et al., 2022a), deep learning computing vision for detecting user path obstacles, car directionality as well as crosswalks near traffic lights (Chandna & Singhal, 2022; Das et al., 2021; Hsieh et al., 2021; Shelton & Ogunfunmi, 2020), and smart traffic lights devices for the safe passage of crossings (Theodorou et al., 2022a).

Despite the AT abundance, their biggest issue is the high abandonment rates. This is difficult to resolve as acceptance depends on correctly performing the assessment of needs and desires, the application design, the selection of performant and cost-efficient equipment, the provision of customization as well as the conduct of special training courses, and, finally, facilitating users to integrate ATs into their daily life. Failure in any of these areas creates a negative proclivity against the AT and given their complexity, they do not become as useful as we hope them to be.

Another factor affecting acceptance according to Lee et al. (2020) is users' perception of technological solutions which in turn depends on whether users have direct or indirect experience with them. The study highlights the significant positive impact of the former on the users' opinions. Considering the above, one way to facilitate direct experience with AT solutions is during the Orientation and Mobility (O&M) courses. Other authors as well, consider training as key ingredient that could decrease abandonment.

Having a framework to understand technology acceptance can help in better understanding the strengths and weaknesses of any solution in that regard. Technology acceptance has matured over the years and can be used to study AT systems. However, acceptance of ATs is underexplored for blind people and the existing attempts neglect the importance of training as an influencing factor.

In this chapter, the link between training and acceptance of technology was explored in terms of how much an improvement in training can positively affect AT acceptance in general. We pursued our goal by extending the widely used UTAUT model and tested its applicability and effectiveness.

In Section 2, we present the original and extended research model (Section 2.1), followed by the hypotheses we made (Section 2.2), and proceed with the methodology utilized in assessing their correctness (Section 2.3). Section 3 presents both the questionnaire's and measurement model's validity (Section 3.1), the EFA, CFA (Section 3.2) and SEM results (Section 3.3). Section 3.4 presents the User Experience results. Section 4 discuss the results' significance, current limitations, and layout the road ahead. Finally, Section 5 restates the chapter's takeaways.

## 11.2 Unified Theory of Acceptance and Use of Technology (UTAUT)

Understanding the acceptance of assistive technologies by individuals who are blind and visually impaired is crucial for the success of a solution. Having a framework to understand whether this is true can help in better understanding the strengths and weaknesses of any solution in that regard. Technology acceptance has matured over the years (Venkatesh et al., 2003) and can be used to study assistive systems. However, there has been little research on the acceptance of assistive technologies for individuals who are blind and visually impaired in spite of the large amount of work in other technology fields. Even the ones that exist do not consider the aspect of training as an important external factor affecting the decision of the target group to eventually adopt an assistive technology solution. Therefore, there is a need to empirically validate models facilitating technology acceptance among the individuals of the target group.

The aim of this research is to study the impact of training on the intention of accepting assistive technology solutions. Up to this point, individuals with blindness are supposed to be dependent on caregivers, as there is a negative preconception and stereotype that they are not capable of performing things by themselves. Additionally, the aim of this study is to examine the degree to which our UTAUT model is applicable and effective for assistive technology solutions.

### 11.4.1 Research Model

The proposed model is based on previous research on the unified theory of acceptance and utilization of technology (UTAUT) (Venkatesh et al., 2003) along with other related results (Davis et al., 1989; Taylor & Todd, 1995b). Previous research (Anderson & Schwager, 2003; Dwivedi et al., 2011; Fusilier et al., 2008; Oshlyansky et al., 2007; Scherer, 2016) has demonstrated the effectiveness of the UTAUT model in explaining the variance in usage intention up to 70% (Aggelidis & Chatzoglou, 2009). The latter provides an extremely high prediction ability (R^2) for behavioral research and constitutes a significant result as it explains over 40% of the variance in acceptance (Venkatesh et al., 2003) showing an improvement over the previously existing models.

UTAUT is based on various models with TAM (Davis, 1989; Davis et al., 1989) being among the most well-known. TAM recognizes the individuals' intention, influenced by attitudes toward technology, as the core factor in determining the actual use of an application. Specifically, it suggests that the intention to accept technology is determined by attitude, perceived usefulness, and perceived ease of use. It has been used widely in several research contexts as well as several types of applications (Chau & Hu, 2001; Lee et al., 2006; Ma & Liu, 2004; Chiu et al., 2012) confirming its validity as well (Abu-Dalbouh, 2013).

The original UTAUT model measures four direct determinants/constructs which explain behavioral intention and use behavior of information systems: performance expectancy (similar to usefulness), effort expectancy (similar to ease of use), social influence, and facilitating conditions. The role of behavioral intention and facilitating conditions are the predictors of usage behavior. Performance and effort expectancy, and social influence are the key determinants of behavioral intention. However, for the factors of social influence and facilitating conditions, there has been found evidence that they directly and significantly affect actual use rather than intention. Key relationships in the original model are controlled by users' gender, age, experience, and voluntariness of use. The factors of gender and age control performance expectancy while the factors of gender, age, and experience control effort expectancy. All factors impact social influence while voluntariness is impacted by the factors of age and experience.

However, due to the widespread use of smartphone devices, the factors of experience and voluntariness of use are no longer relevant (Moon et al., 2020). Similarly, to Moon et al. (2020), we substitute them with factors that are more relevant to the personal characteristics and attitudes of an individual with blindness and visual impairments.

Furthermore, from the discussions during the user requirement elicitation phase of interviews and the compiled results that were used for the development of our proposed assistive technologies for indoor and outdoor blind navigation, aspects of training emerged as a recurring pattern (Theodorou & Meliones, 2022a). Although issues around training are usually addressed by the facilitating conditions construct, it was decided to examine training as an independent factor that impacts the various constructs of behavioral intention. Thus, in our extended UTAUT model, we consider the four main constructs to be moderated by the factors of age, gender, attitude, self-efficacy and training. Figure 11.1 depicts the relations between the various factors and Table 11.1 describes the definitions of the factors involved.

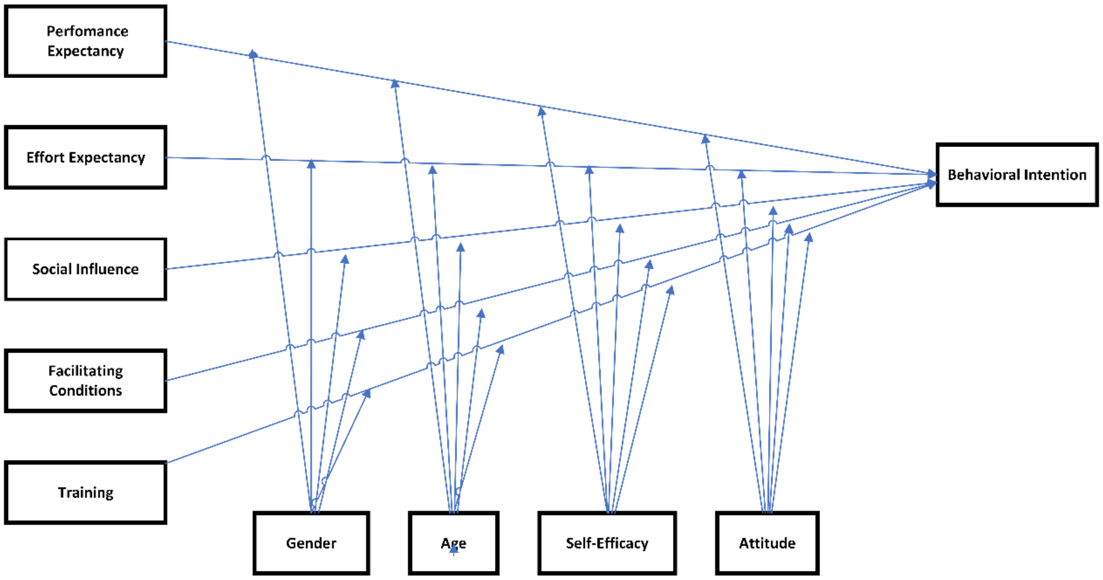


*Figure 11.1. Hypothesized UTAUT Model.*

Table 11.1 Definitions of factors/constructs.

| Research Variable | Definition | Supporting literature |
|---|---|---|
| Performance expectancy | Describes the degree to which the user expects the new technology (i.e., assistive technology) will help achieve performance goals. | (Venkatesh et al., 2003; Davis et al., 1989; Aronson & Carlsmith, 1962) |
| Effort expectancy | Describes the degree to which the user expects to be easy to adopt and use new technology. | (Venkatesh et al., 2003; Davis et al., 1989) |
| Social influence | It describes the degree to which a user is influenced by the adoption and use of new technologies by the surrounding social environment. | (Oshlyansky et al., 2007; Anderson & Schwager, 2003; Venkatesh et al., 2003) |
| Facilitating conditions | It describes the degree to which a user believes that the available infrastructure and resources support the adoption and usage of new conditions. | (Venkatesh et al., 2003; Thompson et al., 1991) |
| Attitude | It describes the degree to which a user has a positive or negative tendency towards the use of new technology. | (Taylor & Todd, 1995a; Fishbein et al., 1975) |
| Self-efficacy | It describes the degree to which a user believes in having the ability to achieve a goal or outcome with the use of new technology. | (Ajzen, 2002; Bandura, 1977) |
| Behavioral intention | It describes the degree to which a user will accept and use new technology. | (Venkatesh et al., 2003; Ajzen, 2002; Warshaw & Davis, 1985) |
| Training | It describes the degree to which a user believes the provided training program adequately introduces and supports the use of the system. | (Agarwal et al., 2000; Aggelidis & Chatzoglou, 2009; Adam Mahmood et al, 2000; Compeau et al., 1999) |

## 11.4.2 Model hypotheses

In the present study the following causal relationships will be examined testing the degree to which the various constructs/factors predict the behavior intention of the blind and visual impaired individuals regarding the use and adoption of mobile application for assisting outdoor navigations. In more detail, Table 11.2 presents the hypotheses that we will make:

Table 11.2 Tested hypotheses.

| # | Hypotheses |
|---|---|
| H1 | Performance expectancy has a positive effect on Behavioral Intention |
| H2 | Effort Expectancy has a positive effect on Behavioral Intention |
| H3 | Social Influence has a positive effect on Behavioral Intention |
| H4 | Facilitating conditions has a positive effect on Behavioral Intention |
| H5 | Training has a positive effect on Behavioral Intention |
| H6 | The relationship between Performance Expectancy and Behavioral Intention is positively moderated by gender |
| H7 | The relationship between Performance Expectancy and Behavioral Intention is neither positively nor negatively moderated by age |
| H8 | The relationship between Performance Expectancy and Behavioral Intention is positively moderated by attitude |
| H9 | The relationship between Performance Expectancy and Behavioral Intention is positively moderated by self-efficacy |
| H10 | The relationship between Effort Expectancy and Behavioral Intention is neither positively nor negatively moderated by gender |
| H11 | The relationship between Effort Expectancy and Behavioral Intention is moderated by age |
| H12 | The relationship between Effort Expectancy and Behavioral Intention is positively moderated by attitude |
| H13 | The relationship between Effort Expectancy and Behavioral Intention is positively moderated by self-efficacy |
| H14 | The relationship between Social Influence and Behavioral Intention is neither positively nor negatively moderated by gender |
| H15 | The relationship between Social Influence and Behavioral Intention is positively moderated by age |
| H16 | The relationship between Social Influence and Behavioral Intention is positively moderated by attitude |
| H17 | The relationship between Social Influence and Behavioral Intention is positively moderated by self-efficacy |
| H18 | The relationship between Facilitating Conditions and Behavioral Intention is neither positively nor negatively moderated by gender |
| H19 | The relationship between Facilitating Conditions and Behavioral Intention is positively moderated by age |

| | |
|---|---|
| H20 | The relationship between Facilitating Conditions and Behavioral Intention is positively moderated by attitude |
| H21 | The relationship between Facilitating Conditions and Behavioral Intention is positively moderated by self-efficacy |

### 11.4.3 Methodology

For the purpose of examining the validity of our proposed model we conducted a study consisting of 231 participants. This was an extension of the sample utilized during the preliminary Usability and User Experience (UX) evaluation of our two proposed applications for indoor (Theodorou et al., 2022a) and outdoor blind navigation (Theodorou et al., 2022b). The population of the sample consisted of individuals with various degrees and cases of visual impairments representing a wide range of ages, all coming from different socioeconomic backgrounds. In particular, the genders were almost equally represented consisting of 55,6% of males and 44,4% of females with ages ranging between 35 and 60. The participants were 53,8% completely blind (over 95% vision loss), 38,4% almost completely blind (90 - 95% vision loss) and the remaining 7,8% faced severe visual impairments. Congenital blindness was the major cause of vision loss amounting to 61,5% of the sample size while the rest 38,5% are due to other causes such as cancer and retinopathy among others. Finally, the sample was divided between those having high and low digital sophistication skills constituting the 48,1% of the sample size respectively, and 7,8% having average skills.

Questionnaires were the main technique for gathering data upon which various statistical tools were applied. In particular, we employed a number of questionnaires with the aim of gathering information about the population’s demographic characteristics, assessing the extended UTAUT model proposal, assessing Usability and UX experience via the UEQ+ framework, and, finally, semi-structured interviews for receiving user feedback about the functionality of the proposed solutions. The questionnaires were filled with two methods; either via Google Form distributed to the emails of the participants or in the vicinity of the Lighthouse of the Blind in Greece aided by the personnel or members of the research team.

## 11.3 Results

For the purpose of analyzing the collected data, the statistical tool of IBM SPSS was utilized for conducting descriptive and Exploratory Factor Analysis (EFA) and IBM AMOS version 26 was used for conducting Confirmatory Factor Analysis (CFA) followed by Structural Equational Modeling (SEM). This is the standard procedure as suggested initially by Anderson & Gerbing (1988) and followed by many similar studies works (Aggelidis & Chatzoglou, 2009; Baroni et al., 2022; Moon et al., 2020). The assessed model is depicted in Figure 11.1.

### 11.3.1 EFA and CFA – Item reliability and validity of the measurement model

Principal Factor Analysis (PCA), one of the most common techniques utilized during the EFA stage, was used to preliminary assess the validity of the constructs (Ajzen, 2002) along with Promax with Kaiser Normalization as the rotation method. According to Bandura (1977), the items that describe a construct need to exhibit higher loadings on the related construct while manifesting lower loading values on unrelated constructs.

Next, during the CFA stage, we modeled every factor of the existing UTAUT model (Venkatesh et al., 2003) as well as our own addition of training factor as a latent variable, each one described by a set of items included in the questionnaire (see Appendix A). The CFA model was estimated utilizing the robust Maximum Likelihood method (MLE) while the parameters of interest were:

a. the item’s loading onto the related UTAUT factor (i.e., item reliability)
b. the correlations among the UTAUT factors (i.e., discriminant validity)

As a rule of thumb, a measurement item loads highly if the loading coefficient has an absolute standardized value of 0.5 and above. Anything lower than that is considered to possess low reliability as 75% (=1-$0.5^2$) or more variance of the item is unique and therefore unexplained by the construct/factor. In order to test the convergent validity of the measurement model the methodology suggested by Fornell & Larcker (1981), was followed. This includes computing Composite Reliability (CR) for each construct, which measures internal consistency and the computation of Average Extracted Variance (AVE) for all constructs, which measures the variance captured by a construct related to the measured variance due to measurement error. For the case of CR, the desired value has to exceed the threshold of 0.70 while for AVE has to exceed the threshold value of 0.50. (Dell et al., 2012). In addition, for the sake of completeness, we report the related Cronbach's alpha coefficient values for each construct. Finally, discriminant validity was tested performing CFA runs examining the relationship and covariance between the constructs. According to Fornell & Larcker (1981), the correlations between items in any two constructs should be lower than the square root of the average variance shared by items within a construct. Furthermore, the heterotrait-monotrait ratio of correlations (HTMT) was used to access discriminant validity.

Regarding the assessment of the model-fit, the following goodness-of-fit measures were used: Comparative Fit Index (CFI), Tucker-Lewis Index (TFI) and the Root Mean Square Error of Approximation (RMSEA). Furthermore, in order to maximize model fitting, the suggestions from the modification index output were taken into consideration (Fornell & Larcker, 1981).

The result model is depicted in Figure 11.2 after removing all non-significant relationships and covariances.

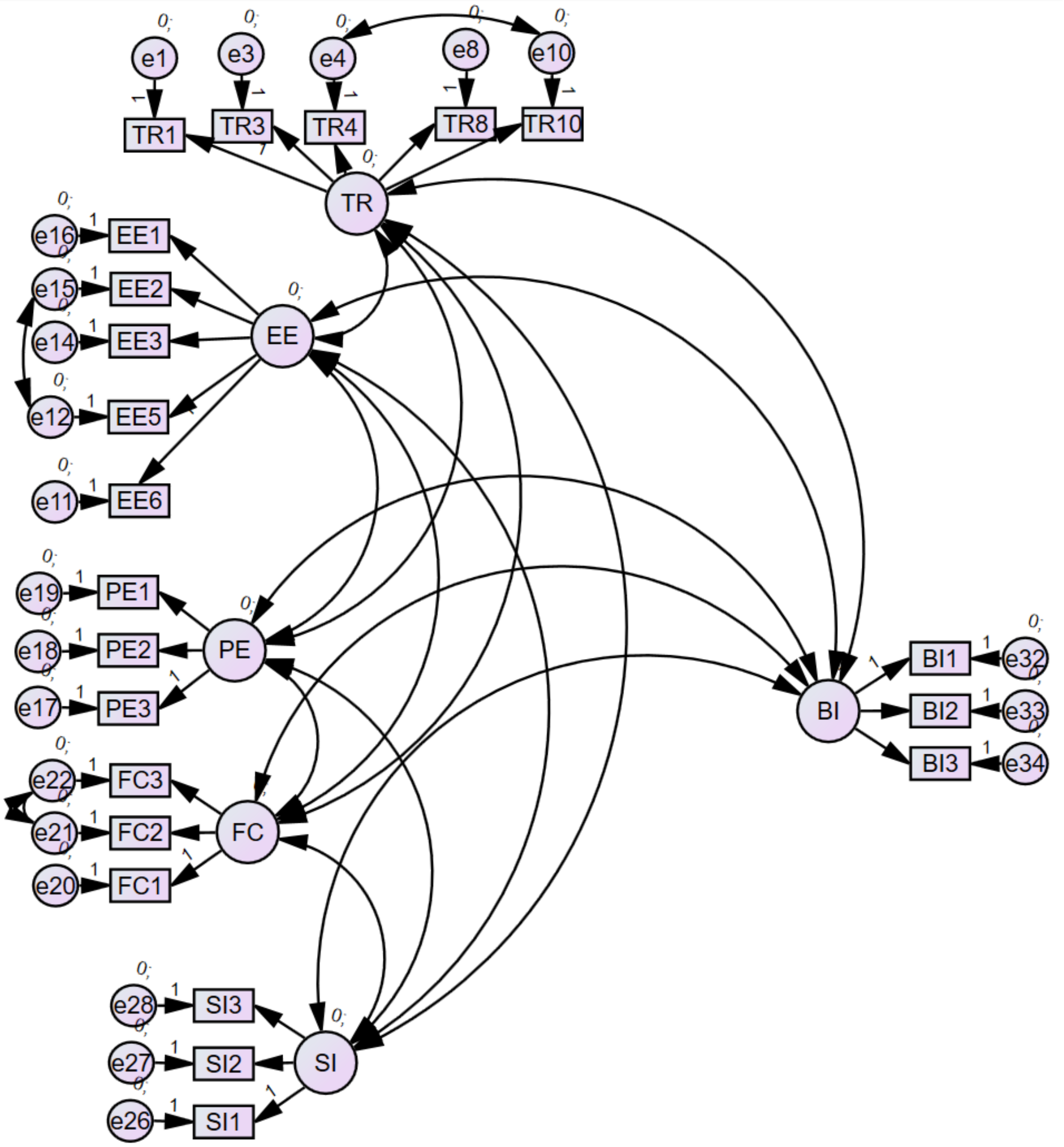


*Figure 11.2. AMOS model for conducting CFA.*

## 11.3.2 EFA and CFA Resutls

The presentation of the results of the improved model starts by demonstrating the output of the EFA analysis. It demonstrates the questionnaire items measuring the required constructs as the intended grouping is achieved (Table 11.3).

Table 11.3 EFA results.

**Pattern Matrix**[a]

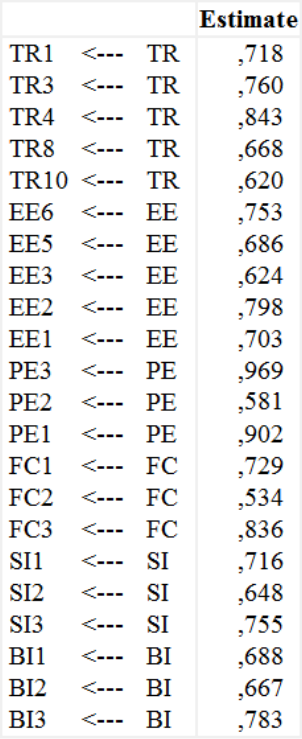
| | Component | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| TR4 | .917 | | | | |
| TR10 | .843 | | | | |
| TR3 | .821 | | | | |
| TR8 | .642 | | | | |
| TR1 | .548 | | | | |
| EE6 | | .888 | | | |
| EE5 | | .803 | | | |
| EE1 | | .778 | | | |
| EE3 | | .745 | | | |
| EE2 | | .605 | | | |
| EE4 | | .462 | | | |
| PE1 | | | .894 | | |
| PE3 | | | .893 | | |
| PE2 | | | .749 | | |
| BI2 | | | | .812 | |
| BI3 | | | | .805 | |
| BI1 | | | | .721 | |
| FC1 | | | | | .877 |
| FC3 | | | | | .822 |
| FC2 | | | | | .637 |

Extraction Method: Principal Component Analysis.

Rotation Method: Promax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Next, the CFA analysis results are presented. Figure 11.3 demonstrates the factor loadings of the questionnaire items on the related construct. As it can be seen, all loadings are above the required threshold with all being statistically significant ($p < 0.001$).

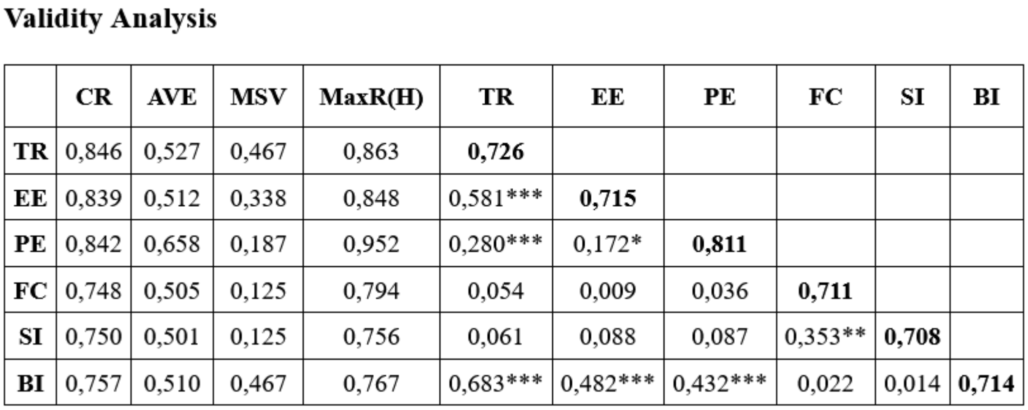


| | | | Estimate |
|---|---|---|---|
| TR1 | <--- | TR | ,718 |
| TR3 | <--- | TR | ,760 |
| TR4 | <--- | TR | ,843 |
| TR8 | <--- | TR | ,668 |
| TR10 | <--- | TR | ,620 |
| EE6 | <--- | EE | ,753 |
| EE5 | <--- | EE | ,686 |
| EE3 | <--- | EE | ,624 |
| EE2 | <--- | EE | ,798 |
| EE1 | <--- | EE | ,703 |
| PE3 | <--- | PE | ,969 |
| PE2 | <--- | PE | ,581 |
| PE1 | <--- | PE | ,902 |
| FC1 | <--- | FC | ,729 |
| FC2 | <--- | FC | ,534 |
| FC3 | <--- | FC | ,836 |
| SI1 | <--- | SI | ,716 |
| SI2 | <--- | SI | ,648 |
| SI3 | <--- | SI | ,755 |
| BI1 | <--- | BI | ,688 |
| BI2 | <--- | BI | ,667 |
| BI3 | <--- | BI | ,783 |

*Figure 11.3 Factor loadings of items on constructs.*

Followingly, the results of the convergent validity of the measurement model as measured by CR, AVE (Table 11.4 and Cronbach's alpha (Table 11.5) is presented. The symbols *, ** and *** indicate a p value lower than 0.05, 0.01 and 0.001 respectively.

Table 11. 4. Validity analysis measures.



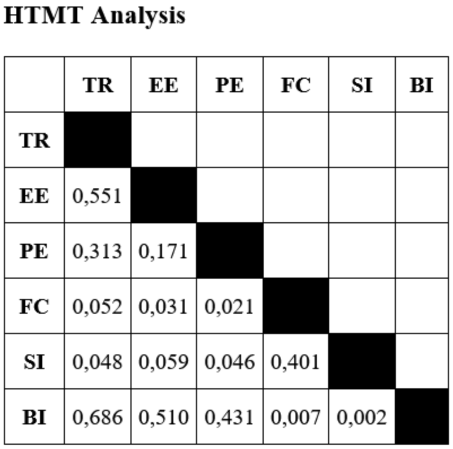
**Validity Analysis**

| | CR | AVE | MSV | MaxR(H) | TR | EE | PE | FC | SI | BI |
|---|---|---|---|---|---|---|---|---|---|---|
| **TR** | 0,846 | 0,527 | 0,467 | 0,863 | **0,726** | | | | | |
| **EE** | 0,839 | 0,512 | 0,338 | 0,848 | 0,581*** | **0,715** | | | | |
| **PE** | 0,842 | 0,658 | 0,187 | 0,952 | 0,280*** | 0,172* | **0,811** | | | |
| **FC** | 0,748 | 0,505 | 0,125 | 0,794 | 0,054 | 0,009 | 0,036 | **0,711** | | |
| **SI** | 0,750 | 0,501 | 0,125 | 0,756 | 0,061 | 0,088 | 0,087 | 0,353** | **0,708** | |
| **BI** | 0,757 | 0,510 | 0,467 | 0,767 | 0,683*** | 0,482*** | 0,432*** | 0,022 | 0,014 | **0,714** |

Table 11.5 Cronbach alpha results.

| Factors | Cronbach alpha |
|---|---|
| PE | 0.816 |
| EE | 0.822 |
| SI | 0.740 |
| FC | 0.700 |
| TR | 0.855 |
| BI | 0.744 |

Table 11.6. Heterotrait-Monotrait Analysis.



**HTMT Analysis**

|  | TR | EE | PE | FC | SI | BI |
|---|---|---|---|---|---|---|
| **TR** | ■ |  |  |  |  |  |
| **EE** | 0,551 | ■ |  |  |  |  |
| **PE** | 0,313 | 0,171 | ■ |  |  |  |
| **FC** | 0,052 | 0,031 | 0,021 | ■ |  |  |
| **SI** | 0,048 | 0,059 | 0,046 | 0,401 | ■ |  |
| **BI** | 0,686 | 0,510 | 0,431 | 0,007 | 0,002 | ■ |

Furthermore, the measurement model satisfies the Fornell & Larcker (1981) criterion as well as the HTMT threshold as every value in the cell of Table 11.6 is below 0.9.

Additionally, the CFA model yields good fit with CFI = 0.957, TLI = 0.947 and RMSEA= 0.045. Finally, prior to conducting SEM analysis, we measured model invariance across the different gender and age groups. We considered two genders (Male/Female) and two age groups (over and under 40). Firstly, we checked about configural invariance followed by a check of metric invariance. The former tests whether the overall structure of our measurement model is equivalent across groups while the latter tests whether the constructs have the same meaning across the different groups. Examining the model fit and model comparison statistics highlights the equivalence of our measurement model among gender and age groups.

### 11.3.3 Structural Equational Model (SEM)

In the second stage, we continued with structural equation modeling (SEM) to examine the hypothesized relationships among the UTAUT factors. SEM analysis was conducted to examine the effects of Performance Expectancy (PE), Effort Expectancy (EE), Social Influence (SI), Facilitating Conditions (FC) and Training (TR) (our newly proposed latent variable) acting as predictors on Behavioral Intention (BI), as well as the moderation effects of gender, age, attitude and self-efficacy on the above relationships. Robust Maximum Likelihood Estimation (MLE) method was used in the SEM analysis.

The initial model of the structural analysis contained all the hypothesized relations between the latent factors, acting as predictors, and the Behavioral Intention (BI) that describes the degree of acceptance of new technologies. After the analysis we concluded that the majority of hypotheses were rejected with the exception of H1 and H5, which were found to be statistically significant. These concern the relationships of Performance Expectancy and Training with Behavior Intention respectively. In particular, the effect of both factors is positive and significant ($p < 0.001$) with a standardized regression weight of 0.264 and 0.538 respectively. This suggests that an increase in Training makes it more plausible for an individual with blindness and visual impairments to use the application in the future. Likewise, the positive impact of Performance Expectancy on Behavior Intention means that the individuals from the target group are more likely to adopt the usage of a new technology and continue using it in the future as long as the product is perceived to be useful. Subsequently, we examined the effects of our moderator variables (gender, age, self-efficacy and attitude) on the relationships between the five factors/constructs and behavioral intention. The analysis indicated that gender, age and self-efficacy do not demonstrate any significant interaction effect on the examined relationships except for attitude with the latent factor of Training. It demonstrates a significant interaction ($p < 0.007$) strengthening the positive relation between Training and Behavioral intention (standardized regression weight (0.142). Finally, the SEM model yields good fit with CFI = 0.957, TLI = 0.947 and RMSEA= 0.045.

### 11.3.4 Qualitative analysis – User Experience evaluation (UX) and Usability

Complementary to the quantitative analysis, we conducted a qualitative one concerning the study of the application's UX characteristics and Usability. For the former, we used the modular UEQ+ framework consisting of a set of scales with questions and the accompanying statistical tool for analysis while for the latter, we used the measures of effectiveness, efficiency and failure rate. For this evaluation, the scales selected for UX were the following: 1) Efficiency, 2) Dependability, 3) Perspicuity, 4) Adaptability, 5) Usefulness, 6) Trustworthiness of Content and 7) Response behavior. For a more detailed presentation of the employed processes, tools and concepts regarding UX as well as the definitions of the Usability measures, the readers are advised to refer to (Theodorou et al., 2022a).

Prior to conducting the analysis, we tested the reliability of the UX questionnaire via assessing the Cronbach alpha coefficient of each scale. All our selected scales passed the widely accepted threshold of 0.7, thus allowing to further analyze the data having confidence about the reliability of the results (Table 11.7).

Table 11.7. UX scales cronbach alpha results.

| Scale | Cronbach Alpha |
|---|---:|
| **Trustworthiness of Content** | **0.77** |
| **Response behavior** | **0.75** |
| **Dependability** | **0.75** |
| **Personalization** | **0.73** |
| **Efficiency** | **0.71** |
| **Usefulness** | **0.71** |
| **Perspicuity** | **0.79** |

The analysis demonstrated that the application was positively evaluated by the users. As a matter of fact, despite the significantly larger sample, we found the same results in terms of the rankings based on the observed scale average value, although with lower scores, when compared to the preliminary evaluation results presented in (Theodorou et al., 2022a). In particular, the scale of Adaptability, which describes the capability of customization to the user's personal preferences, received the lowest score (0.67). On the contrary, the scales of Usefulness (1.05) and Dependability (1.02) received the highest scores as users found that the app removes restrictions concerning pedestrian navigation, while, at the same time, the app's operations were found to be reliable and predictable, respectively. Closely following are the scales of Efficiency (0.88), as users found that their goals can be achieved both quickly and efficiently, and the scale of Trustworthiness of Content (0.86) that emphasizes the quality of the information provided during navigation. The scale of Perspicuity (0.83) received a score that indicates there is room for improvement on how easy it is for the users to familiarize themselves with the application as well as to learn its operation, followed by the scale of Response Behavior (0.72) that shows the desire of users for somewhat better-quality characteristics regarding the app's issued instructions. Finally, the UEQ+ tool provides a Key Performance Indicator (KPI) for the overall evaluation of the UX impression. It received a score of 1.18, which is considered a positive result given that the scale ranges between [−3, 3]. (Remark: The results for the qualitative analysis were produced with 229 participants instead of the 231 as two sets of answers were inadmissible.)

Table 11.8 presents the average values described above along with the standard deviation.

Table 11.8. Mean and standard deviation of scales.

| Scale | Mean | Standard deviation |
|---|---:|---:|
| **Trustworthiness of Content** | 0.86 | 0.87 |
| **Response behavior** | 0.72 | 0.81 |
| **Dependability** | 1.02 | 0.73 |
| **Adaptability** | 0.67 | 0.68 |
| **Efficiency** | 0.88 | 0.88 |
| **Usefulness** | 1.05 | 0.70 |
| **Perspicuity** | 0.83 | 0.76 |

Figure 11.4 depicts the distribution of answers given by the participants. As it can be seen the range of values is between 3 and 7 in a Likert scale having as min the value 1 and max the value 7. Moreover, about 70% percent of the answer receive a score between 4 and 5.

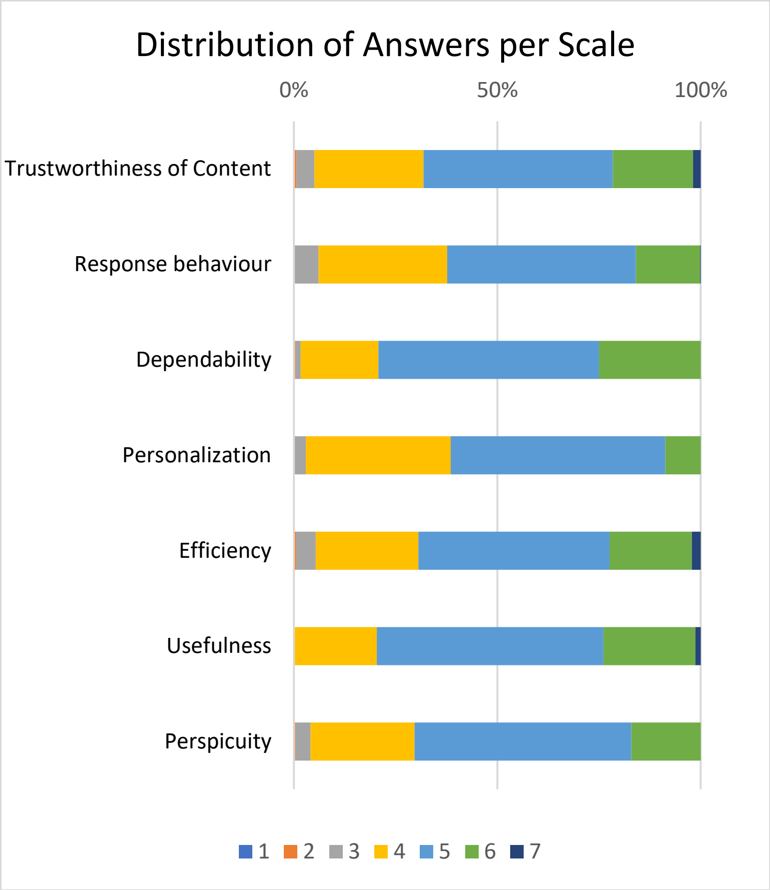


*Figure 11.4 Distribution of answers per scale.*

Usability, on the other hand, was evaluated with fewer participants (62 out of the 231) given the challenges associated with conducting large scale trials with blind and visually impaired individuals. The tasks employed in this phase were three in number and required from the participants to complete certain tasks. These include 1) the completion of a known and unknown pedestrian navigation route, 2) the combination of pedestrian navigation with public means of transport and 3) the passage of marked crossings near traffic lights. Again, for a more detailed description of the tasks, the reader can refer to (Theodorou et al., 2022a). After the analysis of the results effectiveness was measured to be 74,5% while efficiency 72%.

## 11.4 Discussion

Despite the plethora of functional assistive technology solutions, employing a wide range of approaches as demonstrated in the technical review section, the acceptance and usage rate of such applications is very low. Although we do understand that many of the efforts found in the literature are of exploratory nature, nonetheless, there are still enough claiming to address the everyday challenges of the target group. This inevitably raises the question of why none of these efforts have been widely established in the communities of people with blindness and visual impairments. A possible answer can be tracked in the technical review section as we observed that most of the research efforts do not consider neither user evaluation as part of their methodology nor the practical feasibility of their solutions. In order to confirm the latter as well as to uncover other potential causes, we conducted a review around the issue of technology abandonment by members of the specific target group. This effort highlighted the various challenges and common errors that lead to the abandonment of assistive solutions with their origin tracked to technological deficiencies and lack of understanding by the part of the users. Something that stood out about the technological deficiencies was the fact that many of the unresolved issues concern critical aspects such as interfaces, accessibility options and the like where one would anticipate having been solved at an early stage. This reveals that the scientific community neglects issues of that nature and/or is difficult to reach a consensus as well as the inability of the available technology to support the actual needs in a practical way.

As far as it concerns the lack of understanding on behalf of the blind and visually impaired individuals, the way ahead in addressing this issue is the conduct of training sessions with assistive technologies in close as possible real-life scenarios as well as for the research teams to be minimally disruptive of the habits acquired over the course of many years. The incorporation of assistive technologies in training courses has the benefit of more effectively teaching critical O&M skills as well as improving the digital sophistication of people with blindness and visual impairments. However, executing proper training courses for blind and visually impaired require resources, both human and technical, and know-how of their particularities as demonstrated in the section containing the training survey.

The role of training is important as we observed a difference in intention to use the application before and after the completion of the training courses, which led in the exploration of training as a new factor/construct of the widely used UTAUT model for predicting actual usage of assistive technologies targeting blind and visually impaired individuals. In particular, we conjectured that Training, although usually part of the Facilitating Conditions factor/construct, should be an independent factor/construct as from our experience during the user requirement elicitation phase, it became apparent that it could potentially affect behavioral intention, the factor that drives actual usage of technology according to the UTAUT model.

From the conduct of CFA and SEM analysis, we uncovered that no factor beside Performance Expectancy (Standardized regression weight = 0.264, $p < 0,001$) and Training (Standardized regression weight = 0.538, $p < 0.001$) significantly predict Behavioral Intention. Furthermore, the analysis demonstrated a significant interaction ($p < 0.007$) strengthening the positive relation between Training and Behavioral intention (Standardized regression weight = 0.142). This demonstrates that blind and visually impaired individuals are more likely to adopt an application if they are properly trained and acquainted with the features and the way the application responds to real-life scenarios as well as when they find the application to be beneficial for their day-to-day life and activities. Social Influence had no significant effect on predicting Behavioral Intention. To a certain extent this is justified as more that 66% of the participants aged 40 years old and above which are not that easily influenced by their social environment. Likewise, Facilitating Conditions have no significant impact on the factor of Behavioral Intention as the blind and visually impaired. This partial satisfaction of the UTAUT model is found in other similar attempts in the literature as it is demonstrated in the meta-analysis of Dwivedi et al. (2011).

We acknowledge that the validity of our proposed model is not proven with this use case study. However, it does suggest that there is some value to our model and brings forth the role of Training in the UTAUT model under the context of assistive technologies for the blind and visual impaired. In the future, we intent to further validate our proposed model with a variety of assistive technology applications as well as education platforms adjusted for sensory disabilities.

Another limitation of our proposed model is that intention to use assistive technologies, although it is a predictor of actual usage, it cannot determine the actual usage. Tracking users and their usage of assistive is a solution towards that direction, however, not always feasible.

On the other hand, the conduct of the User Experience evaluation confirmed our initial observations found in (Theodorou et al., 2022a) regarding the features of our developed outdoor blind navigation application. However, we were able to utilize only a subset of the extended number of participants for measuring usability. This was due to the challenges presented from having to orchestrate and conduct time consuming and hard to execute tasks. Furthermore, another limitation diluting the generality of the UX results is the unidimensional representation in terms of the included geographical regions and language, due to the consequences of the COVID-19 pandemic, along with the limited diversity in terms of age, gender, living environment and previous experiences with other assistive technology solutions. In the future, the inclusion of participants from around the globe facilitated through related World Wide Web communities can help address this limitation.

Another concern related to the process of conducting the overall evaluation including the UTAUT, and Usability and UX questionnaires is the possibility of response bias due to the perceived, by the participants, socio-economic characteristics of the person conducting the interview and the potential preferences of that person with respect to the subject of the study (Dell et al., 2012). Although the questionnaire was also distributed via digital communication channels, guaranteeing the isolation of the participants, there were cases were help from the research team was requested. This was especially true for the participants with low digital sophistication. In order to address this limitation, in the near future, we plan to release the questionnaires in braille form as well.

## 11.5 Conclusions

In this chapter, we tried to comprehend and address the issue of low technology acceptance rates by the individuals who are blind and visually impaired related to smartphones, which are the most widespread solution for housing assistive technologies. Specifically, we conducted a literature review covering the current state-of-the-art smartphone-based assistive technology solutions followed by another literature review related to the factors and causes of abandonment of new technologies. The result of this work revealed a lot of factors contributing to these phenomena (learning and exploring, adapting mental models, accessibility of applications, forced interfaces, ubiquitous accessibility information, enabling sharing and peer support) and many possible ways to address the issue. Given the scarcity of available resources, it is not realistically possible to address them all. It is in our view that introducing specifically designed training courses for individuals who are blind or visually impaired will be able to provide the most for the available resources. We believe training as a factor is of paramount importance, so we proposed an extended model of UTAUT incorporating this factor explicitly. We evaluated the model and experimentally tested it on our outdoor and indoor blind navigation applications, part of the MANTO project (https://manto.ds.unipi.gr). Although this research is only a first evaluation of our proposed UTAUT model in the context of two applications, we believe that this model can describe more accurately the acceptance rates of assistive technology solutions.

The analysis demonstrates that Behavioral Intention, a predictor of technology acceptance according to the UTAUT model, is strongly and positively affected by Perceived Expectancy and Training while Attitude acts as a positive moderator on the relationship between Training and Behavioral Intention. Despite being an early result, it highlights the importance of training in technology acceptance. This can be leveraged by other research teams to make their solutions more appealing to end users, thus getting a step closer to the desired goal of lifting the barriers as dictated from the social model of disability.

Finally, part of the future work is to apply the extended model to more systems possibly refining or even further extending it.

## Appendix A - Questionnaire

Table A1. UTAUT assessing questionnaire.

| Extended UTAUT Questionnaire | | |
|---|---|---|
| **Factor/Construct** | **Items** | **Supporting literature** |
| **Performance Expectancy:** | 1. Using this application would allow me to accomplish the related tasks more quickly. | 1. Venkatesh et al, 2003; Chen, et al., 2002; Davis, 1989; Gefen, et al., 2003; Moon & Kim, 2001 |
| | 2. Using this application would enhance my effectiveness on the tasks related to its usage. | 2. Moore & Benbasat ,1991; Compeau & Higgins 1995; Compeau et al. 1999; Agarwal & Karahanna, 2000; Chen, et al., 2002; Choi, et al., 2003; Davis, 1989; Gefen, et al., 2003; Koufaris, 2002; Koufaris & Hampton-Sosa, 2002; Teo, 2001; Mathieson et al., 2001; Venkatesh & Davis, 2000; Shih 2004; Yang, 2003; Malhotra, 1999 |
| | 3. Using this application would make it easier to do actions connected to its usage. | 3. Moore & Benbasat, 1991; Agarwal & Karahanna, 2000; Chen, et al., 2002; Choi, et al., 2003; Davis, 1989; Gefen, et al., 2003; Van der Heijden, et al., 2003; Koufaris, 2002; Koufaris & Hampton-Sosa, 2002; Pavlou, 2001; Van der Heijden, 2003 |
| **Effort expectancy:** | 1. Learning to operate this application would be easy for me. | 1. Agarwal & Karahanna, 2000; Chen, et al., 2002; Choi, et al., 2003; Davis, 1989; Gefen, et al., 2003; Hackbarth, et al., 2003; Van der Heijden, et al., 2001; Van der Heijden, et al., 2003; Koufaris, 2002; Koufaris & Hampton-Sosa, 2002; Moon & Kim, 2001; Pavlou, 2001; Teo, 2001 |
| | 2. It seems easy to get this application to do what I want it to do. | 2. Moon & Kim, 2001; Pavlou, 2001; Thompson et al. 1991 |
| | 3. The interaction with this application is clear and understandable. | 3. Chen, et al., 2002; Davis, 1989; Gefen, et al., 2003; Hackbarth, et al., 2003; Van der Heijden, et al., 2001; Van der Heijden, et al., 2003; Koufaris, 2002; Koufaris & Hampton-Sosa, 2002; Moon & Kim, 2001; Pavlou, 2001 |
| | 4. I find this application to be flexible enough to interact with it. | 4. Agarwal & Karahanna, 2000; Chen, et al., 2002; Davis, 1989; Hackbarth, et al., |
| | 5. It would be easy for me to become skilled at using this application. | |
| | 6. Overall, this application seems to be easy to use. | |

| | | |
|---|---|---|
| | | 2003; Heijden, et al., 2001; Van der Heijden, et al., 2003; Moon & Kim, 2001; Teo, 2001 |
| | | 5. Agarwal & Karahanna, 2000; Chen, et al., 2002; Choi, et al., 2003; Davis, 1989; Gefen, et al., 2003; Koufaris, 2002; Koufaris & Hampton-Sosa, 2002; Moon & Kim, 2001; Teo, 2001 |
| | | 6. Chen, et al., 2002; Davis, 1989; Gefen, et al., 2003; Doll & Torkzadeh, 1988; Moore & Benbasat, 1991 |
| **Social Influence:** | 1. My friends who are blind or visually impaired use the system. | 1. Venkatesh et al, 2003; Ajzen 1991; Davis et al. 1989; Fishbein & Azjen 1975; Mathieson 1991; Taylor & Todd 1995a, 1995b |
| | 2. I use certain applications because my social environment uses them. | 2. Venkatesh et al. 2003; |
| | 3. Associations related to blindness and visual impairments support the use of the application. | 3. Thompson et al. 1991 |
| **Facilitating conditions:** | 1. I have the resources necessary to use the application. | 1. Ajzen 1991; Taylor & Todd 1995a, 1995b; Venkatesh et al, 2003; |
| | 2. The system is not compatible with other systems I use. | 2. Ajzen 1991; Taylor & Todd 1995a, 1995b; Venkatesh et al, 2003; |
| | 3. I can get help from others when I have difficulties using an application. | 3. Venkatesh et al, 2003;<br>Venkatesh et al, 2003; |
| **Behavioral Intention:** | 1. In the future, I predict I will use more applications in my daily life. | 1. Davis et al. 1989; Venkatesh et al, 2003 |
| | 2. I plan to use more applications in my life. | 2. Davis et al. 1989; Venkatesh et al, 2003 |
| | 3. I intend to use more applications in the future. | 3. Davis et al. 1989; Venkatesh et al, 2003 |
| **Attitude:** | 1. I find the use of this application a good idea. | 1. Davis et al. 1989; Fishbein & Ajzen 1975; Taylor & Todd 1995a, 1995b; Venkatesh et al, 2003 |
| | 2. I am satisfied with applications for performing my daily living skills. | 2. Davis et al. 1989; Fishbein & Ajzen 1975; Taylor & Todd 1995a, 1995b; Venkatesh et al, 2003 |
| | 3. I enjoy using applications. | 3. Davis et al. 1989; Fishbein & Ajzen 1975; Taylor & Todd 1995a, 1995b; Venkatesh et al, 2003 |
| **Self-efficacy:** | 1. I am confident about using applications. | 1. Venkatesh et al., 2003 |

| | | |
|---|---|---|
| | 2. Using applications would not challenge me. | 2. Venkatesh et al., 2003 |
| | 3. I am comfortable using applications. | 3. Venkatesh et al., 2003 |
| **Training:** | 1. Accessible training material helped me understand the application better. | ▪ Goodhue, 1995; Bailey & Pearson,1983; Igbaria, 1990; 1993; Igbaria, et al. 1997 |
| | 2. I feel more confident on using the application after receiving training | |
| | 3. I believe the duration of training is satisfying | |
| | 4. I believe that training influences my decision to adopt technology. | |
| | 5. I believe that training in familiar places makes technology adoption easier. | |

**Table A2.** UEQ+ (Schrepp & Thomaschewski, 2019)

| Scale | Items |
|---|---|
| **Efficiency:** | • To achieve my goals, I consider the application as slow (1) / fast (7) |
| | • To achieve my goals, I consider the application as inefficient (1) / efficient (7) |
| | • To achieve my goals, I consider the application as impractical (1) / practical (7) |
| | • To achieve my goals, I consider the application as cluttered (1) / organized (7) |
| **Perspicuity:** | • Handling and using the application are not understandable (1) / understandable (7) |
| | • Handling and using the application are difficult to learn (1) / easy to learn (7) |
| | • Handling and using the application are complicated (1) / easy (7) |
| | • Handling and using the application are confusing (1) / clear (7) |
| **Dependability:** | • The reactions of the application to my input and command are unpredictable (1) / predictable (7) |
| | • The reactions of the application to my input and command are obtrusive (1) / supportive (7) |
| | • The reactions of the application to my input and command are not secure (1) / secure (7) |

| | |
|---|---|
| | The reactions of the application to my input and command does not meet my expectations (1) / meet my expectations (7) |
| **Personalization:** | Regarding my personal requirements and preferences, the application is not adjustable (1) / adjustable (7) |
| | Regarding my personal requirements and preferences, the application is not changeable (1) / changeable (7) |
| | Regarding my personal requirements and preferences, the application is inflexible (1) / flexible (7) |
| | Regarding my personal requirements and preferences, the application is not extendable (1) / extendable (7) |
| **Usefulness:** | I consider the possibility of using the application as useless (1) / useful (7) |
| | I consider the possibility of using the application as not helpful (1) / helpful (7) |
| | I consider the possibility of using the application as not beneficial (1) / beneficial (7) |
| | I consider the possibility of using the application as not rewarding (1) / rewarding (7) |
| **Trustworthiness of content:** | In my opinion, the information and data provided by the application are useless (1) / useful (7) |
| | In my opinion, the information and data provided by the application are of no quality (1) / of quality (7) |
| | In my opinion, the information and data provided by the application are untrustworthy (1) / trustworthy (7) |
| | In my opinion, the information and data provided by the application are inaccurate (1) / accurate (7) |
| **Response behavior:** | In my opinion the response behavior of the voice assistant is artificial (1) / natural (7) |
| | In my opinion the response behavior of the voice assistant is unpleasant (1) / pleasant (7) |
| | In my opinion the response behavior of the voice assistant is slow (1) / fast (7) |

| | |
|---|---|
| | • In my opinion the response behavior of the voice assistant is boring (1) / entertaining (7) |

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# Chapter 12 (Content is partially published in #10)

## A Training Smartphone Application for the Simulation of Outdoor Blind Pedestrian Navigation: Usability, UX Evaluation, Sentiment Analysis

**Keywords:** Mobile sensor-based applications; Usability; User Experience; Sentiment Analysis

## 12.1 Introduction

The goal of any training procedure targeting navigation of blind and visually impaired individuals is to make them as much independent as possible. However, it should not only be focused on learning solely to use a specific AT solution but also to enable the target group to acquire Orientation and Mobility (O&M) skills. The proliferation of smart devices integrated with a number of sensors in combination with robust text-to-speech functionalities and multisensory haptic and audio-based interfaces allows to achieve a threefold goal: 1) to make them independent while navigating in familiar and unfamiliar outdoor spaces, 2) to develop training tools that ease and streamlines the process of learning to use AT solutions and 3) to acquire useful long-term O&M skills. Another underappreciated factor of training is the possibility to contribute to the improvement of the AT solutions' adoption rate [1].

It is critical for people with blindness to develop cognitive and mental maps building skills. Specifically, the research literature on blind people's Orientation and Mobility (O&M) covering both familiar and unfamiliar places [2] describes the requirement of providing the information on a perceptual and conceptual level, which are an integral part of any O&M training course. For the former, since the information received from the visual channel is inadequate, the individuals need to leverage the rest functioning senses including the touch, auditory, and olfactory channels to perceive the dangers of the environment. For the latter, blind people acquire and develop suitable cognitive strategies and skills based on their abilities and preferences [3].

Common approaches to facilitate the development of orientation skills involve the use of conventional tools such as the cane and other navigational approaches including preplanning and in-situ aids. The category consisting of the preplanning aids uses tactile maps, verbal descriptions, physical models, digital audio, and tactile screens as mediums of communicating information about the environment before the users' arrival [4 - 6] while the category of in-situ aids provides the information about the environment as users are present in it. The latter employs obstacle detection [7 - 10] and tactile vision substitution systems [11], embedded sensors in the environment [12 - 13] and navigation systems [14, 15].

However, the usage of these two categories of aids has various drawbacks. Tactile and interactive maps, and models, despite their demonstrated effectiveness in the research [16 - 20] are restricted in the sense of requiring larger devices and/or tactile overlays [18, 21, 22], they have low geographical information resolution, they are also difficult to manufacture and update their spatial information, and they are scarce. Furthermore, blind people are less likely to employ preplanning aids in everyday life because of these constraints.

On the other hand, the usage of in-situ aids is associated with an increased risk as most of them are based on auditory feedback which could potentially affect the users' attention when navigating in real spaces. To circumvent the difficulties, one viable option is to obtain spatial and route knowledge indirectly before navigation [16, 17]. Earlier research has demonstrated the power of virtual navigation [23, 24] in virtual environments. The core idea is to allow the blind individual to experience unfamiliar regions through virtual walking while remaining in a safe, regulated setting. Since the complexity of this virtual environment can be dynamically modified, it can be used to provide training scenarios of varying complexity ranging from simple to realistic settings [21]. A common approach for the latter [22, 25] is to employ 3D audio navigation via egocentric exploration.

Various works have shown the effectiveness of the virtual environments approach. The work presented in [26] was the first to highlight the success of integrating a virtual environment application into O&M training sessions for improving the O&M skills of individuals with blindness and visual impairments. She demonstrated an improvement in the target group in performing orientation tasks in real space. Furthermore, the strengths of the tools that utilize virtual environments are threefold: a training simulator for O&M, a diagnostic tool for O&M specialists to track participants' spatial behavior, and a technique for advanced exploration of unfamiliar spaces.

Later, [27], studied the effect of using virtual navigation on building route knowledge and to what extent the acquired knowledge can be transferred to the real world. They found that during virtual navigation users were able to accelerate the learning process of short routes and gradually improve their knowledge of both short and long routes. Afterwards, the users were able to transfer the acquired knowledge from virtual navigation to the real world and successfully complete unassisted navigation tasks.

In [28], extending her work, investigated how virtual environments affect individuals who are blind and visually impaired in exploring, creating cognitive maps, and carrying out activities requiring spatial orientation in real situations. The findings of the study demonstrated that multisensorial VR systems impact the same or even better spatial abilities of the individual when compared with exploring space in the real world. However, it does take some time before the user is able to quickly transfer spatial knowledge from the virtual environment to the real world. These findings emphasize the need for such an orienting tool, particularly when it is impossible to independently explore a new environment. Analogous outcomes were discovered in other VR orientation system studies, [26], ([27], [29], [30], [32 - 38]).

Despite the multiple benefits of employing VR-based solutions, they are not without any limitations. The main disadvantage of this approach is its high cost [25, 26] regarding their complexity in developing and the required tooling and equipment which makes it prohibitive in low-income areas.

To alleviate the problems of both conventional and VR-based approaches and based on the results of [39] demonstrating the effectiveness of smartphone-based approaches in improving navigational skills, route learning and public transit, we tried to explore simpler and more cost-effective solutions based on smartphones devices without making any compromises regarding the quality and effectiveness of the provided learning process. Our attempt resulted in an Android-based application functionally equivalent to our main application for outdoor navigation [40] where it allows to simulate a navigational route that the current user or previous ones have traversed in the past. The proposed solution has the benefit of being easily demonstrated to both instructors and trainees, does not require the availability of special infrastructure and is cost-effective as low-end Android devices can support the application's operation. The conduct of a Usability and UX evaluation confirmed the above statements and demonstrated, also, that the users consider the training application to be useful towards learning to operate the main application's features as well as easy to use, efficient and dependable. This was further validated by a Recursive Neural Network sentiment analysis algorithm on users' responses.

In this paper, we present the design, implementation and validation of a mobile-based training application enabling blind users to learn the features of the main outdoor pedestrian navigation application and develop O&M skills. Section 2.1 presents the user-centered process employed in the design phase of both the main and training application as they are currently implemented. Next, the technical description of the main application (Section 2.2) is presented followed by the relevant description concerning the training version (Section 2.3). Section 2.4 describes the methodology and measures employed for evaluating Usability and User Experience as well as the tools and methods used for sentiment analysis. Section 3 starts demonstrating the results of the previous section. Namely, it presents the results of Usability as measured in terms of efficiency, effectiveness and with the help of the widely used SUS questionnaire, the results of UX as measured with the help of the popular modular UEQ+ questionnaire and the results of sentiment analysis as produced by the Stanford CoreNLP Natural Language Processing Toolkit framework. Section 4 presents a discussion of guidelines/lessons learned. Finally, Section 5 concludes the paper.

## 12.2 Materials and Methods

### 12.2.1 Design Process

For both the main application and its companion training version we applied a cognitively informed design process [41]. It differs from the common engineering approach as it further considers the cognitive procedures utilized in systematic problem solving as part of the design process as well. Moreover, it emphasizes the participation of the immediate beneficiaries in the design process, and it employs safety, reliability, reinforcement and preferences as guiding principles.

Crucial to the success of the design is to understand the needs of the blind and visually impaired in the broader socioeconomic context and the constraints it imposes [42]. With the aid of interviews, we achieved that and identified the various cognitive processes (i.e., allocentric, egocentric and the like) that are employed during navigation. Furthermore, we recognized various psychological constructs (interest, focus, enjoyment and the like) that can be used to create more appealing and acceptable applications [43 - 47].

### 12.2.2 System Description

The proposed system allows for safe and highly precise outdoor blind pedestrian navigation without requiring the mandatory use of tactile ground surface indicators. The system employs voice instructions to continuously inform the user about the status and progress of the navigation and the various obstacles found along the navigational path. Central to this system is an Android application that aggregates data from two different sources, namely an external high-precision GPS receiver tracking real-time pedestrian mobility, a second custom-made external device consisting of an ultrasonic sensor and a servo mechanism that resembles a sonar device in its functionality, and a third custom-made waterproof device attached to traffic lights for identifying their status. The external high-precision GPS receiver (NEO-M8N) leverages information from multiple (up to 16) satellites enabling the system to provide centimeter-level location precision (~10 cm). This From trials reported in [**Error! Reference source not found.**], besides demonstrating its excellent precision unprecedented for the blind pedestrian navigation, it also demonstrated significant improvements in the observed deviation from the actual user location when compared to the smartphone-integrated GPS receiver. The deviation is a crucial factor that can negatively impact the robustness of pedestrian navigation. Specifically, the deviation of the external receiver is measured to be less than 0.4 meters, when receiving signal from 11 satellites, while the readings from the smartphone-integrated GPS receiver deviate in the order of 10 meters. By utilizing this receiver, the application has information on the user’s latitude, altitude, speed, bearing, date, time and number of satellites used.

The ultrasonic sensor integrated to the obstacle detection subsystem is the widely used in robotic applications HC-SR04. It works optimally between 2 cm – 400 cm within a 30-degree cone and is accurate to the nearest 3 mm. Its selection was based on its cost-effectiveness, small weight and size besides its functional characteristics. In order to transmit the ultrasonic burst, a single control pin has to be set high for 10 us. As soon as that happens, the output data pin, responsible for taking the distance measurements, is set to high and remains in that state until the transmitted ultrasonic burst is detected back. In [48] the employed sensor demonstrated a robust performance in sparse outdoor city environments with wide pavements while in densely populated city environments other sensors with narrow beam widths performed significantly better. This is due to the fact that the important factor for achieving reliable results is the width of the beam and not the detection distance.

The third external device is used to detect the change of the traffic light status and communicate the event to the main Android application. The technical details of this device will not be presented as they are part of a pending patent. Traffic light status changes can be detected with no latency and sent via Bluetooth to the main Android application. There a loop responsible for processing those events and turning them into actionable instructions run continuously. The processing phase until issuing the instruction takes around 30 ms. Overall, it takes 100 ms for the system to receive the traffic light status change and calculate the vector representing the user's movement used in the navigation process.

The user interacts with the system via an appropriately designed voice interface to enable fast and accurate interaction. Upon the user's selection of a destination, the system requests information from the Google maps service and feeds the received data in a novel routing algorithm [47]. In case the user selects to include the use of public means of transport, the application requests from the Athens Public Bus Transportation (OASA) real-time telematics service information relevant to the available schedules and bus stops. The algorithm processes the totality of the received data to plan a high-precision navigation route that may or may not include public means of transport and issues a high-level description of the overall route. At the same time, the external high-precision GPS receiver continuously transmits via Bluetooth the coordinates to the Android application where two processes allow the system to adapt to the dynamically evolving environment. The first one is responsible for navigating the user via the use of the aforementioned Google Map service and for updating the list of the available public means of transport. The second process is responsible for utilizing the data received from the GPS and the sonar sensor for reporting user position with a negligible margin of error (<1m) and for obstacle detection, respectively.

The application transmits voice instructions in order to simultaneously ensure the correct and safe navigation of the users and give feedback about potential obstacles on the navigational route. The instructions, information and options requesting user response emitted via the application are better experienced with the use of bone-conducting headphones. In this way, sounds from the enclosing environment are not suppressed enabling the users to remain aware of the dangers which are critical for their safety. Figure 12.1 depicts the architecture of the proposed system at a high level. The operation of the reliable ultrasonic obstacle recognition subsystem is presented in detail in [48].

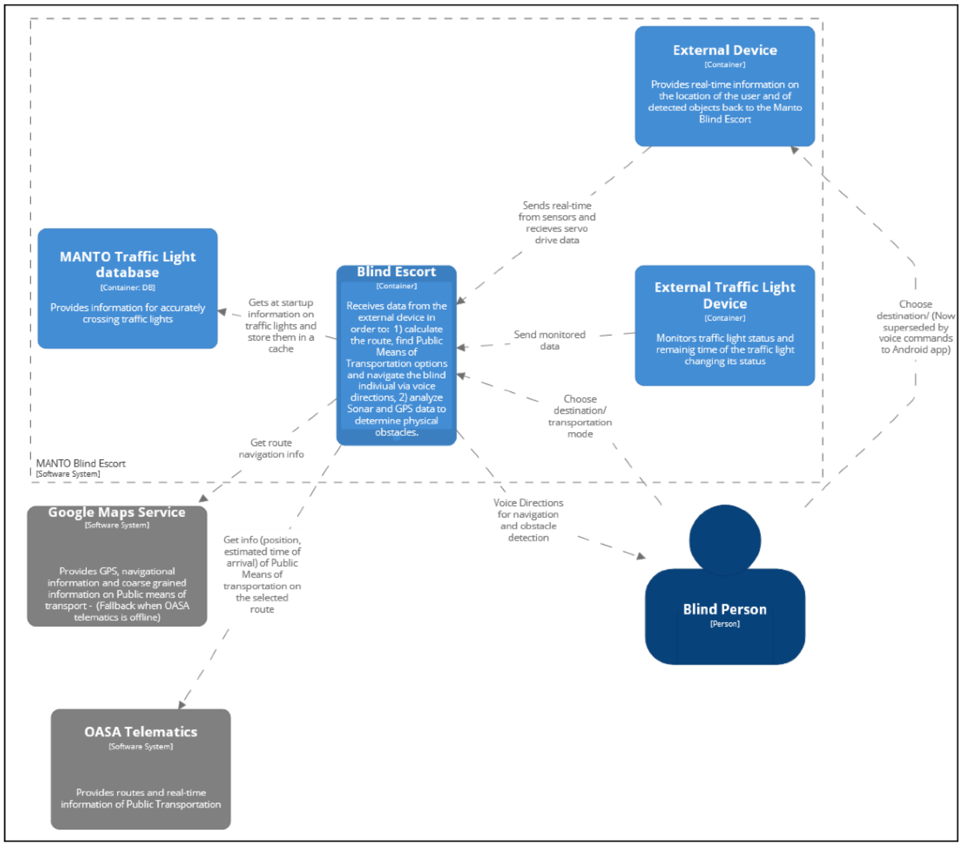


*Figure 12.1. The application's architectural diagram.*

## 12.2.3. Training System Description

### 12.2.3.1. General Description

For people who are blind and visually impaired, independent navigation is difficult, especially in unknown environments. Navigation assistive technologies attempt to provide further assistance by directing users or raising their awareness of their surroundings, but precise solutions are still few. Even when adequate solutions exist, usually there is no companion application that would make it easier for the users to understand the supported features of the proposed solutions. As a response to this inadequacy, we developed for our application an interactive virtual navigation software solution that supports both Android smartphones and PCs. The latter is a user-friendly bundle of the Android emulator that allows users to utilize the same application on a PC as well. The end goal is to ease the engagement with assistive technologies and increase the effectiveness of their usage since spatial information can be obtained indirectly (before navigation).

In the beginning, the simulation environment was just a debugging tool but its value as a functional educational tool soon became apparent and thus, evolved into a full-fledged training environment. This mode of operation avoids the hazards of trials in real scenarios and, as a result, it assures safety and trust, both of which are requirements of fundamental importance. The main functionality of the simulation application is the provision of the capability to replay/rehearse a navigation route without having to move along that route. Since the training version's overall functionality is equivalent to that of the main application, it allows everyone to practice at their own pace, with an increased level of comfort and devoid of any external limitation (instructor, escort). The simulation application provides the capability as well to become acquainted with the obstacle detection mechanism found in the main application. Virtual obstacles can be placed in the navigational path of the simulated route where special audio pitches or haptic-based feedback is used to indicate their presence. The intensity of the pitch or of the vibration increases or decreases depending on whether the user is approaching or moving away from a face-fronting obstacle. When both a navigational instruction and an obstacle detection pitch need to be emitted, the navigational instruction takes precedence unless the obstacle's distance is below a defined threshold value. Overall, the simulation tool is a form of an immersive system [49].

The simulation tool utilizes a custom-made JSON structure that describes locations found on the replayed routes. During the simulation, the application will read the points the user has passed one by one and will issue directions both for navigation reasons and for informing about surrounding Points of Interest (POIs) as if the user were physically walking through them.

The instructors will need to build the JSON file with this structure each time a new path is added either manually or by traversing by themselves the route. In our example, five points have been placed for illustrative purposes. The order must be respected as the points are traversed sequentially. In addition, we assume that the user starts from the first point in the list.

The JSON file follows. As can be seen rootingPaths is an array of UserPoints with the following format:

```
"rootingPaths": [
 {
  "id": 1,
  "lat": 19.427874,
  "lng": 25.464897
 },
 {
  "id": 2,
  "lat": 19.427875,
  "lng": 25.464899
 },
 {
  "id": 3,
  "lat": 19.427876,
  "lng": 25.464895
 },
 {
  "id": 4,
  "lat": 19.427877,
  "lng": 25.464894
 },
 {
  "id": 5,
  "lat": 19.427878,
  "lng": 25.464893
 }
],
  "destination": {
  "lat": 19.427890,
  "lng": 25.464890
}
```

```
}
```

Each UserPoint is a JSON object that contains 3 fields as seen below.

```
{
    "id": 5,
    "lat": 19.427878,
    "lng": 25.464893
}
```

The fields lat and lng are the geographic coordinates of a point that is part of the route while the id field uniquely identifies a point in the array of UserPoints. The final destination of the route has the following format.

```
"destination": {
   "lat": 19.427890,
   "lng": 25.464890
 }
```

### 12.2.3.2. Graphical User Interface (GUI) during training navigation

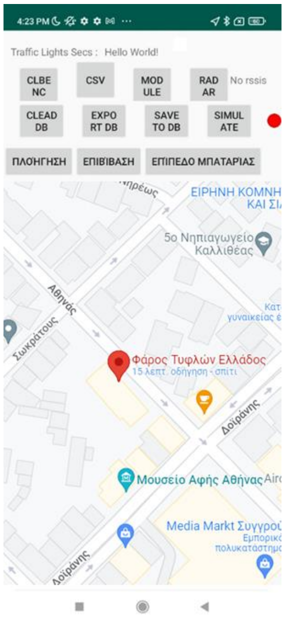
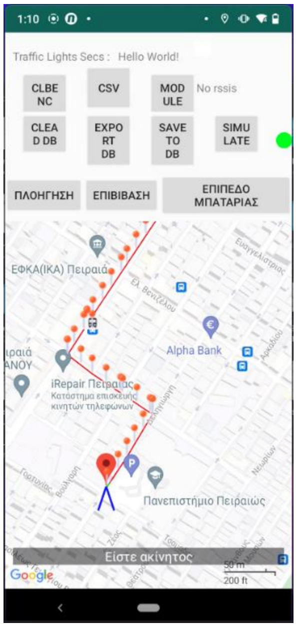


*Figure 12.2. Application’s Training version – Main screen. It consists of three parts: the upper part contains the training app’s menu and the rest depicts the map, the user’s location and the navigational route. The Greek text on the last 3 buttons says from left to right “Navigation”, “Boarding”, and “Battery Level”.*

Figures 12.2 and 12.3 present an exert of the GUI elements of the training version as a scenario is being replayed. It is almost identical to the main application except for the upper part of the screen as shown in Figure 12.2 and the pins (dots) depicted on the map representation (Fig. 12.3) of the route.



Hello World!

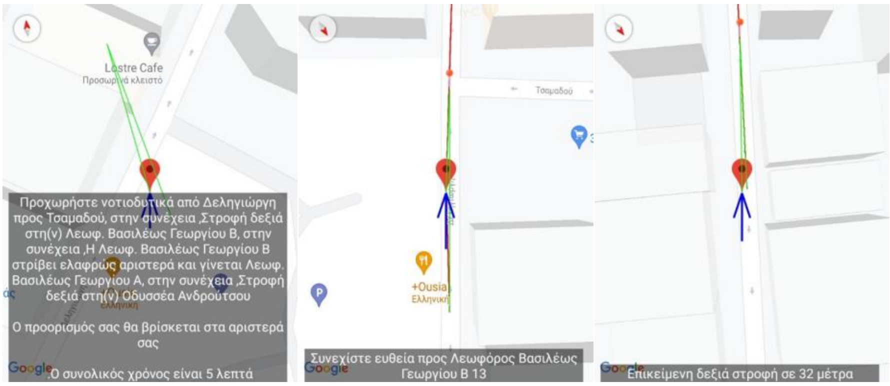
Είστε ακίνητος

*Figure 12.3. Application's Training version – Route selected. The entire simulated route is depicted with dotted pins. These serve as preselected locations that the instructor can set as starting points for navigation. The message at the bottom of the image says in Greek: "You are stationary" as the replay of the route has just begun.*

The menu on the upper part (see either Figures 12.2 and 12.3) allows the instructor to access the features of the app. Specifically, it provides the route simulation features such as 1) selecting the JSON file to load a route via the "Navigation" button located on the first position from the left of the bottom three (described in Greek), 2) the button responsible for simulating the process of boarding a bus and the battery level notification (second and third from left of the bottom three respectively), 3) the feature to record, import and export routes made by the blind and visually impaired users, and, finally, 4) starting and stopping the simulation of the selected route.

### 12.2.3.3. Simulated route navigation

Figures 12.2 up to 12.6 present the output of the application when either the instructor or the user has selected to simulate a route already recorded. When the route has completed loading, the application inserts at regular intervals pins which the instructor can select to reset the simulated navigation. As the simulated walk progresses, the messages are replayed in the same order they were encountered during the recording phase.



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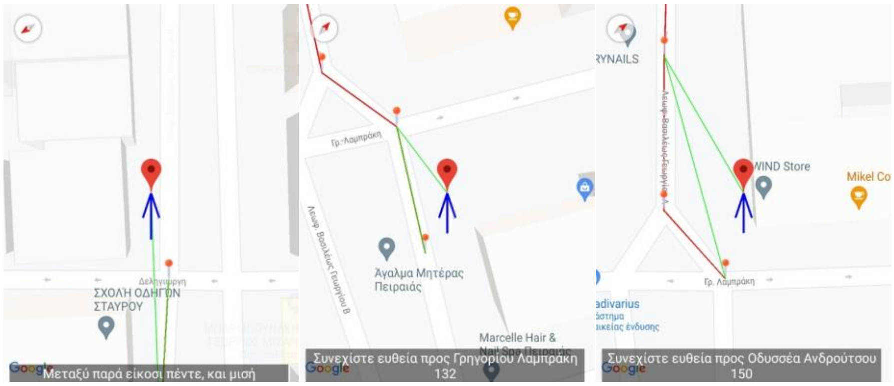
(a) (b) (c)

*Figure 12.4. Application’s Training version – Starting the virtual navigation.*



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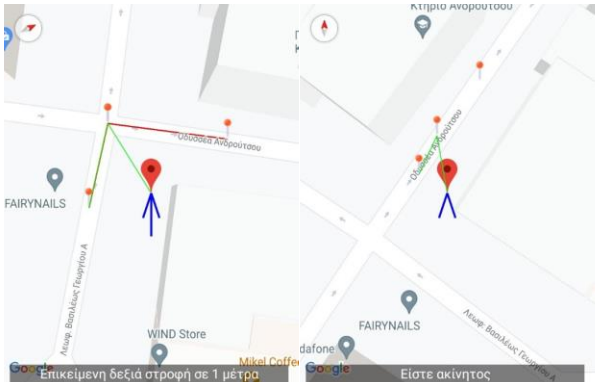
(a) (b) (c)

*Figure 12.5. Application’s Training version – Midway of the virtual navigation.*



Επικείμενη δεξιά στροφή σε 1 μέτρα

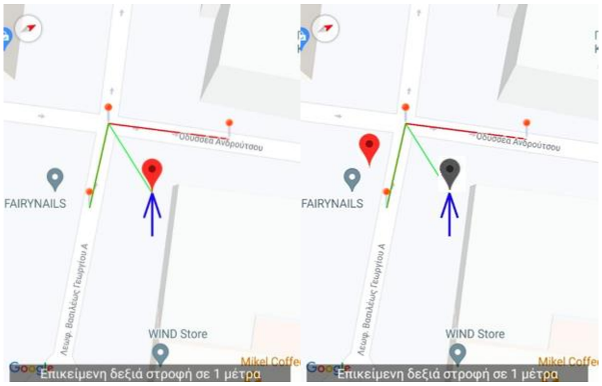
Είστε ακίνητος

(a) (b)

*Figure 12.6. Application’s Training version – End of virtual navigation.*

Figures 12.4 to 12.6 present a recorded route from the vicinity of the Piraeus starting from Deligiorgi 114 and ending at Odyssea Androutsou 150. In these figures, the main capabilities of the application are represented as various events unfold during the navigation. The following messages are issued starting with the description from Figure 12.4 leftmost depiction:

1. Summary Description of the full navigational route and estimation of the time of arrival at the destination. (Figure 12. 4 – (a))
2. “Keep moving straight ahead towards Vasileos Georgiou B 13 Avenue” (Figure 12.4 – (b))
3. “Upcoming right turn in 32 meters” (Figure 12.4 – (c))
4. The user ignoring the voice command to turn right, turns left and the application detects that and provides error correction information by issuing the following message: “The correct direction is between 6 and 7 o’clock” (Figure 12.5 – (a))
5. “Continue straight ahead towards Grigoriou Lampraki 132” (Figure 12.5 – (b))
6. “Continue straight ahead towards Androutsou 150” (Figure 12.5 – (c))
7. “Turn right in 1 meter” (Figure 12.6 – (a))
8. “You have reached your destination” (Figure 12.6 – (b))



Επικείμενη δεξιά στροφή σε 1 μέτρα

Επικείμενη δεξιά στροφή σε 1 μέτρα

(a) (b)

*Figure 12.7. Application's Training version – Snapshot from a simulated route (left figure) while it is being replayed. The instructor pauses the replay and selects to move the position of the user in an arbitrary location on the map in order to demonstrate the behavior of the app when a wrong turn event occurs. Upon selecting the new position, the old is greyed out (right figure).*

In addition, the app gives the capability to the instructor to arbitrarily place the simulated position anywhere on the map for demonstration purposes. Figure 12.7 depicts the case were the instructor placed the simulated position at a different location than the simulated navigation route suggests. This is performed to demonstrate to the blind user the behavior of the application when a wrong turn is taken. When the new position is inserted, the old is greyed out as shown in Figure 12.7. The application will respond with a correction message using instructions based on the hands of the clock identical to the one the main navigation application would give in this case (i.e., the correct direction is between 6 and 7 o' clock).

### 12.2.3.4. Passing near traffic-light crossings

Similar instructional scenarios can be performed for the case of passing near traffic light crossings and for the case of combining the navigational route with public means of transportation. Figure 12.8 depicts the traffic light at the junction of Doiranis and Athinas in Kallithea were the second external device designed by the research team is mounted.

*Figure 12.8. Specially mounted external device on a real traffic light located at the junction of Doiranis and Athinas in Kallithea.*

Φτάσατε στη διασταύρωση. Αναμένατε να ανάψει το πράσινο σε περίπου 20 δευτερόλεπτα.

Πράσινο. Διασχίστε τη διάβαση εντός 25 sec

(a) (b)

*Figure 12.9. Application's Training version – Snapshot from simulating the passage of the crossing near the traffic light of the Doiranis and Athinas junction in Kallithea. The issued message displayed on the left figure informs that the user has arrived at the junction and instructs to wait for 20 secs until the traffic light is in the green status. On the right figure the traffic light is green and, thus, informs the user to pass the crossing in the remaining 25 seconds.*

The application in combination with the latter device helps the blind user to pass traffic light crossings by detecting the traffic light status changes and by reporting the duration in which the traffic light remains in the green status. Figure 12.9 (a) depicts the user approaching the traffic light and the messages issued. When the user has reached the traffic light, the application, then, informs of the event and instructs to wait for 20 secs, the time required for the traffic light to change in the green status at the time of the recording. When the traffic light is green, then the application issues a message requesting the user to pass the traffic light crossing in 25 seconds as shown in Figure 12.9 (b), which is the time until the green status changes to another state at the time of recording.

## 12.2.3.5. Enhanced route navigation with bus transportation

Figures 12.10 and 12.11 depict the case of using a bus as part of pedestrian navigation. In contrast to the other cases where street view is being used, the snapshots are taken with the satellite view.

Κατευθύνεστε προς την στάση ΜΑΡΚΕΑ Υμηττός φτάνετε σε 84 μέτρα, και θα πάρετε το 856

Άγνωστος χρόνος άφιξης του λεωφορείου 856 απο τον ΟΑΣΑ , εκτιμώμενος 6:08μ.μ.

Το λεωφορείο σας 856 φτάνει σε 3 λεπτά

(a) (b)

*Figure 12.10. Application's Training version – Snapshot from simulating pedestrian navigation coupled with public means of transportation. The left figure depicts the following message: "Heading toward MARKEA - Ymittos stop at 84 meters distance. You will take bus line 856" while the right figure the message: "Unknown time of arrival for the bus line 856 from the Telematics Service", "The bus line 856 is estimated to arrive in 3 minutes".*

Φτάσατε στην στάση ΠΛ.Υμηττού, επόμενη στάση Αστυνομία

Φτάσατε στην στάση Πλ.Μακρυγιαννη, όπου αποβιβάζεστε

(a) (b)

*Figure 12.11. Application's Training version – Snapshot from simulating pedestrian navigation combined with public means of transportation. The left figure depicts the message when reaching and passing intermediate bus stops: "You reached Ymittos square stop. Next stop is Astinomia" while the right figure displays the message: "You reached Makrigianni square stop. You exit here".*

The user in this recorded session took bus line 856 from the MARKEA - Ymittos stop heading to Makrigianni square stop. When the user starts approaching the first bus stop, the application starts informing the user about the distance remaining. It emits the message: "Heading toward MARKEA - Ymittos station. Remaining 84 meters. You will take bus line 856" (Figure 12.10 – (a)). While the user is waiting for the bus to arrive, the application informs about the estimated time of arrival based on input form the telematics service supporting the bus. In this recording, the messages the user heard were: "The bus is estimated to arrive at 6:08." followed in a few moments by the message: "The bus will arrive in 3 minutes" (Figure 12.10 – (b)). To simulate the button required to indicate the user is on board the bus, the training application has a relevant button as described in a previous section. As the user passes intermediate bus stops, the application informs about those events ("You reached Ymittos square stop. Next stop is Astinomia", Figure 12.11 – (a)). Finally, when the user reaches the destination, the following message is emitted: "You reached Makrigianni square stop. You exit here" (Figure 12.11 – (b)). When the replay of the recorded route completes, the user can restart either form the beginning or from any other point of the route.

## 12.4. Methodology

The training of the blind and visually impaired with the aforementioned educational tool took place on the premises of the BlindHouse of Greece. The training course, which was part of the Orientation and Mobility courses, included a series of lectures and demonstrations that explains Orientation and Mobility (O&M) techniques, how to navigate routes and where to find information about Public Means of Transport, or other conveniences and, finally, all the above in conjunction with the proposed technology. The selection of the O&M class as a venue for our training course was the result of numerous meetings and interviews between the research team and the O&M instructors to get acquainted with the ins and outs of the course as well as the different educational tools that are used.

The sessions were held once a week for blind and visually impaired users to familiarize themselves with the training version of the application. The sessions were either private or organized as small group classes depending on the needs of the trainees and the limited resources, providing at the same time socialization opportunities.  The instructor, a permanent employee of the BlindHouse of Greece who had previously received training from our research team, would start the exhibition of the application by informing the trainees about the existence of two separate versions of the application having almost identical functionality. Particularly, the instructor described both the supported functionality and generic capabilities as well as the common mistakes of the users to accelerate the learning procedure. Furthermore, during the sessions, seasoned users, if present, would frequently assist others by providing step-by-step instructions while performing the activities on their own devices and waiting for others to complete each step. Overall, the participants favored an active style of learning over handing up their gadgets to others.

In order to assess the training application, we created a procedure including carefully defined tasks as well as questionnaires. The sample consisted of 25 individuals from the population of the blind and visually impaired including both males and females with varying causes of disabilities, ages between 30 and 60 years old as well varying digital sophistication skills. The bulk of the participants had little to no digital expertise, which explained the demand for training sessions.

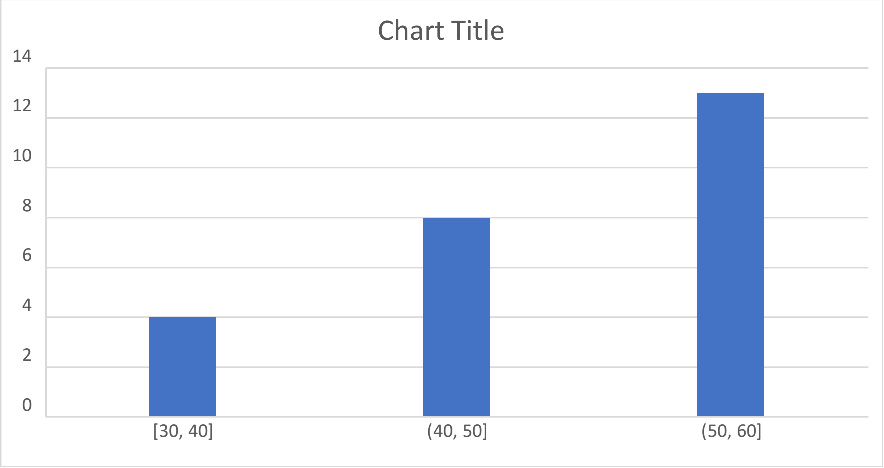


*Figure 12.12. Participant's age distribution.*

In order to evaluate the Usability and User Experience of the training application, we capitalized on the results from a previous research attempt [47] to search the literature for commonly used tools and methods, and definitions as well. There we discovered that there is neither consensus on the method used to assess both Usability and User Experience nor a commonly agreed definition of the concepts involved as a matter of fact, and typically, a combination of tools and methods are employed, the majority of which are based on questionnaires. For example, UX is a term that many researchers and practitioners use to incorporate different concepts [50].  It can include a range of dynamic concepts, such as traditional usability (see e.g., [51, 52] as well as affective, emotional (see e.g., [53 - 56]), hedonic (see e.g., [57, 58]), experiential (see e.g., [50 - 59]), and aesthetic dimensions (see e.g.,  [60]. Furthermore, UX, according to ISO 9241-210:2019 [61], includes users' emotions, beliefs, physical and psychological responses, and it is also the result of system performance, brand image, presentation, the user's internal and physical state resulting from prior experiences, skills, personality and attitudes among others.

Despite the disagreement in the field, a prominent definition that stands out is the ISO/IEC 25,010 2011 [62] standard where usability is defined as "the degree to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. This definition of Usability has the added feature of incorporating User Experience as one of its components under the name of satisfaction [47]. In our experiment and in accordance with the above standard, we utilized the measures of effectiveness and efficiency to quantitively assess Usability and the modular extension of the popular User Experience Questionnaire (UEQ+) to assess the dimension of satisfaction. Without restricting the choice of tools from the above definition, we utilized the widely popular System Usability Scale (SUS) to qualitatively assess Usability as well. In our effort to further understand how well received was the training process, we conducted sentiment analysis, a common technique used in assessing product reviews. Finally, independent of the previous efforts, we employed a semi-structured questionnaire where the participants freely gave feedback to the research team concerning the functionality of both the training and the main version of the application.

The evaluation results from both Usability and UX can be used to make statements about the application’s overall behavior and to some extent more general statements for those types of applications despite being deduced from a relatively small sample. Finally, the participants are representative of the population of the Blindhouse of Greece in terms of age, gender, age of visual loss, and capability to utilize digital devices.

### 12.4.1. Effectiveness and Efficiency

Effectiveness and efficiency measure the degree to which users can complete a task and the time it takes users to complete a task respectively. For our case, we employed the following tasks [47] where we requested from them: 1) to select and traverse “virtually” a route, 2) to combine a route with the use of Public Means of Transport and 3) to pass a traffic light crossing. The participants completed these tasks after they had been shown earlier how to utilize the training application. Finally, for the calculation of the above, the following types were used:

$$Effectiveness = \frac{total\ \#\ of\ tasks\ successfully\ completed}{total\ \#\ of\ tasks\ undertaken} = \frac{\sum_{l=1}^{U}\sum_{i=1}^{M} task_{li}}{U * M} \quad (1)$$

where U = # of participants, M = # of tasks per participant and 〖task〗_li=i-th task of the l-th user.

$$Efficiency = \frac{\sum_{j=1}^{U}\sum_{i=1}^{M} tasks_{ij} t_{ij}}{\sum_{j=1}^{U}\sum_{i=1}^{M} t_{ij}} \times 100\%$$

Where $t_{ij}$= $EndTime_{ij} - StartTime_{ij}$, which in turn, EndTimeij is defined as the time required for the $i - th\ task\ of\ the\ j - th\ user$ to be completed successfully or the time until the user quits.

## 12.4.2. UEQ+ Standardized Questionnaire

To the best of our knowledge, there are no questionnaires available that evaluate the user experience of blind and visually impaired individuals. UEQ+ was selected to address the issue of having predefined general-purpose questionnaires without the ability to selectively examine specific aspects of a software artefact. It promotes modularity as it provides a number of scales to select from, each decomposed into four items, evaluated on a Likert scale that ranges from 1 to 7. Furthermore, each scale is evaluated by the participants for its relevance or importance. Alongside the modular questionnaire, the UEQ+ framework provides a statistical tool to ease the analysis. Finally, the set of scales selected for the User Experience evaluation is the following: Efficiency, Perspicuity(educability), Dependability, Adaptability, Usefulness, Trustworthiness of content, Response behavior. For a detailed description of their meaning, the reader can refer to [47].

### 12.4.3. System Usability Scale (SUS)

The System Usability Scale (SUS) was proposed in 1986 by Brooke as a "quick and dirty" tool to measure usability. Since then, it has become one of the most popular questionnaires used in subjective assessments of the usability of software products [63]. SUS is a ten-item questionnaire evaluated on a 1 to 5 Likert scale and, according to a recent study, it accounts for 43% of post-test questionnaire usage of unpublished studies [64]. Despite the original characterization of "quick and dirty", in a study of 2324 cases conducted by Bangor, Kortum and Miller SUS was found to have an alpha coefficient of 0.91. Furthermore, they provided some evidence of the validity, both in the form of sensitivity and concurrent validity [65]. Finally, Appendix A presents the SUS questionnaire utilized in this study.

### 12.4.4. Semi-structured questions

We have designed a seven-point Likert scale questionnaire to get feedback about the training version's functionality and comprehend better the challenges. This format was chosen as it captures the users' views despite being less amenable to statistical analysis. The reader can learn about the details of the semi-structured questions in [47].

### 12.4.5. Sentiment Analysis

To assess the user feedback more objectively, we conducted sentiment analysis on the text-based responses of the participants. This technique, besides being utilized to evaluate product reviews [66], has been applied even to software engineering tasks such as analyzing developers' emotions in commit messages among others [67]. The selected tool for sentiment analysis was built on top of the Stanford CoreNLP Natural Language Processing Toolkit [68]. In particular, the sentiment classifier is built on top of a recursive neural network (RNN) deep learning model that is trained on the Stanford Sentiment Treebank (SST), a well-known data set for sentiment analysis. The scale of the classifier distinguished 5 levels of sentiments starting from very negative to very positive. Table 12.1 describes the levels of sentiments in more detail. Since the CoreNLP toolkit includes a sentiment classifier that evaluates only at the level of sentences, we decided to calculate a weighted average of the sentences comprising the text block as a way to create an aggregate score. In more detail, our approach associated larger weights with the first and last sentence of a participant's response. Although not all the answers strictly follow the suggested pattern, nonetheless, the majority of them were very close. Furthermore, this pattern is commonly found in product reviews as well, in which the participants' responses share a resemblance. Subsequently, the set of evaluated responses to the questionnaire per user was aggregated using a linear average as all questions were considered of equal importance. Likewise, the overall sentiment score was calculated as the linear average on the values of the previous step. Again, we considered all the users equally important in determining the score for the training app and training procedure.

Table 12.1. Sentiment analysis Levels

| Level | Sentiment |
|---|---|
| 0 | Very Negative |
| 1 | Negative |
| 2 | Neutral |
| 3 | Positive |
| 4 | Very Positive |

Finally, the questionnaire employed in the process of conducting the sentiment analysis is presented in Appendix B. It consisted of 11 questions, to which the participants were requested to respond and share their opinion on the aspects of the training session and the training app as well.

## 12.3 Results

### 12.3.1. UEQ+ Results

The UX analysis demonstrated that the training application was positively evaluated by the users. In particular, the scale of Personalization, which concerns the customizability of the user's personal preferences, received the lowest score (Mean = 0.67). The top two scores were assigned to the scales of Usefulness (Mean = 2.01) and Perspicuity (Mean = 1.91) as the users found that the training application both helps them in understanding the functionality of the main application and it does it in an easy-to-learn way. Closely following are the scales of Efficiency (Mean = 1.64) and Dependability (Mean = 1.59) as the users considered the training application fast and responsive, and reliable respectively. Furthermore, the scale of Trustworthiness of Content received a relatively high score (Mean = 1.43) as users consider the provided information of high quality, while the score assigned to the scale of Response Behavior (Mean = 1.26) suggested a desire for better quality characteristics regarding the app's issued instructions. Finally, the Key Performance Indicator (KPI), an overall assessment metric provided by the UEQ+ statistical tool, received a score of 1.53, which is considered a positive result. Figure 12.13 below shows the mean values of the scales presented above in a graphical form.

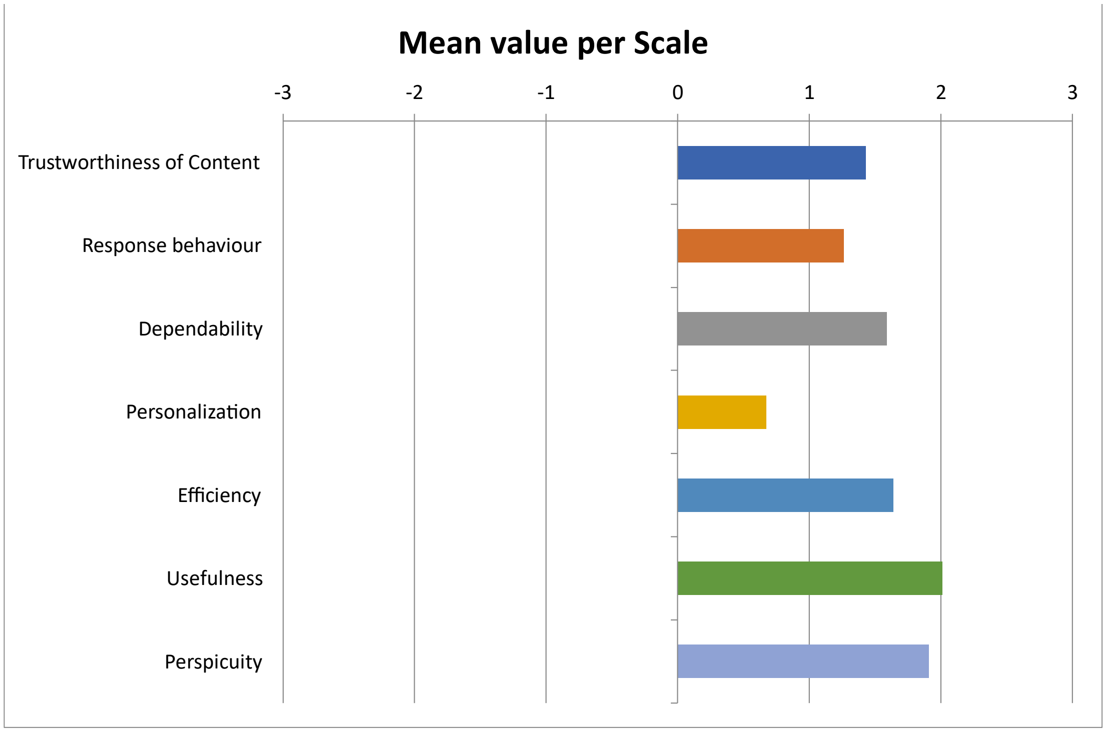


*Figure 12.13. Mean value per Scale.*

Cronbach's alpha coefficient was used to assess the validity of the results for each scale. The results are presented in Figure 12.14. From there, we can see that each scale passed the threshold value for validity (0.7).

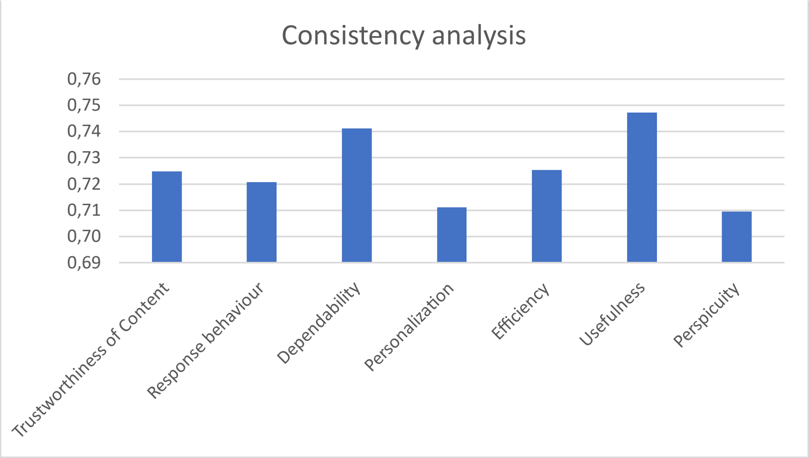


*Figure 12.14. Cronbach's alpha coefficient.*

Finally, we conclude the presentation of the UX analysis with a demonstration of the distribution of answers per scale (Figure 12.15). The totality of the responses ranged from 4 to 7 with the vast majority of them receiving scores between 5 and 6. The only exception to this is the scale of Personalization which received 4 for a large portion of responses, thus justifying the lower overall score it received.

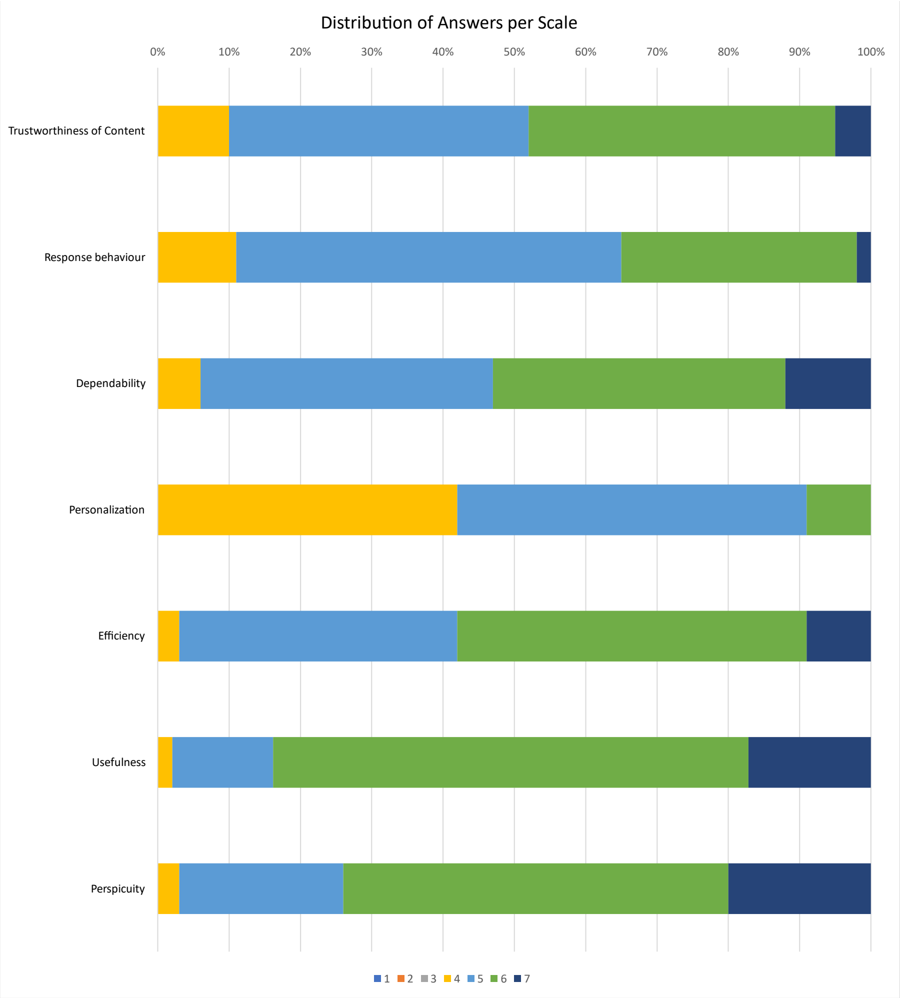


*Figure 12.15. Distribution of answers per scale*

### 12.3.1. SUS results

The overall score for SUS was 69,1, which according to [69] is marginally above the threshold value of 68 (Figure 12.16). The answers given by the users revealed a balanced view of the training application's features with an overall positive attitude. Although there is no particular aspect that either stands out or is severely criticized, we could say that the users found the training application's functionality very well integrated while they found the overall application slightly complex. Furthermore, the evaluation scores ranged between 52,5 and 95. Figure 12.17 presents the distribution of the scores of the participants. As can be seen, 88% of the participants' responses fall in the range of 52,5 and 82,5 while more than half of the responses are confined within the ranges of 52,5 and 72,5.

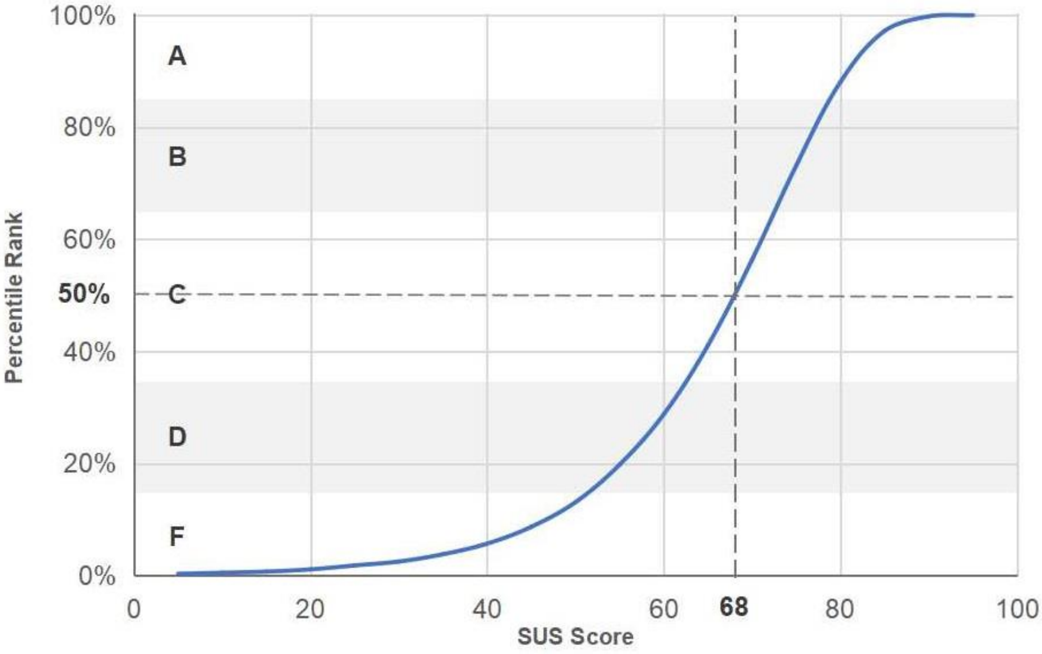


*Figure 12.16. SUS score*

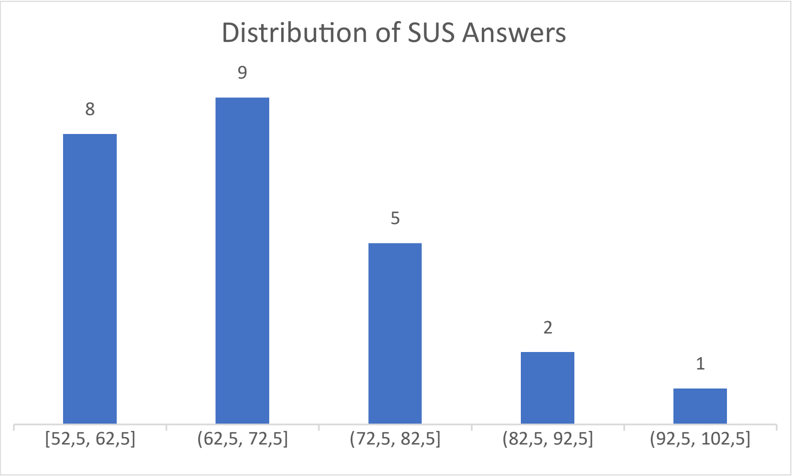


*Figure 12.17. Distribution of SUS Answers*

### 12.3.3. Sentiment analysis results

The users' sentiments were mostly positive with a few neutral assessments; thus, the overall assessment was deemed to be positive. Besides the results of the sentiment analysis, the questionnaire also provided feedback that can give us the opportunity to further improve our approach. Table 12.2 presents the overall assessment scores per user.

Table 12.2. Assessment scores per user.

| Participant | Sentiment | Participant | Sentiment | Participant | Sentiment |
|---|---|---|---|---|---|
| #1 | 3 | #2 | 3 | #3 | 3 |
| #4 | 3 | #5 | 3 | #6 | 3 |
| #7 | 3 | #8 | 3 | #9 | 3 |
| #10 | 3 | #11 | 3 | #12 | 2 |
| #13 | 3 | #14 | 3 | #15 | 3 |
| #16 | 3 | #17 | 3 | #18 | 3 |
| #19 | 3 | #20 | 3 | #21 | 3 |
| #22 | 3 | #23 | 3 | | |

Table 12.3 presents an example of the answers given by a participant and how the sentiment classifier evaluates them.

Table 12.3 Sample of sentiment classifier mappings from answers to scores

| Answer from participant #2 | Evaluation |
|---|---|
| "It was so and so. I wanted the training application to have more roots available" | 2 |
| "The instructions made me feel at ease. I am very happy." | 3 |
| "Yes, it was very convenient." | 2 |
| "Yes, I prefer the orthogonal instructions." | 2 |
| "I would prefer to be better." | 2 |
| "It is not representative of the real case." | 1 |
| "Yes. It makes me feel confident as to what I have to do when entering and exiting a bus." | 3 |
| "Yes. I think it does a good job of describing the situation. " | 3 |
| "The screen read worked fine. " | 3 |
| "Yes. It was easy for me." | 3 |
| "I think it gives a good idea as to what to expect from the main application." | 3 |

## 12.4 Discussion

Throughout the development of both the main and training application, we overcame a lot of challenges, identified potential areas of improvements, and gained useful insights.

### 12.4.1. Lessons learned with the obstacle detection system

The obstacle detection system [48], which was developed in the context of the MANTO project, was leveraged to train people with blindness and visual impairments by associating its obstacle detection distance capabilities with varying intensity pitch or haptic feedback. In this way distance information was encoded in an accessible format for the visually disabled providing a smartphone-based augmented reality feature. However, due to the currently employed cost-effective wide ultrasonic beam sensor, there are restrictions as far as it concerns the spatial configuration of the training location. From trials with the ultrasonic sensor HC-SR04, we concluded that its characteristics in conjunction with the developed obstacle detection framework are suitable for sparse city environments and, thus, our choice of training spaces was influenced by that fact. In contrast, experimentation with narrow/pencil beam ultrasonic sensors and various configurations of the obstacle detection framework demonstrates the effective application of the solution in dense city environments as well. However, these COTS sensors are considerably more expensive and, thus, might not be feasible to utilize them in training sessions where the probability of breaking is high.

### 12.4.2. Guidelines concerning the training process and training app

Throughout our ongoing effort of designing and implementing applications targeting groups of people with special needs, we have found that it benefits the most when a cognitively informed approach is followed [41]. The latter is an extension of the common iterative process followed in the engineering method with cognitive-based concepts that describe the mental processes utilized during problem-solving. This integration results in solutions that are very close to how individuals address their day-to-day challenges, thus, making their adoption easier and, simultaneously, reducing the high abandonment rates. This framework considers, also, as first-class criteria the pillars of safety, reliability, reinforcement and preferences as well as incorporates the immediate beneficiaries in the design process. Coupled with the above approach is the requirement to consider the users' needs in the broader social context as it makes clear the social implications of the available design choices, thus significantly pruning the design space.

The recommendations given in [70] were found to be effective. In particular, the authors suggest the employment of real-time object detection methods, relatively short in duration training sessions, easy-to-carry and use devices, limited communication of information pertinent to the situation for safety reasons, awareness regarding the social implications of the design choices as well as the adoption of procedures that ensure the privacy and security of the user's data.

Another useful consideration is to recognize that individuals who are blind or visually impaired are equally skilled to sighted individuals with the distinction of being unable to access the wealth of environmental information [71]. Due to the diversity in the amount and kind of environmental information individuals acquire and store, adaptable solutions are required to prioritize differentiated needs and preferences.

Crucial to the design of effective training applications is the input given by the O&M specialists as well. These specialists have invaluable information on what works regarding the processes and techniques employed to effectively teach orientation and mobility skills to the blind and visually impaired. Moreover, from our experience, the O&M courses can be leveraged to introduce new applications and features as individuals with blindness and visual impairments are more receptive since it takes place in familiar to them locations. Working in small groups preferably brings better results and organizing the available functionality to enable and promote self-discovery is important.

From a technological point of view, location-aware mobile devices can play an important role in spatial learning by detecting current user context and location, utilizing logging and, subsequently, analyzing navigational path traces to determine the user's routines.

Controlling the amount of the given information is critical to the success of the training application. Participants expressed their requirement to be in control, even with a push-based style of interaction, to determine when and the amount of information they would like to receive. Furthermore, as a better form of control the participants requested a combination of push and pull style of interaction, where they request information from the system and, in turn, the system continues to provide information to them for a period of time before fading out.

Given users prefer the combination of push and pull-based styles of interaction, as mentioned above, the next step is to find the correct balance for the training application. In contrast to the main application where the interaction should be geared more in favor of push-based interaction since the main responsibility is to transmit navigational instructions and other relative information, the training application instead needs to provide the users with the necessary options to control at their own will the required information in order to facilitate the learning process.

Finally, another suggestion made by the participants concerned the use of audio cues instead of issuing navigational instructions to signify the types of places and other points of interest they are passing by and thus expedite the process of tracing the virtual path.

### 12.4.3. Virtual Reality, training, adoption and overcoming challenges

Over the last 25 years, researchers and developers have worked on developing multisensory VR-based systems to help blind individuals develop orientation skills. The advantages of these solutions as highlighted in previous works include improved spatial information perception, solving spatial problems, practicing, and improving O&M skills, and developing O&M strategies [24, 26, 28], as well as enabling the user's independent interaction, displaying immediate feedback tailored to the user's sensory and cognitive abilities, and providing the opportunity to practice in a safe environment without time or professional constraints. Furthermore, virtual environments (VEs) can facilitate the work of O&M professionals in providing better training services [33]. Most VR systems contain both indoor and outdoor areas, allowing blind learners to preview a new environment ahead of time. In this way the learner while exploring the virtual environment can interact with landmarks and clues, thus collecting spatial information critical for the construction of cognitive maps applicable to real environments.

Smartphone-based AT applications, a complementary solution that tradeoffs virtual environment immersion with accessibility to a massively larger population, play an important role in helping blind people to conduct their life with as much independence as possible. Training them with regard to the usage of these applications is important to increase the chances of keep using them in the future as demonstrated in [72]. However, a number of other issues hindering smartphone-based ATs adoption need to be addressed as well. Specifically, these can be the result of either environmental conditions or specific design choices.

One of the environmental challenges affecting the adoption of smartphone devices is the case of situational impairments as they have been shown to degrade the performance of users. The study by [73], identified with the help of various participants several such factors that negatively affected their ability to use their smartphone devices. Specifically, using the smartphone device while walking presented challenges to some participants as it reduces motor control over situational awareness and makes it impossible to listen to sounds in the environment. Further compounding the challenge of using smartphone devices while walking is the case when other tasks are involved where situational awareness can be degraded even more. This is backed up by previous research that shows performance degradation from using a smartphone device during these kinds of circumstances, demonstrating simultaneously these effects may be more adverse for people with visual impairments. This suggests that it may not be possible to use smartphone devices without reducing situational awareness [74].

## 12.5 Design decisions and challenges

The challenges related to the design decisions made for smartphone-based applications include the following: 1) gestures-related issues, 2) a lack of consistency in the applications as there is no single way to access a feature, 3) different interfaces per application leading to confusion, 4) non-accessible-friendly features for non-visual users and 4) issues related to learning to use the talkback service by novices. This list is by no means exhaustive.

In order to address the challenges and deficiencies despite the selected technological approach, resources are required to aid the adoption process. However, our research team discovered that there is a scarcity of those relevant resources available further compounding a difficult problem that is both time-consuming and difficult to undertake. Currently, it is expected from the users to be persistent and willing to ask for aid. Especially the latter is impossible to eliminate no matter how well-designed a solution is as has been demonstrated by all of these years of research. Furthermore, even with the progress made where many challenges have been identified, there are several still overlooked or underexplored [75]. Below we provide a comprehensive list of open challenges that future research needs to address to achieve better smartphone-based accessibility:

- Learning and exploring - Challenges related to learning and performing movements on touchscreens have not yet been overcome, despite the effort put into that area. It remains difficult for individuals with blindness and visual impairments to discover and learn based on any given description, leaving them only with their support network for substantive assistance.
- Adapting mental models - New releases of the widely available operating systems and applications usually bring new changes to the existing interfaces, without any accompanying relevant descriptions in an accessible format, thus forcing users to adapt their daily routines to the new conditions every time a redesign of user experience occurs.
- Accessibility of applications - Although there is a great number of efforts targeting accessibility aspects of smartphone applications, the results are fragmented without providing a common frame of reference or any sort of actionable advice.
- Forced interfaces - The choice of a touchscreen interface does not seem to be the most appropriate one for blind users. Instead, a redesign of smartphones for the target group having more physical buttons could be a step in the right direction.
- Ubiquitous accessibility information - Individuals with blindness and visual impairments require access to a centrally available repository of information relative to accessibility issues for applications and devices, to facilitate the adaptation of the users' mental model caused by the ongoing non-standard interface changes introduced in each re-iteration. Users might be able to make meaningful choices with the help of a dedicated accessibility rating and other statistics.
- Enabling sharing and peer support - Many individuals find no support for their cases as it is either inaccessible or incompatible with their device configuration. Rodriguez et al. in [76] identified the shortcomings of the current communication methods that include asking questions to other people and/or searching online as both being time-consuming and removing the user from the context of the problem often providing no results. To address and achieve effective communication in an accessible manner, the right understanding and tools are required.

Finally, our prioritization for the future concerns the fine-tuning of the existing version of the simulation app as well as the design, implementation and validation of a VR application that will hopefully improve the trainability of the blind and visually impaired.

## 12.6 Conclusions

We created a supplemental training version, functionally equivalent to the main application, to help the user become familiar with the provided features in the context of training courses. This was a highly demanded request as besides learning to use the application itself, the training sessions can be used for acquiring long-term Orientation and Mobility skills. Furthermore, this demand is provoked partially by the varying skills blind individuals have in using complex technologies as well as from the challenges arising from the interaction with a complicated and dynamic environment.

The way forward in overcoming these challenges and somewhat reducing the burden on the blind and visually impaired is the provision of simulation-based navigation applications that incorporate in their process the use of familiar equipment and, at the same time, enable users to repeatedly navigate routes at their own pace and location. Additionally, another benefit of a simulation application is its friendliness and flexibility in not having to carry special equipment.

In our effort to design an effective training tool, we searched the literature for any shortcomings in the process related to learning about route navigation in complex environments. Typically, various in-situ navigation tools, tactile maps and virtual navigation solutions are used to facilitate the previously mentioned process. Nonetheless, these tools are time-consuming whereas our application avoids this issue by being less restrictive. Another added benefit of our application is the capability to protect the user from real-life hazards while providing a very close-to-reality simulation of the navigation process.

Users were, also, asked to review their interactions with the application and the educational process as soon as the training sessions were over. In general, most of the users evaluated the above process positively. Sentiment analysis on user responses confirmed the Usability and UX results. Finally, we concluded with the lessons learned and designated open challenges and future directions for achieving better smartphone-based accessibility.

## Appendix A

Table A1. SUS Questionnaire [183, 184]

| # 1 | Item |
|---|---|
| SUS-1 | I think that I would like to use this system frequently. |
| SUS-2 | I found this app unnecessarily complex. |
| SUS-3 | I thought the system was easy to use. |
| SUS-4 | I think that I would need the support of a technical person to be able to use this app. |
| SUS-5 | I found the various functions in this app were well integrated. |
| SUS-6 | I thought there was too much inconsistency among the app functionalities. |
| SUS-7 | I imagine that most people would learn to use this app very quickly. |
| SUS-8 | I found the app very cumbersome to use. |
| SUS-9 | I think I would feel very confident using this app. |
| SUS-10 | I needed to learn a lot of things before I could get going with this app. |

## Appendix B

This questionnaire was used to receive feedback from the users on the training procedure as well as utilize the collected data to conduct sentiment analysis to reach automatically a conclusion concerning the attitude of the users.

Training course assessment questionnaire :

1. Was the training application helpful in becoming accustomed to the main application’s functionality?
2. Are the command instructions accurate and helpful enough to control the application?
3. Is minimal action attainable for completing tasks? Does the completion of tasks require a minimal number of actions? (Minimal action)
4. Are the available formats of the issued instructions (orthogonal or clockwise) satisfactory enough?
5. Is the example concerning the recovery from an error back to the correct navigational path satisfactory?
6. Is the scenario concerning the obstacle detection device illuminating?
7. Is the scenario concerning the combined navigation with public means of transportation illuminating?
8. Is the scenario concerning passing traffic light crossing illuminating?
9. Is the training application compatible with screen readers?
10. Is the training procedure easy?
11. Would you consider the training application attractive to you?

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# Conclusion

Designing, implementing and validating assistive technology solutions for the sensory disabled individuals have an extra unique set of challenges. This is due to the fact that the predominant platform utilized for such solutions (i.e the smartphone) is not designed by any means to meet the special needs of the sensory disabled. As a matter of fact, smartphones, as have been demonstrated in the literature, fit poorly for such purposes due to the touch-based interface. Throughout, this dissertation various issues of design, implementation and validation were addressed, and many lessons were learned.

This dissertation started the presentation with a multi-dimensional survey that spanned the technical landscape of indoor and outdoor blind navigation systems, the literature for the reasons contributing to the low acceptance and adoption rates among people with blindness and visual impairments of those systems, and the training courses that help the users familiarize themselves with the provided functionality. We started with the technical review which is followed by the second part of issues around acceptance and training. Despite the technology solution employed, a navigation assistive system must provide support to individuals with visual impairments during independent mobility. This is usually accomplished via augmenting their senses and providing contextual awareness of their surrounding environment via audio-haptic interfaces. Nonetheless, the various modalities for providing navigation assistance need to constantly adapt to the preferences and behavior of the users that are changing along with the gained experience, preferences and necessity.

One would consider that with the plethora of solutions existing in the space, the problem of abandonment would be solved. However, as research-based evidence demonstrates, this is not the case. Taking a closer look into the challenges blind and visually impaired face when using such technologies reveals the errors that arise and, subsequently, the causes of abandonment. Studies have identified several factors that negatively affected their ability to use their smartphone devices. Specifically, using the smartphone device while walking presented challenges to some participants as it both reduced their motor control over their situational awareness and made it impossible to listen to sounds in the environment. Further compounding the challenge of using smartphone devices while walking is the case when other tasks are involved where situational awareness can be degraded even more. This is backed up by previous research that shows performance degradation of using a smartphone device during these kinds of circumstances, demonstrating simultaneously these effects may be more adverse for people with visual impairments. This suggests that it may not be possible to use smartphone devices without reducing situational awareness. Other challenges related to the design decisions made for smartphone-based applications include the following: 1) gestures-related issues, 2) a lack of consistency in the applications as there is no single path to a feature, 3) different interfaces per application leading to confusion, 4) non-accessible-friendly features for non-visual users, 5) lack of learning and exploring the available functionality of the solution, 6) lack of information on the available solutions and support, and 7) issues related to learning to use the talkback service by novices. This list is by no means exhaustive.

Training reviewed the basic skills required from blind users to develop for their well-being and as much as possible independent navigation along with the role of virtual and augmented reality applications in relation to learning and acquiring useful orientation, mobility skills as well as learning to use navigation applications. Another area to pay close attention to is that both individuals who are blind and visually impaired and the entire community that supports O&M for the target group are unfamiliar with the plethora of available systems, their capabilities, and subsequently their usage in O&M sessions.

From the interviews with the blind and visually impaired, the requirements were formed and categorized into the following categories:

1. Special characteristics of the BVI
    a. Perception of the Environment
    b. Navigation (in general)
    c. Pedestrian navigation
    d. Use of smartphones and browsers
    e. General features and suggestions
2. Requirements concerning usefulness and capabilities
    a. Obstacle detection
    b. Navigation
    c. Additional characteristics
3. Functionality requirements
    a. External stimuli
    b. Audio/voice interaction between the BVI and the apps
    c. Tracking and positioning accuracy and auxiliary devices
4. Usability Requirements
    a. Characteristics/features of apps and devices
    b. Device handling
5. Requirements concerning the learning process of the assistive apps and devices
6. Compatibility—parallel operation with other applications. Critique of applications, operating systems, and infrastructures
    a. Compatibility and parallel operation with other apps
    b. Critique on other apps, operating systems and infrastructure

From this effort two Applications were designed, BlindRouteVision to support outdoor blind navigation and BlindMuseumTourer to support indoor blind navigation. BlindRouteVision is an application emitting critical information, via issuing voice instructions, for ensuring the well-being of the individual during outdoor navigation. It combines high precision tracking capabilities coupled with an obstacle detection system that helps in avoiding them. The system consists of two subsystems that are tightly integrated. These include a wearable device incorporating an external GPS receiver with high precision tracking pedestrian mobility in real-time, a second device with an ultrasound sensor mounted on a servo mechanism functioning similarly to sonar, an Android application that acts as the central component of the system and, finally, a custom-made voice interface to enable fast and accurate user interaction with the application. The system, also, offers the capability to optionally combine pedestrian navigation with Public Means of Transportation via the incorporation of available real-time telematics services along with guaranteeing the safe passing of crossings near traffic lights. The latter, a result of a thorough survey of existing solutions presented in Chapter 8, is achieved with the help of another designed external waterproof device that allows monitoring and transmitting with zero latency both the status of the traffic light and its remaining time until the next change occurs. A carefully designed set of voice instructions, customizable to user preferences, provides the required information to ensure the correct and safe navigation of the users, as well as to convey information about potential obstacles along their path.

BlindMuseumTourer is, also, an Android application that enables individuals with blindness and visual impairments to autonomously navigate in indoor spaces with high accuracy and safety. It combines a newly proposed Pedestrian Dead Reckoning (PDR) algorithm with surface tactile ground indicator guides, the gyroscope sensor found on smartphone devices, and, optionally, BLE technology radio beacons that are used to correct the accumulated error of the PDR method. The capabilities of BlindMuseumTourer were evaluated inside the spaces of the Tactual Museum of Athens, one of the five tactual museums worldwide, organized around thematic tours including copies of famous artifacts from antiquity. The proposed PDR algorithm accurately tracks the user's position and the traveled distance minimizing as much as possible the associated error. The application provides a voice command-based interface to the users that, additionally, can be configured to match their preferences. In case of an emergency, BlindMuseumTourer can guide the users to designated places inside the museum as well as facilitate them to make emergency calls either to family members or public services. Finally, for the required internal space mappings, the proposed solution provides a companion web application that allows the employees of the Museum to create and modify the maps containing the configuration of the exhibition rooms. Based on the outcomes of this particular use case, in the future, we intend to evolve the application to enable navigation inside complex spaces including hospitals, shopping malls, universities and other public and private buildings.

Besides the technical evaluation of both these solutions, we also assessed issues relative to usability and user experience (UX). Through the use of quantitively measured tasks and standardized questionnaires, we received invaluable feedback. It greatly helped to improve the applications and, furthermore, highlighted the following:

1. The importance of having a guiding application that allows blind users to complete all their activities.
2. The necessity to adopt a design process that involves the blind and visually impaired users for the development of applications where users can recognize the functionality of the cognitive processes used during their navigation.
3. The necessity to design and implement a training framework for increasing the adoption and learning rate of the application.
4. The importance of blending the design process of both the educational framework and the technical capabilities of the system is to get a better and more robust result.

With these observations taken into consideration, we designed both a training course and designed, implemented and validated a training version on Android for the outdoor navigation. It is functionally equivalent to the main version and was used in the context of the special O&M courses. There, its value was demonstrated as users were able to learn orientation and mobility skills and, also, became familiar with the features of the main navigation application. All blind and visually impaired users who participated in the training sessions reported a desire to continue using the application in the future, which is in line with the goal to increase technology acceptance, in contrast to those who did not.

Finally, in order to validate the importance of training in relation to its potential to increase assistive technology acceptance, the widely used UTAUT was extended with training as a new external factor. The outdoor navigation system BlindRouteVision was used to assess the validity of the proposed extension. Statistical analysis by means of Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA) and Structural Equational Modeling (SEM) demonstrated the partial satisfaction of our model as training along with performance expectation predict behavioral intention. In the future, more assistive technology solutions will be used to further validate the proposed extension to UTAUT.

# Appendix

## UEQ+ Questionnaire

### Efficiency

**To achieve my goals, I consider the product as**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| slow | ○ | ○ | ○ | ○ | ○ | ○ | ○ | fast |
| inefficient | ○ | ○ | ○ | ○ | ○ | ○ | ○ | efficient |
| impractical | ○ | ○ | ○ | ○ | ○ | ○ | ○ | practical |
| cluttered | ○ | ○ | ○ | ○ | ○ | ○ | ○ | organized |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

### Perspicuity

**In my opinion, handling and using the product are**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| not understandable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | understandable |
| difficult to learn | ○ | ○ | ○ | ○ | ○ | ○ | ○ | easy to learn |
| complicated | ○ | ○ | ○ | ○ | ○ | ○ | ○ | easy |
| confusing | ○ | ○ | ○ | ○ | ○ | ○ | ○ | clear |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

### Dependability

**In my opinion, the reactions of the product to my input and command are**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| unpredictable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | predictable |
| obstructive | ○ | ○ | ○ | ○ | ○ | ○ | ○ | supportive |
| not secure | ○ | ○ | ○ | ○ | ○ | ○ | ○ | secure |
| does not meet expectations | ○ | ○ | ○ | ○ | ○ | ○ | ○ | meets expectations |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

### Personalization

**Regarding my personal requirements and preferences, the product is**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| not adjustable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | adjustable |
| not changeable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | changeable |
| inflexible | ○ | ○ | ○ | ○ | ○ | ○ | ○ | flexible |
| not extendable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | extendable |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

## Usefulness

**I consider the possibility of using the product as**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| useless | ○ | ○ | ○ | ○ | ○ | ○ | ○ | useful |
| not helpful | ○ | ○ | ○ | ○ | ○ | ○ | ○ | helpful |
| not beneficial | ○ | ○ | ○ | ○ | ○ | ○ | ○ | beneficial |
| not rewarding | ○ | ○ | ○ | ○ | ○ | ○ | ○ | rewarding |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

## Trustworthiness of Content

**In my opinion, the information and data provided by the product are**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| useless | ○ | ○ | ○ | ○ | ○ | ○ | ○ | useful |
| implausible | ○ | ○ | ○ | ○ | ○ | ○ | ○ | plausible |
| untrustworthy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | trustworthy |
| inaccurate | ○ | ○ | ○ | ○ | ○ | ○ | ○ | accurate |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

## Response behavior

**In my opinion the response behaviour of the voice assistant is**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| artificial | ○ | ○ | ○ | ○ | ○ | ○ | ○ | natural |
| unpleasant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | pleasant |
| unlikeable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | likeable |
| boring | ○ | ○ | ○ | ○ | ○ | ○ | ○ | entertaining |

I consider the product property described by these terms as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Completely irrelevant | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

## SUS Questionnaire

| # 1 | Item |
|---|---|
| SUS-1 | I think that I would like to use this system frequently. |
| SUS-2 | I found this app unnecessarily complex. |
| SUS-3 | I thought the system was easy to use. |
| SUS-4 | I think that I would need the support of a technical person to be able to use this app. |
| SUS-5 | I found the various functions in this app were well integrated. |
| SUS-6 | I thought there was too much inconsistency among the app functionalities. |
| SUS-7 | I imagine that most people would learn to use this app very quickly. |
| SUS-8 | I found the app very cumbersome to use. |
| SUS-9 | I think I would feel very confident using this app. |
| SUS-10 | I needed to learn a lot of things before I could get going with this app. |

## Sentiment Analysis Questionnaire

This questionnaire was used to receive feedback from the users on the training procedure as well as utilize the collected data to conduct sentiment analysis to reach automatically a conclusion concerning the attitude of the users.

Training course assessment questionnaire:

1. Was the training application helpful in becoming accustomed to the main application's functionality?
2. Are the command instructions accurate and helpful enough to control the application?
3. Is minimal action attainable for completing tasks? Does the completion of tasks require a minimal number of actions? (Minimal action)
4. Are the available formats of the issued instructions (orthogonal or clockwise) satisfactory enough?
5. Is the example concerning the recovery from an error back to the correct navigational path satisfactory?
6. Is the scenario concerning the obstacle detection device illuminating?
7. Is the scenario concerning the combined navigation with public means of transportation illuminating?
8. Is the scenario concerning passing traffic light crossing illuminating?
9. Is the training application compatible with screen readers?
10. Is the training procedure easy?
11. Would you consider the training application attractive to you?

## Interviews Questionnaire

We are developing two systems that aim to assist blind people to navigate.

1) The first concerns outdoor navigation and autonomous and safe pedestrian travel to predetermined destinations.

(a) Description: The app is intended to be used by Android smartphones.
Questions:

- Are there any comparative advantages of the iPhone over the Android smartphones? If so, what are they?
- Do you know smartphones specially designed for blind people (for example SmartVision 2)?
- What is the preferred operating system by blind people?
- Should they opt for the Apple iPhone?
- Will it be easy to switch to Android smartphones or to get a second smartphone that will use Android?

(b) Description: Our system utilizes Google maps for voice-guided navigation.
Questions:

- Are the voice capabilities of smartphones used by blind people and to what extent?
- Do you find Google maps easy and functional to use?

(c) There will be used headphones that do not isolate both eardrums. We recommend use of bone conduction headphones, or of a single ear headphone so that the ambient sounds are not dampened.

- Do blind people use headsets connected to their smartphones?
- Is it easy for a blind person to simultaneously recognize sounds from different sound sources by each ear?
- Do you find this specification reasonable?
- Do you have anything else to recommend?
- What kind of handset do you prefer? Bluetooth or wired?

(d) A simple keypad will be used for the blind person to easily interact with the application, to select routes and other available functions.

- Do you think the keypad should have any specifications regarding its functionality, ease of use and usability? (that is, how good it is to use and how easy it will be to use it)

(e) Description: The app will use voice commands to inform the BVI for obstacles in the direction of their movement.
Questions:

- How do you think obstacles should be reported and what instructions would be given to them along their route?
- Increasing continuous sound, interrupted sound, or vibration with increasing frequency as the obstacle approaches?
- Simultaneous or only voice reporting? How do you think the warning about the obstacle will be more user-friendly or practical?

(g) *Description*: There will be a configuration activity that allows the user to create an extensive list of destinations to be selected from the keyboard.
Questions:

- Do you find this easy for the blind?
- Are there any examples of navigation in the options menu?
- Are option menus widely used? (e.g. smartphone smartvision has an audio description function for the menu)

(h) *Description*: It will be possible to synchronize the application with traffic lights. We recommend that the system will be implemented centrally through the traffic management system so that the blind person does not depend on whether or not each traffic light is equipped with a sound broadcasting system.
Questions:

- Do you have any suggestions concerning these features?
- Is it sufficient that the mobile phone be able to produce a sound similar to that of traffic lights equipped with sound broadcast features for the blind people?
- Do you have any suggestions for improvements?

(i) Description: Weather information will be provided so that the blind person can dress appropriately for the pedestrian route.
Question:

- How do you keep up to date with the current weather?

(i) Description: The app will allow notifications of selected persons about the current position of the blind in case of need.
Questions:

- Who should be informed (relative, police, ambulance)?
- In case of automatic activation, is there a close person who can receive the message? (logically if there is no one answers the phone there will be a hierarchy of options on who will be automatically called).

(l) Description: The app will use real-time information from the OASA telematics system for routes and stops for the development of complex routes that may include urban transport, etc.
Question:

- How does a blind person now choose the means of transport?

(m) Description: The app will be connected to an external wearable subsystem, which could be fitted to, e.g., a hat to ensure clearer reception of the GPS receiver and sonar.
Questions:

- Do you think a wearable device can easily be adopted by a BVI?
- What could be the type of wearable device that should be used / worn by the BVI to improve GPS accuracy (eg vest, hat, or embedded in a cane)?

(n) Description: The application will be able to extract semantic information (along the way) which will be communicated to the blind person.
Question:

- What do you think are the objects of interest that a blind person would want to identify along the way (toilets, pedestrians, obstructed vehicles, shops / species identification)? - list completion.

2) The second application is a blind navigation system in public interior spaces with a pilot application to the autonomous tour of museums.

(a) It is designed for Android smartphones (as for the 1st app)
(b) It will use voice guidance (as for the 1st app)
(c) Description: Guidance will be provided along the tour route.
Question:

- What is the suggested way? Voice guidance (speech), audio or a combination of both?

(d) Description: The app will provide audio information about the exhibits the BVI has approached and notify the user about whether it is allowed to touch the exhibit.

Question:

- Do you have any suggestions for an additional specification?

(e) The app will have the ability to give accurate voice guidance at any time on how to access the help desk, the exit, the WC or the restaurant. Are there any other similar points of interest?

(g) Description: Ability to request assistance from Museum staff at any time.

(h) Description: Emergency call option. (will be answered by 1st app)

(i) Description: Design and implementation of an appropriate simple user interface on the touch screen of the smartphone.

Question:

- How do you propose to split the screen of the smartphone so that the blind can choose commands?

(j) Description: Screen reading will support special reading functionality for the blind and visually impaired.

Question:

- What is applicable today?

(k) The app will be used at the Lighthouse Museum of the Blind, and after the completion of the project at the National Archaeological Museum and the Acropolis Museum.

Question:

- Is there another indoor destination you would like to visit?

Questions:

- Do you find appealing what these apps have to offer?
- Will we be able to have mass participation of the BVI in the training on these apps, concerning device use, and by which means?
- How much time would a BVI person spend on training in these apps?
- What is the process and training through which the BVI will be able to gain confidence to navigate on their own?

Question:

- Now that the main features of the assistive navigation apps have been described to you, do you believe that the presence of a sighted escort along your trip (outdoors or indoors) is still necessary, given that you have learnt how to use the apps?
- To what extent these apps can support autonomous navigation of a BVI person?

Question:

- Do you believe that a training version of the apps, which could be easily parametrized and applied in familiar to you routes or locations by a sighted trainer, would increase the rate of acceptance and engagement of the apps?
- Do you believe that this could successfully substitute the need of training in real conditions (for example, in a museum)?

# List of publications

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10. Theodorou, P., Tsiligkos, K., Meliones, A., & Filios, C. (2022). A Training Smartphone Application for the Simulation of Outdoor Blind Pedestrian Navigation: Usability, UX Evaluation, Sentiment Analysis. Sensors, 23(1), 367. https://doi.org/10.3390/s23010367