IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 12 January 2023, accepted 4 February 2023, date of publication 10 February 2023, date of current version 16 February 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3244073

SURVEY

A Survey on Outdoor Navigation Applications for People With Visual Impairments

FATMA EL-ZAHRAA EL-TAHER[1], LUIS MIRALLES-PECHUÁN[1], JANE COURTNEY[2], KRISTINA MILLAR[3], CHANTELLE SMITH[3], AND SUSAN MCKEEVER[1], (Senior Member, IEEE)
[1]School of Computer Science, Technological University Dublin, Dublin 7, D07 H6K8 Ireland
[2]School of Electrical and Electronic Engineering, Technological University Dublin, Dublin 7, D07 H6K8 Ireland
[3]National Council for the Blind of Ireland, Dublin 9, D09 E4E9 Ireland

Corresponding author: Fatma El-Zahraa El-Taher (fatma.e.eltaher@mytudublin.ie)

This work was supported in part by the Science Foundation Ireland under Grant 18/CRT/6222.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Research Ethics Committee at the Technological University of Dublin.

ABSTRACT Outdoor navigation remains a challenging activity for People with Visual Impairments (PVI). Having examined the current literature, we conclude that there are very few publications providing a nuanced understanding of how PVI undertake a journey in an outdoor environment and what are their main challenges and obstacles. This is a critical step towards developing robust solutions that meet the requirements of this user group. We undertook a questionnaire-based study with the National Council for the Blind of Ireland (NCBI) and 49 PVI. According to the feedback from our questionnaire, current journey navigation apps do not provide PVI with sufficient information about traffic lights, crossroads, and physical obstacles to support a satisfactory interaction. Our study reveals key aspects of how PVI interact with outdoor navigation applications. Critical gaps exist, for example, over 63% of respondents indicated they had suffered an injury on at least one previous occasion when navigating outdoors. Based on the questionnaire feedback, we present a solution covering the main aspects of outdoor navigation for PVI. Our work aims to contribute to the improvement of outdoor navigation applications for PVI in the future.

INDEX TERMS Accessibility, outdoor navigation, users with blindness or visual impairment, sensory substitution devices, assistive technology.

I. INTRODUCTION

Vision impairment affected at least 2.2 billion individuals worldwide in 2021 [1]. Vision disabilities affect the independence of people in daily life activities such as reading, shopping, or commuting. This problem is more common in older adults, with one in three having vision loss after the age of 65 [2]. The main causes of vision loss in elderly people are age-related macular degeneration (AMD), cataracts, glaucoma, and diabetic retinopathy [3].

As assistive and universal approaches to technologies advance, People with Visual Impairments (PVI) are becoming more integrated and independent in society. Public services, public transport, and other entities need to adapt services, facilities, and information channels to their needs. Even though human aspects are crucial in the design process of assistive technologies, there is frequently a disconnect between the requirements of PVI and the developed products. This results in PVI opting to reduce or avoid the use of assistive solutions [4], [5].

Creating better applications also includes adapting them to the range of user types and needs. Therefore, a thorough understanding of the PVI's interests, activities, and habits is needed [6]. Increasing accessibility awareness is at the core of achieving universal design [7]. There is a variety of assistive technologies to support people with a visual impairment such as selecting clothing [8], differentiating banknotes [9], [10], and identifying people [11]. However, in the realm of outdoor navigation systems and Sensory Substitution Devices (SSDs), while some progress has been made [4], [12], [13],

The associate editor coordinating the review of this manuscript and approving it for publication was Alessandro Floris.

there is still a great deal of improvement to be achieved. As we have encountered in our survey, outdoor navigation remains one of the most difficult tasks for PVI, with over 63% of respondents in our survey injured during outdoor navigation at some point.

The navigation support needs of PVI, as well as the identification of the barriers they face for safe and independent travel, have been the subject of previous studies in the literature [4], [14]. We examined these studies in detail in Section II, noting that they do not investigate critical aspects of the PVI's outdoor navigation such as the preparation stage of an outdoor journey, locating and using safe crossing points at street junctions (intersections), and accessing visual information on the road such as signage, and temporary changes. We saw the need to conduct a comprehensive questionnaire, covering the gaps in the literature, to give insights into ways to decrease barriers, improve the provided support from institutions, and enhance the interaction between PVI and navigation technologies.

In this work, we designed and launched a questionnaire[1] in collaboration with the National Council for the Blind of Ireland (NCBI).[2] The questionnaire includes 24 questions about outdoor pedestrian navigation and defines challenges that PVI face during outdoor navigation (i.e., moving from one location to another, walking through different roads, and using public transport). We then report, analyze, and discuss the responses of the 49 PVI to our questionnaire.

Our contribution is two-fold. First, we highlight the information needed by PVI about the environment before and during their journey. This information includes road networks, whether or not there is a pavement, and public transport information (e.g., timetables, accessibility to the stations and stops, or stop locations). Secondly, we propose a solution for the development of assistive outdoor navigation systems based on the important insights provided by the participants' responses.

Our aim in this work is to address current gaps in the field and to propose a solution that improves the interaction between PVI and navegation applications. We expect our contribution expands the awareness of governments and institutions that support the PVI community, as well as the public. While our survey is based in the Irish context, we suggest that the needs of this group will be common across urban environments throughout the world.

The following is the outline for this paper: Section II discusses related work. Section III explains the questionnaire method and defines the focus group. Section IV reports the details of questions and answers. Section V provides a discussion about the main findings and limitations of our questionnaire. Section VI presents a potential solution. And finally, section VII highlights the key conclusions.

[1]The questionnaire is freely available and is open access: https://doi.org/10.21427/YQH2-1362

[2]The national association for PVI is a sight loss charity that serves approximately 55,000 people who are blind or vision impaired to live confidently and independently https://www.ncbi.ie/

II. RELATED WORK

This section provides a review of earlier work along three areas of investigation: outdoor navigation assistive systems, SSDs, and previous user-needs surveys. For each of these areas, we examine where gaps exist in understanding and serving PVI for outdoor navigation. A summary is provided for each of the three areas.

A. OUTDOOR NAVIGATION ASSISTIVE SYSTEMS

Significant development has been achieved in the field of assisted outdoor navigation systems for PVI over the past decade [4], [12], [13]. Assistive outdoor navigation systems refer to any technology related to supporting PVI in safe outdoor navigation. Therefore, it may include technologies aimed at enhancing maps for route planning or it can refer to any real-time application or technology useful to PVI during their journey. In a previous paper [4], we developed a taxonomy (Figure 1) for tasks and phases in outdoor navigation.

This taxonomy was created based on a systematic review of the research published on navigation supports for PVI. At the most basic level, it identified three key sequenced phases that cover the entire field of outdoor navigation systems, from environment mapping through journal planning and real-time journey execution. Each phase includes different tasks. The tasks are a set of actions and challenges that people with visual impairment must do to safely and efficiently go from the starting point to the final destination. These three phases effectively represent the higher-level research fields, while each task represents the research sub-domains.

AI is used to build navigation systems. Different AI approaches are utilized in environment mapping, journal planning and real-time navigation phases. However, to understand the area of outdoor navigation, further specifics need to be studied and analyzed.

1) ENVIRONMENT MAPPING

This phase entails mapping elements of the environment to information that PVI can access and use. These elements include intersections, traffic lights, crosswalks, sidewalks, and public transportation information.

In general, the purpose of the *intersection detection*[3] task is to detect features of intersections (e.g. location and shape) to support other downstream navigation tasks [15], [16]. It is regarded as the foundation of the route selection task [17], [18]. With the rise of AI for automated navigation, machine learning can now be used to digitise physical street features into map information. To date, three machine learning approaches have been used by researchers in the AI domain to address the problem of intersection detection: classification [19], [20], [21], [22], road detection and intersection detection [16], [23], [24], and object detection [25].

Defining the location and type of *traffic lights* is an important part of the environment mapping phase. Traffic lights are

[3]Note that in this section, words in italic style refer to one of the tasks in Figure 1.

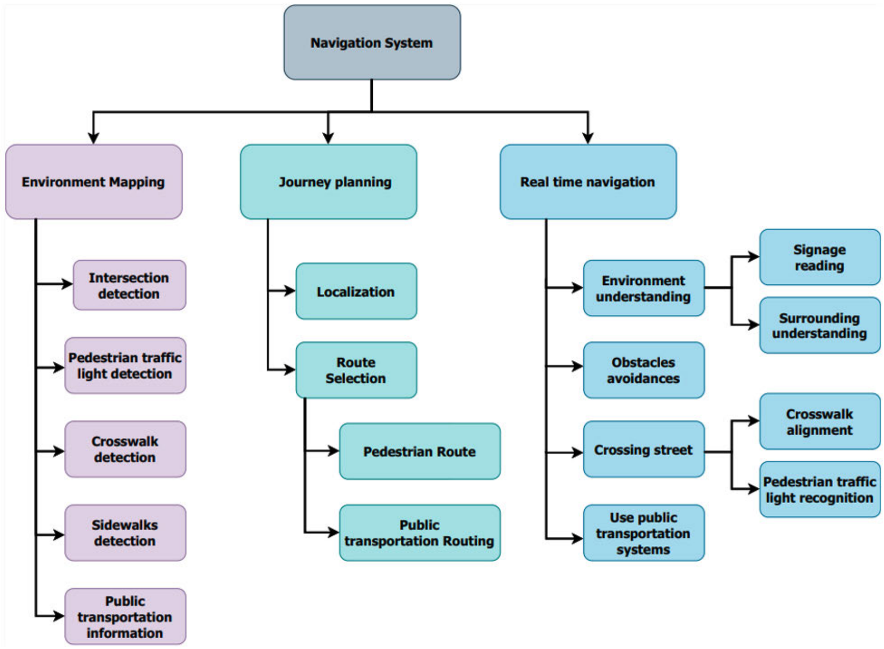


FIGURE 1. Taxonomy of navigation support tasks for people with visual impairment. It contains three main phases: environment mapping, journal planning, and real-time navigation [4].

necessary for crossing roads but are particularly critical for the PVI community [26]. The aim is to determine whether traffic lights are available at intersections and to define the type of traffic lights. Recently, the detection and geolocation of different objects from street images, such as traffic lights, telegraph poles, and trees are solved using two different approaches: one based on semantic segmentation using a machine learning segmentation model called fully convolutional neural networks (FCNN), [27], [28] and another one based on object detection approach using the Faster-RCNN model [29].

In the environment mapping phase, indicating *crosswalk* locations is a critical task to help increase the safety of crossroads [30]. Recently, different deep learning approaches are used to detect crosswalk form images such as classification [24], [31], [32], object detection [33], [34], segmentation [35], and location detection [26].

In outdoor navigation, the *sidewalk* is the safest place to walk, especially for PVI. Detecting sidewalks to produce a precise map is a considerable piece of work. A precise map can help in offering PVI more accurate instructions [36].

Public transportation is an important stage of outdoor navigation. To use public transportation, a lot of information must be detected and provided to PVI such as locations and accessibility information about stations or stops [37], [38]. The environment mapping phase as a pre-stage for PVI navigation has not been addressed by previous outdoor navigation assistive systems [12].

2) JOURNEY PLANNING

The journey planning phase involves determining travel routes between the starting and ending points. The user can choose the route between two points or between his location and destination. The journey planning phase contains two tasks: localization and route selection.

The user's current location is defined in the *localization* task. For generating correct directions, localization precision is critical. Global Positioning Systems (GPS) [39], [40], [41], [42], [43], [44], [45], [46] and image-based [47], [48], [49], [50] techniques can be used to allow PVI to identify their location.

After defining the start point, *route selection* determines the shortest path between two points. There is a scarcity of research to address this issue from the standpoint of this user group [51], [52]. The majority of PVI outdoor navigation systems relied on public route navigation services like BaiduMap [40], and QQMap [46]. These services do not consider the preferences of PVI.

3) REAL-TIME NAVIGATION

The purpose of the real-time navigation phase is to support PVI during the journey. This includes environment understanding, obstacle avoidance, crossing roads, and using public transportation.

The goal of the *environment understanding* phase is to assist PVI in comprehending their surroundings. This can be accomplished by reading any road signage, such as temporary closure notices [53], [54]. And also by describing their current environment. Understanding the environment boosts the confidence of PVI during outdoor navigation [50], [55], [56].

Obstacle avoidance is a critical task during outdoor navigation, enabling PVI to avoid colliding with obstacles such as post boxes, lamp posts or other pedestrians. There are two main approaches in this task: obstacle detection [57], [58], [59] and obstacle recognition [60], [61], [62].

Road crossing is a dangerous task for PVI. To do so securely, PVI must first align themselves correctly with the crosswalk [30]. Secondly, they must be able to recognize when a pedestrian traffic light turns green to determine when it is safe to cross the road [26].

For longer journeys, it is critical to use *public transportation*. PVI need assistive outdoor navigation systems to support them in using different public transport such as bus and metro [4]. The bulk of assistive systems does not incorporate functionality such as reading signs or interpreting the environment. There are numerous systems to avoid obstacles, but each one covers a restricted number of obstacles. There is currently no general way to support the use of all public transportation modes.

B. SENSORY SUBSTITUTION DEVICES AND APPLICATIONS

PVI utilize Sensory Substitution Devices (SSDs) and applications to support them in outdoor navigation. SSDs are used to convert an external input (audio, vision, etc.) into different inputs for helping individuals with an impairment in each sense. An example of SSD applied to PVI would be those devices that transform the images obtained from a camera into sound. Table 1 shows the tasks coverage in various SSDs and applications. A ranking from limited to high functionality is assigned, depending on the tasks supported by the application or device: one to two tasks supported for the phase are ranked as limited functionality. If most tasks are supported, they will be rated as having high functionality.

Environment mapping is not included in most SSDs and applications. In the real-time navigation phase, most SSDs and applications serve a subset of PVI navigation needs, such as obstacle avoidance. None of them provides PVI with the full breadth of support across all three areas.

To summarize, earlier work in real-time outdoor navigation assistive systems has not addressed all the tasks required to complete an outside excursion. It is critical to understand the gaps and wants of the end-user before introducing new enhancements to the field. Past attempts to understand PVI preferences need to be analysed to understand the gaps.

C. PREVIOUS END-USER SURVEYS

Although different surveys have been conducted to study PVI's preferences and needs when they navigate outdoors, there are still important gaps in the literature that need to be covered. This section provides a review of surveys in this area and discusses, from the PVI's perspective, the main findings, and gaps in the literature about the problems PVI face with the current applications.

In the last decade, there had been numerous surveys covering the disconnect between the information provided by navigation applications and the information required by PVI. Navigation applications have been geared towards people with full sight, with limited effort to cover PVI's needs. An example of this is shown by Williams et al. [82] who revealed these inconsistencies after a series of interviews with PVI. Their paper shows that sighted people struggle to understand the challenges faced by PVI when walking outdoors. It also points out that navigation instructions provided by sighted people to PVI are generally ambiguous or inaccurate, which makes clear the lack of understanding of PVI's needs and the importance of investigating the navigation activity from the PVI's perspective.

Along the same lines, Quinones et al. [83] conducted semi-structured interviews (a research methodology that allows open questions that give more space to the interviewer to focus on particular aspects) to discover PVI's strong dependence on mental maps to navigate to a familiar destination. Furthermore, when changes occurred in a familiar environment, PVI reported difficulties in navigating to the point of getting lost. This is not surprising because when navigating unfamiliar routes, they depend on private transportation services, sighted guides, or being accompanied by friends or family. The work of Quinones et al. [83] provides an accurate overview of the outdoor navigation process but without including details about the subtasks of each step, e.g., how to cross roads.

Another attempt to understand PVI's needs in outdoor navigation systems is the work of Alwi and Ahmad [84]. In their research, they designed a survey that contained groups of questions: two questions about occupation details, four questions about vision medical history, five questions about outdoor navigation history, and one question about the required features of a navigation system. Although this survey gives insights about outdoor navigation history, it only asked one question about PVI's needs in outdoor navigation systems. Since PVI's needs regarding navigation systems and the critical stages of outdoor navigation (e.g., journey planning) are such an important area, many more questions need to be asked for a proper understanding.

Interviews are a suitable approach to getting insights into PVI's experiences in navigation. An example of this is the work of Williams et al. [6] which presents the results of interviews with 30 people with vision impairment. The analysis of these interviews reveals valuable information in terms of orientation, mobility training, daily navigation issues, helpful and unhelpful devices, and the significance of social interaction in navigation. And it also gives a better understanding of the many personalities and scenario-based characteristics that influence navigation. Although these interviews cover many PVI-navigation subjects, Williams et al. [6] only asked one question about each subject during these interviews, and more questions are required to dig into the specific aspects of each area. There is still a lot to learn about the difficulties and the planning phase for outdoor navigation, even if these interviews go over a lot of material in terms of PVI navigation.

The literature in this area also shows important efforts to understand PVI navigation insights. For example, Nagraj et al. [85] studied the commuting habits of 14 PVI in India from low and middle-income neighbourhoods. They

TABLE 1. **Extent of functionality support by Sensory Substitution Devices and applications for tasks in three navigational phases for users with visual impairment.**

Name	Environment mapping	Journey planning	Real-time Navigation
Maptic [63]		H	L
Microsoft Soundscape [64]	L	H	L
SmartCane [65]			L
WeWalk [66]	L	H	H
Horus [67]			H
Ray Electronic Mobility Aid [68]			L
UltraCane [69]			L
BlindSquare [70]	L	H	L
Envision Glasses [71]			H
Eye See [72]			H
Nearby Explorer [73]	L	H	L
Seeing Eye GPS [74]	L	H	L
PathVu Navigation [75]			L
Step-hear [76]		H	L
Lazarillo App [77]	L	H	L
Lazzus App [78]	L	H	L
Sunu Band [79]			L
Ariadne GPS [80]			H
BrainPort [81]			L

	No functionality	L	Limited functionality	H	High functionality

covered different phases of the journey such as crossing highways and roads, travelling in the wet season, navigating at night, and using older public transportation. The research conducted by Banovic et al. [86] shows that PVI prefer to learn about their environment through four types of spatial information: high-level understanding, safety, navigation, and destinations and activities of interest. And that many factors influence how much information PVI acquire, including user skills, navigation aids, changes in the environment, frequency of visits, and familiarity with the path to the destination [86]. The main limitation of Banovic et al. [86] and Nagraj et al. [85] studies are that their sample size is small.

There are also contributions to this area focused on specific aspects of navigation activities. For example, Shiri et al. [87] conducted semi-structured interviews with PVI and hearing-visually impaired people to understand how they use public transportation. In the same line, Brewer and Kameswaran [88] interviewed PVI to understand how they use ride-sharing services such as Uber and Lyft. Similarly, Lee et al. [89] interviewed twelve remote sighted assistance users to gain a deeper understanding of the technical and navigational challenges that face both agents and users of sighted-assistance services (services where a sighted person guides remotely a PVI). Miyake et al. [90] conducted a questionnaire and interviews with six PVI. The scope of their work was to investigate problems that PVI faced when they walked up and down stairs. And the participants were asked about the importance of each guidance message and where it was necessary to notify them. The main findings were used to propose a navigation method for climbing stairs. This highlighted the effect of understanding PVI needs in the design of navigation aids.

Various research works have studied specific aspects of outdoor navigation for PVI over the years. For example, Kameswaran et al. [91] performed an investigation of how persons with visual impairments utilise accessible navigation applications and technology during navigation. They discussed the usage of navigation apps and technologies in the pre-journey, on-journey, and post-journey stages. Similarly, Hersh [92] interviewed one hundred PVI in five countries to investigate the importance of mental maps. These semi-structured interviews were designed to address three issues: how PVI understand space; how they use these representations to travel; and the implications in their journey of aids, assistance, and mobility training. In the same way, Bandukda et al. [93] conducted semi-structured interviews conducted with twenty PVI participants and eight mobility and orientation trainers. Their goals were to learn about orientation and mobility tools; give PVI training on orientation and mobility technology; change personal and social circumstances; and evaluate social influences. The aforementioned questionnaires and interviews [87], [88], [89], [90], [91], [92], [93] are focused on particular facets of the PVI's navigation activity, which is crucial to fully comprehend these facets. However, none of them covers critical aspects of the journey such as crossing a road and understanding surrounding visual features.

Many researchers have conducted their investigation into the suitability of certain types of navigation and wayfinding devices. For example, Arditi and Tian [94] conducted a short questionnaire with a group of ten PVI. The aim was to study the needs and preferences of a group of PVI who used a wearable camera-based navigation and wayfinding device in their journey. They mainly focused on the way users received and sent the information through the user interface.

Similarly, Limin [95] and Mauro et al. [96] conducted questionnaires about outdoor navigation for PVI. They focused on the outdoor travel experience, mobile phone usage, and GPS navigation tools. These questionnaires were not focused on understanding the outdoor navigation process, instead, they studied specific types of supportive tools.

To sum up, each of the previous surveys covers different aspects of PVI's requirements. However, we discovered that there are three important gaps in the literature. First, we were not able to find a survey that addressed the details of the preparation stage of an outdoor journey, even though they are critical for PVI navigation. And second, we did not find investigations covering the navigation piece of locating and using safe crossing points at street junctions (intersections). Additionally, we were unable to find a published study that addressed utilizing various forms of public transit and requesting assistance while doing so.

III. METHOD AND FOCUS GROUP

This section is divided into two parts. In the first part, the details of the methodology of this survey are discussed. In the second part, the participants' responses to our questionnaire are presented. The questions are grouped into six categories: outdoor navigation activity, navigation support, outdoor navigation hazards, journey preparation, crossing a street intersection and surrounding visual features.

A. METHOD

We conducted the questionnaire as part of a large study project on supporting PVI during outdoor navigation. Our first step in our work analysing this domain was to study the scope of outdoor assistive navigation systems. Our second step was to collect the experiences and requirements of PVI during outdoor navigation.

The purpose of the questionnaire is to understand what problems PVI face in the navigation environment, both when planning and while undertaking their journey. During the design phase of the questionnaire, we worked with the NCBI to identify appropriate questions regarding outdoor navigation as experienced by PVI. The questionnaire contained free-text questions, in addition to multiple-choice, and check-box questions. This approach was used to ensure the participants were given sufficient flexibility and freedom to convey their concerns regarding navigation. This includes inquiries on the type of environmental information PVI look for, how they prepare for a journey, what kind of assistance they require along the way, and the challenges they face.

The questionnaire was conducted in Ireland in the English language. To be able to take part in the study, participants were asked to confirm that they had read and understood the provided information about the project and data protection statement. As the data is anonymous, any reported findings are also anonymous. This study design was approved by the Ethics Committee of the Technological University Dublin (TU Dublin).

TABLE 2. Characteristics of the participants with blindness or visual impairment.

Characteristics	Participants
Information of vision impairment(%)	
- No vision	6.12%
- Light perception only	16.33%
- Loss of peripheral vision	38.78%
- Loss of visual acuity	46.94%
- Neurological vision loss	12.24%
- Difficulty with light adaptation/ glare -sensitivity	51.02%
- Difficulty with depth perception	44.9%
- Other	24.49%
Geographical distribution(%)	
- City or close to city	42.9%
- Rural or close to a town/village	55.1%
- Remote area	4.1%
- Other	2%

The questionnaire was prepared and carried out in collaboration with the NCBI. Given the COVID-19 environment at the time, it was decided to conduct the survey remotely, delivering the survey request by email to the NCBI service users. The NCBI reviewed the questionnaire as part of the survey development. With their expertise, they ensured that the questions were meaningful to PVI. The PVI participants responded to the questionnaire online.

The survey was promoted via Twitter and LinkedIn. A direct email was also sent through an Advocacy Network and promoted via the external NCBI Labs technology newsletter (approximate readership of 550 per week), and via the Labs Podcast. The survey users may have some bias towards those with good tech literacy to access email/social media.

As we seek to define the needs of PVI in outdoor navigation, we analyze the comments of participants and propose solutions. Free text questions were answered by part of the participants. The percentages of the participants in these questions are calculated based on the number of PVI who replied.

B. PARTICIPANTS

The questionnaire was open for three weeks and during that time we collected responses from 49 participants. We collected information on participants by asking them about their level of vision impairment, their demographic location, their age bracket, and the length of their vision impairment. Some responses to these questions are described below (see Table 2).

1) DESCRIPTIONS OF VISION IMPAIRMENT

The participants had the option of selecting multiple descriptions of their vision impairment: 6.12% of respondents have no vision, 16.33% of respondents have light perception, 38.78% of respondents have a loss of peripheral vision, 46.94% of respondents have a loss of visual acuity, 12.24% of respondents have neurological vision loss, 51.02% of respondents have difficulty with light adaptation/glare sensitivity, 44.9% of respondents have difficulty with depth perception,

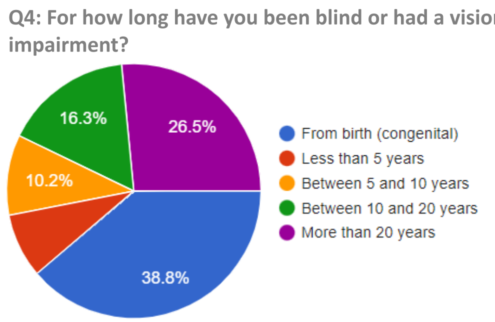


FIGURE 2. The period of time that individuals were blind or partially blind before taking the survey.

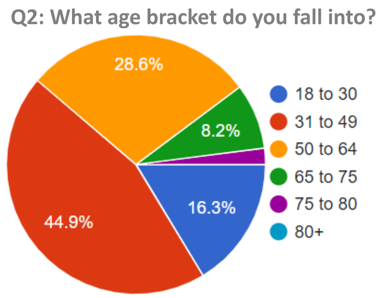


FIGURE 3. Percentage of participants in each age bracket.

and 24.49% of respondents have other descriptions of their vision impairment.

2) LENGTH OF VISION IMPAIRMENT

The length of time that each person has been blind or has a vision impairment varies, as shown in Figure 2. 38.78% of subjects are PVI from birth (congenital), 8.16% of subjects are PVI for less than 5 years, 10.20% of subjects are PVI for a period between 5 and 10 years, 16.33% subjects are PVI for a time of 10 and 20 years, 26.53% subjects are PVI for a period more than 20 years.

3) GEOGRAPHICAL DISTRIBUTION

Participants were grouped according to their geographical distribution: 55.1% of them live in rural or close to a town/village while 42.86% participants live in a city or close to a city. Just 6.12% of respondents live in remote or other areas.

4) AGE BRACKETS

The participants fall into different age brackets: 16.33% of the participants are between 18 and 30, 44.9% of the participants are between 31 and 49, 14% of the participants are between 50 and 64, 8% of the participants are between 65 and 75, and 2% of the participants is between 75 and 80 (see Fig. 3).

IV. SURVEY RESULTS

In this section, we analyze and discuss the questions and the participants' responses. We grouped questions according to their focus as shown in the following subsections.

A. OUTDOOR NAVIGATION ACTIVITY

The purpose of the questionnaire is to understand what limitations PVI encounter when navigating and how this can be used to identify improvements. First, we asked them about how frequently they walk alone in an outdoor environment to familiar destinations, such as work or the store, as well as to unfamiliar destinations. According to the responses, 73.5% walk alone (summation of positive answers) to familiar places on a daily and weekly basis (see Fig. 4). On the other hand, only 22.5% travel alone to unfamiliar destinations on a daily and weekly basis.

PVI independence rises when they are acquainted with the location in outdoor navigation (see Fig. 4). While 38.8% of participants walk alone to familiar destinations on a daily basis, only 8.2% of them do so in unfamiliar destinations. According to the responses, the number of participants who never walk alone in an unfamiliar place (26.5%) is more than double that in familiar areas (10.2%). This indicates the loss of independence that comes with not knowing the areas, pointing towards a need for better environment information to increase this confidence and ability to visit new places independently.

Public transportation is a key component of outdoor navigation, enabling longer journeys than pedestrian-only, and thus, enabling PVI to be further integrated into society. We asked participants about the means of transportation they regularly use. In this question, the participants could choose more than one option. According to the answers, 63.3% prefer to use the bus as a means of transportation and only 18.4% need sighted-guide assistance during the journey (see Figs. 5 and 6). 32.6% is the summation of infrequent users or those who never use public transport which means that they do not travel independently for anything other than a pedestrian-length journey (see Fig. 5). Other factors influence this outcome. For example, the bus network in Ireland is larger than the tram (Luas in Ireland) and train networks inside the same city, bus stops are street-based and generally accessible, and bus journeys tend to be less expensive than taxi or train journeys. Obviously, even for sighted people, aeroplane usage is for rarer longer journey trips.

For PVI, using public transportation systems is a complicated task as it entails a series of steps such as finding a stop/station, buying tickets, and finding the correct service [4]. Figure 7 shows that the number of people who use public transportation on a regular basis is inversely proportional to the percentage of people who need assistance using the same mode of transportation. This could be due to a variety of circumstances. If PVI used a transportation mode more frequently, they would become more familiar with it and better able to board and disembark with ease (see Fig. 7). In addition, the type of station has an impact on the accessibility of required services. For example, at a bus stop, the 'Finding the Correct Service' step is about catching the correct bus for the destination when it arrives at a bus stop [97], [98], [99], [100]. In contrast, in an airport or in a huge train station, this step is more difficult [37], [101].

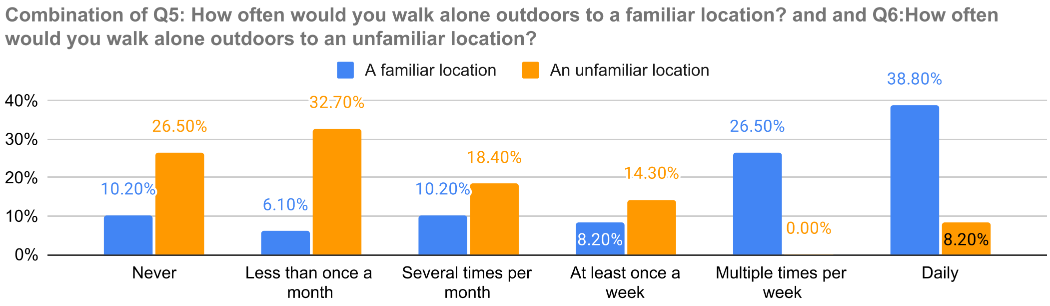


FIGURE 4. The change of independence in outdoor navigation based on destination familiarity.

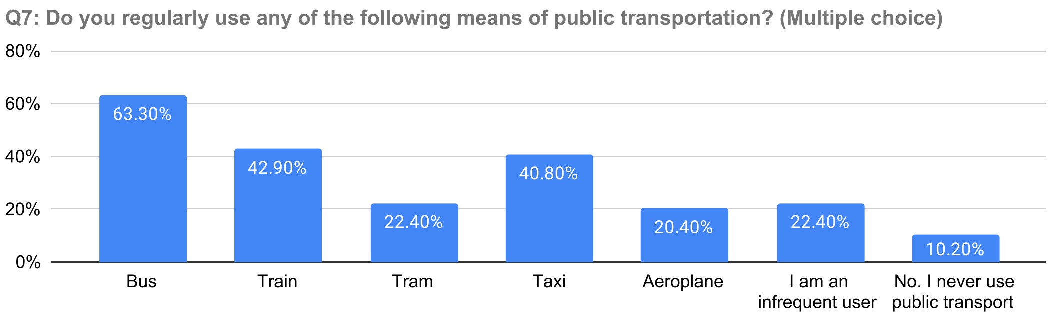


FIGURE 5. Percentage of public transportation types used regularly.

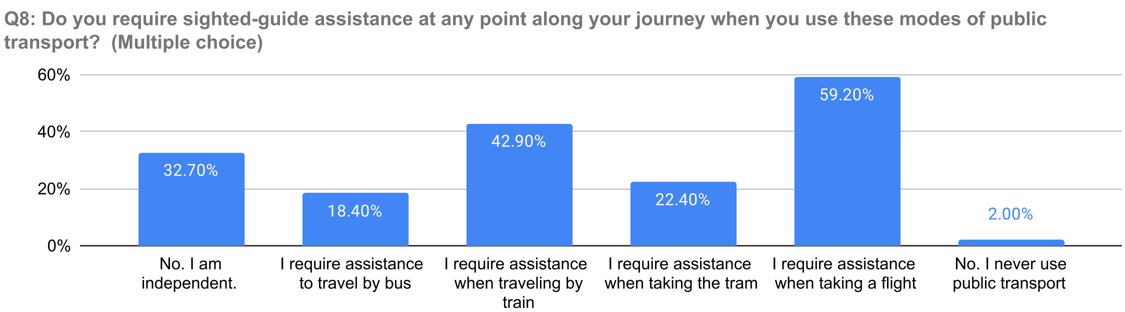


FIGURE 6. Percentage of requiring sighted-guide assistance by means of public transportation.

1) SUMMARY AND IMPLICATIONS

It can be stated that the level of independence with which PVI navigate to various destinations differs substantially depending on whether or not they are familiar with the journey route. They are more likely to be confident navigators when they are in familiar surroundings. This emphasizes the PVI's need to become better familiar with the environment before embarking on their journey. Knowing the route to the target destination, especially if it is unfamiliar, is insufficient. To navigate independently, PVI need further information about the environment, which will be confirmed in Section IV-D. This opens a new area of research in the navigation assistive system to enable PVI to acquire information about the navigation area.

Amongst PVI, the bus is the most popular mode of transportation in Ireland. PVI may rely on a sighted guide to use public transport, reducing their independence. Governments can improve the accessibility of transportation options to help PVI become more self-sufficient. Disability service providers could teach PVI how to use various modes of transportation. Since there is no assistive outdoor navigation system that supports PVI in using all modes of transportation [4], this is a promising research subject.

B. NAVIGATION SUPPORT

The following questions focus on discovering the different types of supportive methods that PVI use when accessing a community on foot.

We define technology here to refer to any form of electronic device or mobile application that is used to support PVI when travelling within the community. 61.2% of the participants use PVI-focused technology (see Fig. 8). Also, 20.4% of the participants would like to use technology but they did not receive any training. The others either refuse to use technology or do not have access to it. The high expense of technology, its reliability, and its complexity could explain why some individuals do not use it [6], [85], [91].

To understand their level of independence, we asked about the kind of support that they use. 42.9% of the participants are not independent on their pedestrian journey, i.e., they depend on sight-guide assistance. A long cane is the most popular supportive device used by 40.8% of the participants (see Fig. 9) followed by mobile applications (34.7%). After analyzing the responses based on the sort of information the supportive methods supply to PVI, we can see that PVI relies on long canes and guided dogs to avoid obstacles.

We also asked participants to define which device or mobile application they normally use. This was a free-text question to allow them to write the name of the device or mobile application they use. For this question, we got responses from 63.27% of the participants. We extracted the used application and device from the answers. While we asked them about devices or mobile applications they used, only a few SSDs were mentioned such as a magnifier, Trekker Breeze (a talking GPS for people who are blind or have low vision), a large screen, AirPods, or bioptic glasses. The rest of the answers are the names of mobile applications. Only one of the participants did not mention any mobile applications and depended on Trekker Breeze for navigation. Most of them rely on Google Maps to support them in travelling (see Table 3). Google Maps does not provide information such as street layout, which is required by PVI. Despite these limitations, Google Maps' advantages include the integration of public transportation and pedestrian routes, the accuracy of the data points, and the tool's relative accessibility [91]. Other aspects that may influence choices for using sensory substitution devices and software are their cost, reliability, and complexity [6], [85], [91]. According to the answers, 35.5% of the respondents use more than one application. This is aligned with the responses of participants in interviews with Kameswaran et al. [91] and Williams et al. [6]. PVI relied on a variety of technologies and apps to navigate because they required different forms of assistance in different situations [6], [91].

1) SUMMARY AND IMPLICATIONS

During outdoor navigation, the majority of PVI rely on an electronic device or a smartphone application. Nearly a quarter of the respondents do not utilize technology, either because they need training or because they do not have technological equipment. The provisioning of training support may be an important factor for a user to use navigation-assistive technology.

TABLE 3. Percentage of used technology to support travel in the community.

Used Technologies	Percentages
Google Maps	54.84%
Electronic Time tables	12.90%
Soundscape	6.45%
Apple map	6.45%
Be my eyes	6.45%
Blind square	6.45%
Other	35.48%

Many PVI (42.9%) depend on the sighted guide's assistance in outdoor navigation. This means PVI are not independent and the sensory substitution devices are not enough to support them. We can state that PVI rely on long canes and guide dogs to avoid obstacles. Google Maps is a popular option for helping PVI to navigate outdoors.

C. OUTDOOR NAVIGATION HAZARDS

The following questions are related to hazards that PVI face during outdoor navigation. Avoiding obstacles in a real-time navigation phase is a constant problem for PVI. It entails assisting PVI in avoiding collisions with stationary or moving street objects, whether on the ground or on a raised level, to reduce harm, distress, and loss of confidence. The majority of assistive navigation systems provide obstacle avoidance functionality [4]. First, participants were asked about their confidence in avoiding obstacles and street furniture (e.g., benches, bins, bus stops, or sandwich boards). According to the answers, nearly half of the participants do not feel confident in avoiding obstacles.

Related to the frequency of injuries when walking in public, 63.2% is the summation of the participants that have been injured at least once when walking in public areas, confirming the reason why they do not feel confident in avoiding obstacles. Only 36.7% of the participants did not get injured (see Fig. 10). This could be because the participants did not use a recent supportive navigation tool/app that provides information about road obstacles, the type of used supportive navigation device or app is unable to detect all types of obstacles, or simply that the situation was extremely difficult to navigate for a PVI regardless of assistive tools.

To understand more about the obstacles that they face on the road, we asked them to describe details of the event(s) when they were injured. This was a free-text question. We got a variety of responses including details about a single event, details about multiple events, and a list of obstacles. For this question, we received responses from 59.22% of the participants. We extracted and compiled the obstacles from the answers. The most common responses are uneven pavements/ground, poles, and hanging trees/branches (see Table 4). The nature of these obstacles varies based on the

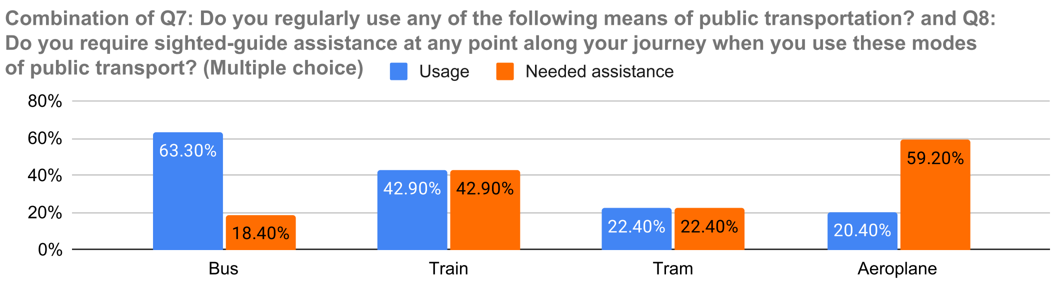


FIGURE 7. The difference between the percentage of usage and the required assistance at public transportation.

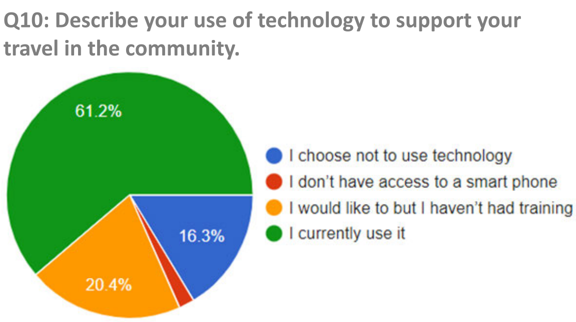


FIGURE 8. The percentage of PVI who use support technology while travelling in the community.

TABLE 4. Percentage of hazards that cause injury for PVI (Free-text question).

Hazards	Percentages
Hanging trees/branches	24%
Poles	24%
Uneven pavements/ground	24%
Tied bike/scooter	17%
A bike/scooter rider	14%
Bins	14%
Cars	14%
People	10%
Steps	10%
Bollards	7%
Signs	7%
Other	48%

level and the movement. Some are at head or waist level, such as hanging trees/branches, and others are on ground levels, such as uneven pavements/ground, bins, steps, and bollards. Some obstacles are moving barriers, such as cars and people, while others, such as poles and tied bikes and scooters, are stationary.

1) SUMMARY AND IMPLICATIONS

Nearly half of the participants did not feel confident in avoiding obstacles. The majority of PVI have been injured at least once while walking outdoors. There are different types of obstacles that PVI mentioned in their responses. These obstacles are at different heights and can be static (bollard) or dynamic (bike rider). Other road users' behaviours are to blame for some of these obstacles such as tied bikes, scooters, and cars.

Supportive institutes can provide training for PVI that includes methods and approaches for avoiding obstacles. The public's awareness can aid in reducing the number of impediments in the natural environment. PVI must avoid obstacles at all levels (head, knees, and ground) and movement statuses (static and dynamic). Despite the fact that there are several obstacle avoidance systems, each one only covers a small number of obstacles [4]. This is an active branch of research in navigation assistive systems. Cost, complexity, and precision must all be considered during the design process.

D. JOURNEY PREPARATION

Preparation for an outdoor navigation journey is a logical step for everyone to ensure that the correct route is taken on any journey. PVI participants depend on different ways to plan their journeys such as journey planning apps, website information, and a sighted person. For PVI, the most popular way is journey planning apps (see Fig. 11).

We asked the participants to describe other ways in which they plan their journey, if relevant, via a free text response. Less than half of the participants (46.9%) answered this question. The majority of them confirmed that they walk on their own after preparing their journey using one of the following methods: a navigation app, asking a sighted person, and depending on their memory.

PVI use a mental map in their navigation activity [83], [86], [92], [102]. A mental map is a route representation using high-level spatial processing that includes a survey-type image of the environment for efficient mobility between sites [92], [103]. Participants interviewed by Hersh [92] defined three advantages of using mental maps. First, mental maps are employed to organize information and provide hints about what is to come. Second, participants can determine the optimum path using mental maps. Finally, mental maps assist participants in comprehending the answers of sighted individuals when seeking assistance from sighted people.

Travel aids can be thought of as information processing devices that collect data from the environment and provide it to the user in a useful fashion [92]. Previously, Banovic et al. [86] discovered four forms of spatial

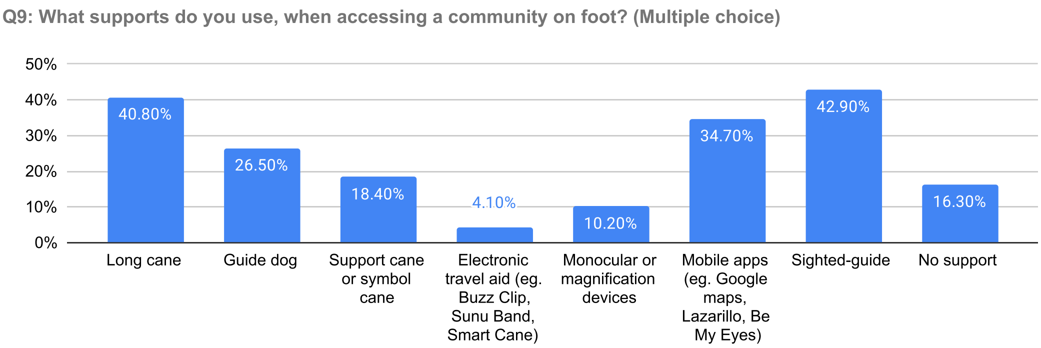


FIGURE 9. **Percentage of used supportive methods when accessing a community on foot.**

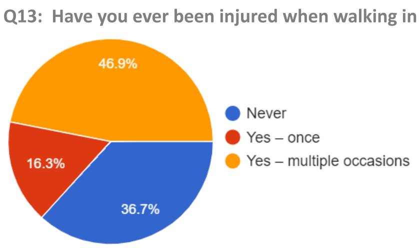


FIGURE 10. **The percentage of the participants who were injured when walking in public.**

information users learn about their environment: high-level information; safety; navigation; and places and activities of interest. For more details, we inquired about the kind of information PVI need to have before embarking on its journey. According to Figure 12, the top five important pieces of information for participants respectively are; whether there is a pavement, public transport information, street crossing point (e.g. zebra crossing), whether there are traffic lights at a junction, and street junction location and type.

Challenges in outdoor navigation had been the subject of previous surveys [95], [96]. Our results introduce new details about the type of needed environmental information to overcome these challenges. Most of these challenges can be overcome by providing PVI with information about the outdoor environment at various stages of the journey. For example, before embarking on their journey, PVI can be given information regarding public transition stops, traffic signals, sidewalks, and pedestrian crossing places. During the journey, information on a building's entry, stairs, obstacles, and holes could also be provided.

1) SUMMARY AND IMPLICATIONS

According to respondents, planning a journey in advance is an essential part of the trip. The findings reveal a variety of approaches used by PVI to assist throughout the planning stage. Environmental data must be provided ahead of time for the preparation stage.

The technology could be very useful in detecting environmental data and providing it to PVI during planning time. This information could boost route selection flexibility by allowing the inclusion or exclusion of roads based on PVI preferences.

E. CROSSING A STREET INTERSECTION

To get to planned destinations, the ability to crossroads safely is critical. For PVI, intersections are considered one of the main challenges during outdoor navigation [6], [85]. We need to know the level of information about a street intersection that is useful for participants. The most significant information for PVI is whether or not a street intersection is controlled by traffic lights and whether or not it has a pedestrian island or refuge (see Fig. 13). In Ireland, traffic light-controlled intersections typically include pedestrian lights, and tactile controls with audio feedback to indicate when it is safe for PVI to cross the intersection.

In a survey by Nagraj et al. [85], participants based in India explained their situation regarding crossing busy highways. The justification for crossing was that it was either the quickest route or that they were unaware of other options (e.g., pedestrian crossings or bridges over highways). We asked our participants about the strategy that they use to cross a road in a free text question. These responses were aggregated and summarized to define the common strategy. PVI depend on sighted people and audible light when crossings a road. If unavailable (no sighted people and no audible pedestrian crossing), they wait for traffic to stop or walk until finding a traffic light in another intersection area. In general, this matched the Indian participants' road-crossing method. However, the Indian participants stated that they cross the road even if there are no pedestrian crossings or highway bridges, whereas the Irish participants did not mention that.

1) SUMMARY AND IMPLICATIONS

For a street intersection, the presence of traffic lights and/or a pedestrian island, and the layout of the intersection are key pieces of information for PVI. Overall, PVI respondents use consistent approaches for crossing the road. Sighted

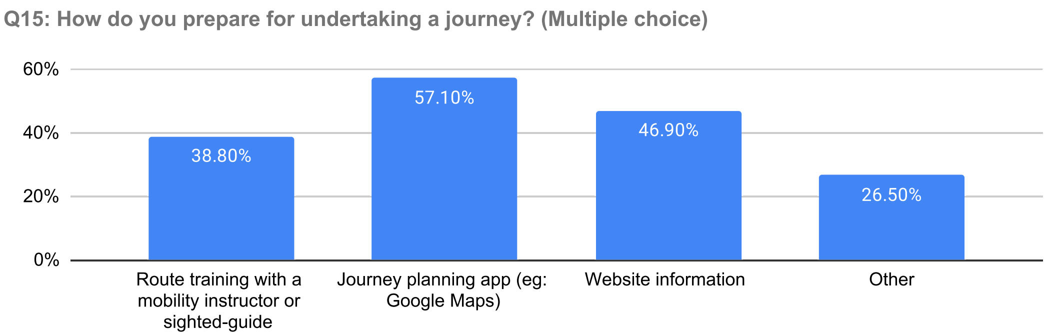


FIGURE 11. Percentage of used journey planning methods.

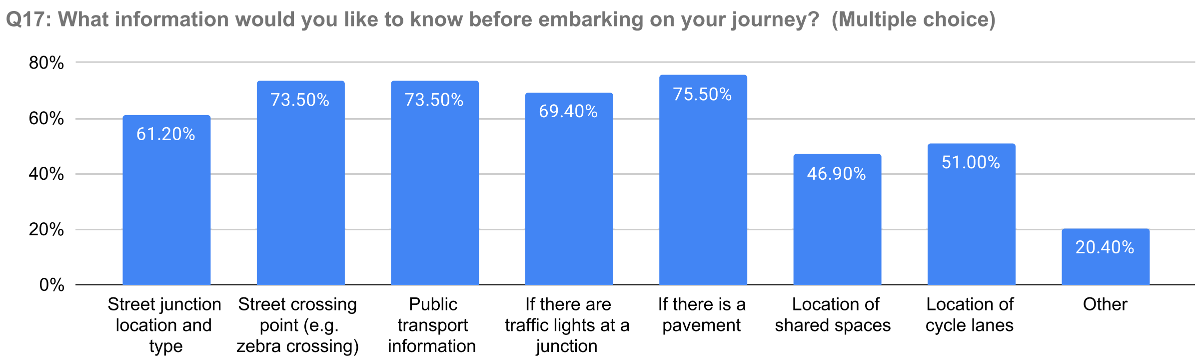


FIGURE 12. Information required before embarking on a journey by the percentage of respondents.

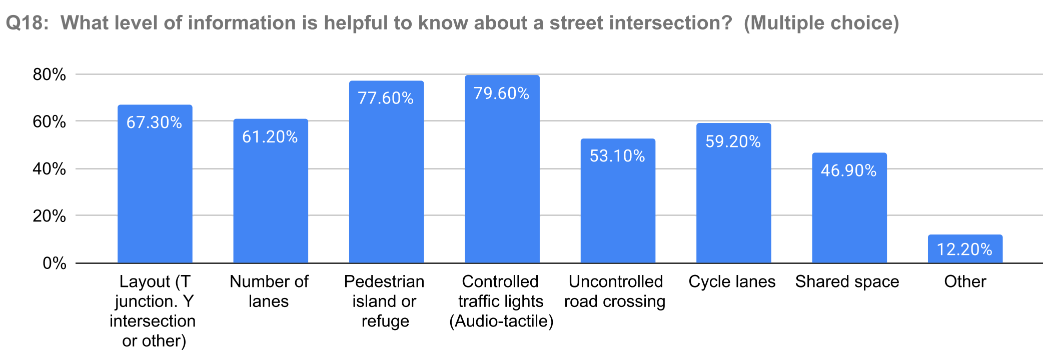


FIGURE 13. Information required about a street intersection before embarking on a journey by the percentage of respondents.

individuals and audible light are essential for PVI to cross the road. They wait for traffic to stop or walk until they find a traffic light in another intersection location if there are no sighted individuals or audible pedestrian crossings.

Detecting information about intersections automatically is a promising research topic. New approaches such as deep learning can be used to detect intersections from satellite images. Governments must consider PVI's needs while constructing intersections by including audible traffic lights.

F. SURROUNDING VISUAL FEATURES

For PVI, the objective of the environment understanding task is to be able to get a picture of their physical surroundings in real-time. This refers to the ability of PVI to read signs and understand their immediate environment. Our aim is to find out more details about what type of visual information PVI can access. We asked them about their ability to access road signage information as free text. We read and aggregate the answers. The responses showed that 59% of them cannot see

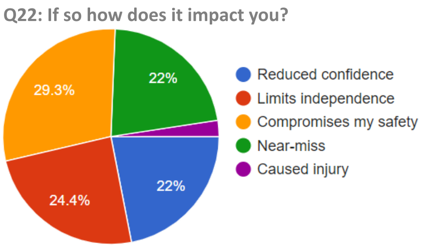


FIGURE 14. Percentage of the impact of temporary changes to the road and pavement on PVI.

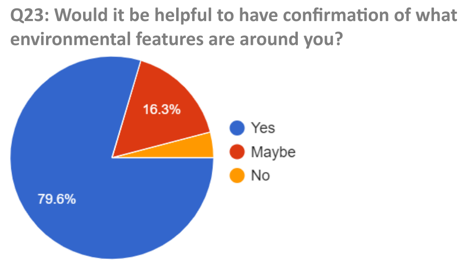


FIGURE 15. Percentage of PVI who confirm the need for environmental features.

road signage, 22.4% can, and the rest sometimes (it is unclear if this is because they can see under certain circumstances or because help is available).

On unfamiliar roads, the chances of mistakes, confusion, or simply getting lost might cause a breakdown. Another cause of the breakdown is the changes in the environment such as a tree that once served as a landmark might have been taken down; a sidewalk might be closed for development; and the weather might make some paths more difficult to navigate [83]. In a free text question, we asked PVI to describe the difficulty of accessing temporary changes on the road. According to the answers, 67.3% of them face problems accessing information about temporary changes such as when a road is closed during construction work. Current assistive navigation systems are unable to detect changes in the surroundings, let alone redirect navigators when they occur [4], [83].

PVI are affected in several ways by the difficulty of accessing temporary modifications on the road. In relation to this question, 22% of them indicated that it reduced their confidence in taking a journey, a further 24.4% of the participants found that modifications limited their independence, 29.3% of the participants expressed that their safety had been compromised, 22% of the participants had experienced near-miss, with a further 2.4% of the participants being physically injured (see Fig. 14).

The next question was about accessing information related to immediate walking areas such as crowded roads, shops on each side, or a construction area on a roadside. Almost 80% of the participants thought it would be helpful to have confirmation of what environmental features are around (see Fig. 15).

In another question related to external factors, the participants confirmed, as shown in Figure 16, that the increase in bicycles, e-scooters, shared spaces, and cycle lanes have a negative effect on their confidence.

1) SUMMARY AND IMPLICATIONS

During outdoor navigation, temporary changes in the road or surface have a negative impact on PVI. Most of them are unable to access temporary adjustments or interpret information posted on signs. PVI emphasizes the importance of having access to information about the surrounding area during navigation time. Bicycles and e-scooters undermine PVI's confidence.

Teamwork between governments and navigation apps/websites is required to notify and reroute PVI when temporary changes happen. PVI could be provided with knowledge about surroundings and read signs through the development of a current navigation assistive system. Governments should construct a separate lane for bicycles and e-scooters to offer a safe environment for PVI.

V. DISCUSSION OF OUR STUDY

After analyzing the questionnaire's responses, we highlighted the key findings from PVI responses and we also discuss the main limitations.

A. MAIN FINDINGS

The survey shows that 10.2% of the participants do not walk alone even in familiar places. In addition, more than a quarter of the participants never walk alone in unfamiliar places. This finding is consistent with previous research on PVI outdoor navigation [83], [95]. Also, the increase in the number of PVI who travel alone in well-known locations is back to using mental maps for familiar routes [83]. This indicates that the used assistive technologies are insufficient for fully independent outdoor navigation, with 42.9% of the participants dependent on sighted assistants in outdoor navigation. The total percentage of infrequent or never-users of public transportation—those who never travel for distances longer than a short walk—is 32.6%.

Additionally, 61.2% of participants employ PVI-focused technology. Similarly, existing research has shown that the majority of PVI use technology during outdoor navigation [6], [95]. In this study, 2% of the participants do not have access to a smartphone and 20.4% of the participants do not use assistive technology during their navigation because they do not know how to use it. Therefore, training them in the use of technology becomes a priority to increase their independence. Almost half of the participants do not feel confident in avoiding hazards. For example, 46.9% were hurt multiple times and 16.3% at least once, while walking in a public area. This is in line with the conclusions made in previous publications [6], [84], [86], [95], where obstacles are listed as one of the key issues that their participants cited. This

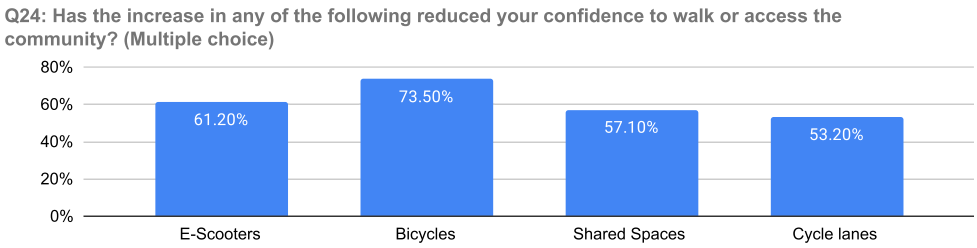


FIGURE 16. Effect of different factors in reducing confidence in users with blindness or visual impairment.

may indicate that the currently used assistive technologies do not fully fulfil the function of assisting in avoiding obstacles in outdoor environments.

PVI need to know certain conditions about the environment above and beyond the directions to a destination such as whether or not there is pavement, public transport information, street crossing points (e.g., zebra crossing), whether or not there are traffic lights at a junction, or street junction location and type. PVI do not have access to this kind of information, so it is considered a promising area of work for the research community.

The main objective of outdoor navigation assistive systems is to help PVI commute between different points of a city. The importance of outdoor navigation technology in PVI travel planning is highlighted by Kameswaran et al. [91]. As explored in the literature on challenges in outdoor navigation, crossing roads is considered one of the most challenging tasks for PVI [6], [84], [95]. PVI find it difficult to traverse routes that include intersections, especially if the intersections do not include traffic lights. According to our survey, 79.6% of participants affirm that knowing if an intersection is controlled by traffic lights is essential, and 59% of participants cannot read the road signage. Most of the participants cannot access information about temporary changes in the road and pavement because this information is not available on websites or journey planning apps.

This finding aligns with the literature as updating PVI about changes in the environment is not yet possible [83], [86], [96]. Based on our survey results, lack of access to information about environmental changes has a variety of negative implications on PVI, including reduced confidence, limited independence, compromises of safety, and an increase in near misses. Also, most participants agree that knowing about nearby environmental characteristics, such as busy roads and shops, is also beneficial.

B. LIMITATIONS

Our study has some limitations. First, there is an unbalanced number of respondents who live in various geographic locations, have various types of vision impairment, have been visually impaired for varying periods of time, and are of varying ages. This may introduce some biases in the responses. For example, the bulk of the participants (75.23%) is under the age of 50, probably because young users are more likely to fill out a survey online. This may have an impact on the type of supportive devices/applications PVI use during travel in the community as younger people are more likely to use phone applications.

Our survey is conducted with PVI with navigation experience in Ireland. Other countries may have different nuances, such as the behaviour of pedestrians around jaywalking versus using traffic lights, the availability of traffic lights with PVI-friendly controls, and the cultural level of acceptance and ad-hoc support for PVI when venturing out alone. We acknowledge such nuances exist and that our findings should be considered with these differences in mind.

There is uncertainty about the number of PVI who do not use public transportation. When PVI are asked about the kinds of public transportation that they use on a regular basis, 10.2% of the participants stated that they do not utilize public transportation. In contrast, when we inquired about the need for assistance in public transportation, only 2% of the respondents answered that they do not utilize public transportation.

The amount of information visually impaired people can learn before and during their journey depends on a variety of factors, including user skills, navigation aids, changes in the environment, frequency of visits, and familiarity with the area [86]. The impact of these variables was not investigated in this paper.

VI. PROPOSED SOLUTION

This section discusses our proposed structure for a solution for PVI support during outdoor navigation. In the ideal world, a unified technical solution that contains all mapped environment information to support journey planning would be available - alongside a second or same solution to support real-time navigation. Such a solution is emerging from the research and technical community in a fragmented fashion, as individual parts of what needs to be addressed.

Our goal is to find the safest and most comfortable route between the start and destination points for PVI in outdoor urban environments. As shown in Figure 4, 38.8% PVI walk alone daily and 26.5% do it multiple times a week. This means that 65.3%, travel on their own and therefore, they rely heavily on technology to navigate. They also walk in familiar locations (only 8.2% go to unfamiliar locations daily and only 14.3% do so once a week).

For PVI, crossing the street is a difficult task. To support PVI safety, we define the safest path as the route that has the most controlled intersections (intersections that have traffic lights). Controlled intersections support people during crossing roads, especially PVI. People depend on their vision to perceive surroundings information and make the best judgment about the right time to cross the road. Crossing the road without traffic lights is extremely perilous for PVI. Until they get to a junction, many times PVI do not know whether it is controlled by traffic lights. If PVI were able to receive information about intersections and traffic lights (an offline stage), they could choose the route with a maximum number of controlled intersections. Our proposed solution for suggesting the safest route to PVI combines developing approaches in an offline stage with generating an online enhancement routing algorithm.

The offline stage and the routing online stage are the two key steps of this solution. The information about the location and type of intersections and if traffic signals can be detected is done in the offline stage. Satellite and street view images can be used to detect this information using state-of-the-art deep learning models. This data can be added to existing maps. Pre-defining controlled intersection information gives flexibility to the routing phase by allowing users to select roads based on their preferences.

A. STRUCTURE OF OUR SOLUTION

In this subsection, we explain the structure of our solution using the diagram shown in Figure 17. According to Q15 (see Fig. 11), most PVI prepare their journey using a website or an application, therefore we proposed a navigation application that covers the main aspects that have been highlighted in our survey.

Our solution is structured in four different phases. The first one focuses on gathering and structuring the data so that when the user plans to undertake a journey, the system can recommend the most suitable one. The other three phases are executed just before, during, and after the user decides to take a journey. Our solution is compatible with other SSDs such as canes and guide dogs that PVI already use according to Q9 (see Fig. 9).

1) PHASE 1: BUILDING STATIC MAP

In this phase, information about roads is extracted from satellite images. Using computer vision and ML is possible to automatically create maps that can be used when calculating the best route for PVI.

The following activities can be performed using ML:

- **Detect intersections, traffic lights, and crossroads:** Based on Q17 (see Fig. 12), PVI need information mainly about street intersections, crossing points, and traffic lights. Traffic lights include a sound signal that alerts PVI when they can cross. Based on Q18 (see Fig. 13) knowing if the traffic lights had a sound signal is the most important information with 79.6%.
- **Detect and evaluate the pavement:** According to Q17 (see Fig. 12), the most important thing for PVI before embarking (with 75.5%) is whether or not there is a pavement on the ground. There is a special kind of surface designed for PVI called tactile pavement that uses different textures (corduroy, blister, stripes…) to assist PVI in their navigation.
- **Detect static obstacles and cycle lines**: According to Q17 (see Fig. 12), 51% of the users find it difficult to detect if they are walking over a cycle line. Cycles lines are becoming more popular in cities as a strategy to combat climate change [104], so presumably, there will be more in the coming years, and it could become an important factor for PVI outdoor navigation. According to Q24 (see Fig. 16), the increase in bicycles, e-scooters, and cycle lines impacts the confidence of PVI in a negative way.
- **Collect public transportation information:** Information about public transport is one of the priorities of PVI according to Q17 (see Fig. 12). This fact is confirmed by other publications [105]. PVI need to know where the stop is (location), when the vehicle arrives (timetables), which one is the right vehicle (vehicle identification), or when to get off the vehicle (destination arrival).

2) PHASE 2: BEFORE JOURNEY

The journey planning phase involves determining travel routes between the starting and ending points. Users can choose the route between two points or between their location and destination. The journey planning phase contains tasks such as localization and route selection, temporary changes, estimating human density, and estimating the best routes.

- **Set start and destination points:** Setting the starting and finishing point might seem pretty obvious but PVI struggle to do so. According to Q10 (see Fig. 8) 61.2% already use technology, but there is still a large percentage (20.4%) that would like to use it but cannot because they need training. Again, it is not just building the app, we need to teach PVI how to use it. Some of them may find it more difficult due to their advanced age.
- **Check temporary changes in the area:** According to Q22 (see Fig. 14), temporary changes in the road or pavement are a great threat to the PVI's safety and also limit their independence. Facilitating this information is key for the safety and comfort of PVI.
- **Estimate human density:** According to Table 4, 10% of the injuries have been caused by colliding with pedestrians. Other studies confirm that crowded areas make it difficult for PVI to interact with crowded areas because they have to avoid bumping into someone while using the mobile device at the same time [106]. Preventing PVI from navigating high human-density areas makes their journey more comfortable and prevents injuries.

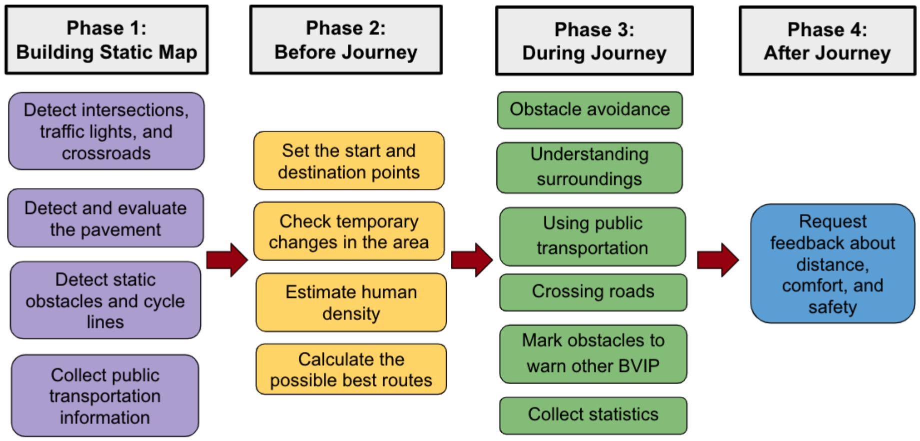


FIGURE 17. Proposed structure for the solution for PVI outdoor navigation composed of four different phases.

- **Calculate the best possible routes:** The best route should be calculated considering all the important things that make a journey safe and comfortable for a blind person. There is a trade-off between safety and distance, and sometimes PVI users will need to decide based on the different options. For example, if one route is twice the distance of the other but the longer one has tactile pavement, which one should the system recommend?

3) PHASE 3: DURING JOURNEY

The purpose of this phase is to support PVI during their navigation in real-time. This includes environment understanding, obstacle avoidance, crossing roads, and using public transportation.

- **Obstacle avoidance:** Avoiding obstacles is one of the main priorities an app should have since, according to Q13 (see Fig. 10), 46.9% of the participants have been injured multiple times during the navigation. Table 4 suggests that some obstacles could be removed if they were reported such as hanging trees and branches, poles, or bins. Those will always be in the same position, and they can be removed. Alternatively, PVI can get a warning message when navigating near an obstacle. There are other obstacles such as parked cars, motorbikes, and bikes that are more difficult to avoid since they appear for little time (normally a few minutes/ hours).
- **Understanding surroundings:** It is very important for PVI users to have information if they are going through a park, a pedestrian area, a crossroad, etc. And if there is an intersection, they would like to know how many roads the intersection has and if cars are coming in one way or both ways.
- **Using public transport:** PVI in Ireland prefer to travel by bus and according to Q7 and Q8 (see Fig. 7), it is also the transport they required less assistance (only 18.4%). Additionally, according to Q17 (see Fig. 12) in which 73.5% require information about public transportation before embarking on a journey. This fact is also confirmed by other publications [105]. PVI prefer to know the timetables and when their bus arrives rather than having to rely on other passengers.
- **Crossing roads:** According to Q18 (see Fig. 13) the information related to street intersections is especially sensible for PVI since it is here where there is more risk of having an accident. Having information in advance about the number of lanes, if there is a pedestrian refuge/island, if the traffic lights include sound signals, and so on, is also very important for them.
- **Mark obstacles to warn other PVI:** Reporting an obstacle such as a fallen tree, a bench, or any other obstacle, can prevent PVI from crashing in their future travel by giving them a warning message when they are near that location. As can be seen in Table 4, there are a lot of obstacles that could harm them. And according to Q13 (see Fig. 10), 46.9% of PVI have been injured multiple times. Reporting obstacles can be done in collaboration with sighted people.
- **Collect Statistics:** This step gathers some statistics about the journey such as time, average speed, time stopped, and number of stops, among others.

4) PHASE 4: AFTER JOURNEY

In order to improve and refine the system we need to ask users for feedback on different aspects of their journey.

- **Request feedback about distance, comfort, and safety:** Asking PVI about their experience on their journey helps to update the information for improving the route suggestions in the future. There will be questions like the quality of the route if a larger distance justifies safety, if there was any obstacle, if there was tactile pavement, if the access was easy, or if they felt uneasy at some point in the journey. Information about the level of crowding in the areas is also relevant. Finally, we suggest including a text box in case users want to report anything else.

VII. CONCLUSION

This paper adds to the body of knowledge on outdoor navigation for PVI by providing in-depth information regarding PVI's habits and needs. It reports and discusses the responses of 49 PVI to a study conducted in collaboration with NCBI. The study questionnaire targeted PVI who live in Ireland. The paper reports the responses of the participants and conducts a deep analysis of them. After analysing the responses, the main findings are highlighted and explained. We also introduced a solution composed of four phases that include new features and enhancements in assistive outdoor navigation systems. We contend that our solution can improve the interaction between PVI and outdoor navigation systems.

The findings of this questionnaire can help the research community, governments, support institutions, and the public to better understand PVI's needs to improve their interaction with navigation apps. Our solution considers these aspects to allow the development of more inclusive and accessible applications in the future.

The main findings of our research are presented in the following points:

- The research community needs a better understanding of both PVI requirements and current gaps in meeting those, towards producing assistive navigation systems that match the end-user expectations. There is still work to be done by the research community to make environmental information available and accessible by PVI. The research community has an important role in investigating and improving new technologies to support PVI during real-time navigation.
- Governments, both local and national, should consider PVI needs in environmental design and funding, such as the provision of adequate pavements and the design of appropriate traffic lights. We see the collaboration between governments and providers of websites and journey-planning apps as key to tackling the problem of temporary changes in the environment. As a result of this collaboration, routing apps and websites could ensure that any changes in the environment are fed into the route planning information sources that serve the PVI community well. To help PVI, we suggest governments ensure that every intersection is controlled by traffic lights.
- The institutions that support the PVI community could train PVI to walk alone in familiar and unfamiliar environments. Supportive institutions can hold training to teach PVI how to walk alone in a familiar and unfamiliar environment and how to use technology. Older adults tend to have the most problems with technology and we found training them in the use of technology is necessary.
- For the public, greater awareness of the problems that PVI face will make people more considerate and supportive of their behaviour. The public could assist PVI by removing obstacles from sidewalks to lessen the likelihood of being hit and injured.
- PVI need to know more about the environment before starting their journey such as knowing if there is a pavement, reading public transport information, locating street crossing points (e.g., zebra crossing), detecting a street junction location and type, and knowing if there are traffic lights at a junction. According to the answers, 63.2% of PVI have been injured in outdoor navigation. The participants' responses show that PVI have no mechanism to find out if an intersection is controlled by traffic lights until they arrive at the intersection. Intuitively, a lack of traffic lights at intersections makes crossing a road a very dangerous and time-consuming activity. PVI need training on how to use technology during outdoor navigation to feel more confident and independent.

For future work, we would like to design some of the modules presented in our solution by implementing state-of-the-art techniques in ML and computer vision. For example, detecting intersections and crossroads from satellite images and maps, detecting if those intersections have traffic lights, and calculating the number of roads they have.

REFERENCES

[1] WHO. (Jan. 2023). *Blindness and Vision Impairment*. [Online]. Available: https://www.who.int/en/news-room/fact-sheets/detail/blindness-and-visual-impairment
[2] D. A. Quillen, "Common causes of vision loss in elderly patients," *Amer. Family Physician*, vol. 60, no. 1, pp. 99–108, 1999.
[3] P. T. Harvey, "Common eye diseases of elderly people: Identifying and treating causes of vision loss," *Gerontology*, vol. 49, no. 1, pp. 1–11, 2003.
[4] F. E.-Z. El-Taher, A. Taha, J. Courtney, and S. Mckeever, "A systematic review of urban navigation systems for visually impaired people," *Sensors*, vol. 21, no. 9, p. 3103, Apr. 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/9/3103
[5] H. Walle, C. De Runz, B. Serres, and G. Venturini, "A survey on recent advances in AI and vision-based methods for helping and guiding visually impaired people," *Appl. Sci.*, vol. 12, no. 5, p. 2308, Feb. 2022. [Online]. Available: https://www.mdpi.com/2076-3417/12/5/2308
[6] M. A. Williams, A. Hurst, and S. K. Kane, "'Pray before you step out': Describing personal and situational blind navigation behaviors," in *Proc. 15th Int. ACM SIGACCESS Conf. Comput. Accessibility (ASSETS)*. New York, NY, USA: Association for Computing Machinery, 2013, pp. 1–8, doi: 10.1145/2513383.2513449.
[7] T. Chambel, P. Antunes, C. Duarte, L. Carriço, and N. Guimarães, "Reflections on teaching human-computer interaction to blind students," in *Creativity and HCI: From Experience to Design in Education*. Boston, MA, USA: Springer, 2009, pp. 123–142.
[8] K. Tateno, N. Takagi, K. Sawai, H. Masuta, and T. Motoyoshi, "Method for generating captions for clothing images to support visually impaired people," in *Proc. Joint 11th Int. Conf. Soft Comput. Intell. Syst. 21st Int. Symp. Adv. Intell. Syst. (SCIS-ISIS)*, Dec. 2020, pp. 1–5.
[9] L. Dunai Dunai, M. C. Pérez, G. Peris-Fajarnés, and I. L. Lengua, "Euro banknote recognition system for blind people," *Sensors*, vol. 17, no. 12, p. 184, Jan. 2017.
[10] C. Park, S. W. Cho, N. R. Baek, J. Choi, and K. R. Park, "Deep feature-based three-stage detection of banknotes and coins for assisting visually impaired people," *IEEE Access*, vol. 8, pp. 184598–184613, 2020.

[11] B. Mocanu, R. Tapu, and T. Zaharia, "DEEP-SEE FACE: A mobile face recognition system dedicated to visually impaired people," *IEEE Access*, vol. 6, pp. 51975–51985, 2018.

[12] S. Khan, S. Nazir, and H. U. Khan, "Analysis of navigation assistants for blind and visually impaired people: A systematic review," *IEEE Access*, vol. 9, pp. 26712–26734, 2021.

[13] C. Prandi, B. R. Barricelli, S. Mirri, and D. Fogli, "Accessible wayfinding and navigation: A systematic mapping study," *Universal Access Inf. Soc.*, pp. 1–28, Sep. 2021. [Online]. Available: https://link.springer.com/article/10.1007/s10209-021-00843-x#citeas

[14] A. Aladrén, G. López-Nicolás, L. Puig, and J. J. Guerrero, "Navigation assistance for the visually impaired using RGB-D sensor with range expansion," *IEEE Syst. J.*, vol. 10, no. 3, pp. 922–932, Sep. 2016.

[15] P. Li, Y. Li, J. Feng, Z. Ma, and X. Li, "Automatic detection and recognition of road intersections for road extraction from imagery," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 43, pp. 113–117, Aug. 2020.

[16] D. Costea, A. Marcu, M. Leordeanu, and E. Slusanschi, "Creating roadmaps in aerial images with generative adversarial networks and smoothing-based optimization," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops (ICCVW)*, Oct. 2017, pp. 2100–2109.

[17] J. Dai, Y. Wang, W. Li, and Y. Zuo, "Automatic method for extraction of complex road intersection points from high-resolution remote sensing images based on fuzzy inference," *IEEE Access*, vol. 8, pp. 39212–39224, 2020.

[18] J. Cheng, T. Liu, Y. Zhou, and Y. Xiong, "Road junction identification in high resolution urban SAR images based on SVM," in *Proc. Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput.* Basel, Switzerland: Springer, 2019, pp. 597–606.

[19] A. Kumar, G. Gupta, A. Sharma, and K. M. Krishna, "Towards view-invariant intersection recognition from videos using deep network ensembles," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 1053–1060.

[20] D. Bhatt, D. Sodhi, A. Pal, V. Balasubramanian, and M. Krishna, "Have I reached the intersection: A deep learning-based approach for intersection detection from monocular cameras," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2017, pp. 4495–4500.

[21] M. Oeljeklaus, F. Hoffmann, and T. Bertram, "A combined recognition and segmentation model for urban traffic scene understanding," in *Proc. IEEE 20th Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2017, pp. 1–6.

[22] T. Koji and T. Kanji, "Deep intersection classification using first and third person views," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2019, pp. 454–459.

[23] K. Rebai, N. Achour, and O. Azouaoui, "Road intersection detection and classification using hierarchical SVM classifier," *Adv. Robot.*, vol. 28, no. 14, pp. 929–941, Jul. 2014, doi: 10.1080/01691864.2014.902327.

[24] V. Tümen and B. Ergen, "Intersections and crosswalk detection using deep learning and image processing techniques," *Phys. A, Stat. Mech. Appl.*, vol. 543, Apr. 2020, Art. no. 123510. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378437119319582

[25] M. Saeedimoghaddam and T. F. Stepinski, "Automatic extraction of road intersection points from USGS historical map series using deep convolutional neural networks," *Int. J. Geograph. Inf. Sci.*, vol. 34, no. 5, pp. 947–968, May 2020.

[26] S. Yu, H. Lee, and J. Kim, "Street crossing aid using light-weight CNNs for the visually impaired," in *Proc. IEEE/CVF Int. Conf. Comput. Vis. Workshop (ICCVW)*, Oct. 2019, pp. 2593–2601.

[27] V. Krylov, E. Kenny, and R. Dahyot, "Automatic discovery and geotagging of objects from street view imagery," *Remote Sens.*, vol. 10, no. 5, p. 661, Apr. 2018.

[28] V. A. Krylov and R. Dahyot, "Object geolocation from crowdsourced street level imagery," in *Proc. ECML PKDD Workshops*. Dublin, Ireland: Springer, 2019, pp. 79–83.

[29] S. Branson, J. D. Wegner, D. Hall, N. Lang, K. Schindler, and P. Perona, "From Google Maps to a fine-grained catalog of street trees," *ISPRS J. Photogramm. Remote Sens.*, vol. 135, pp. 13–30, Jan. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924271617303453

[30] R. Cheng, K. Wang, and S. Lin, "Intersection navigation for people with visual impairment," in *Proc. 16th Int. Conf. ICCHP*. Linz, Austria: Springer, Jul. 2018, pp. 78–85.

[31] R. F. Berriel, F. S. Rossi, A. F. de Souza, and T. Oliveira-Santos, "Automatic large-scale data acquisition via crowdsourcing for crosswalk classification: A deep learning approach," *Comput. Graph.*, vol. 68, pp. 32–42, Nov. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0097849317301334

[32] R. F. Berriel, A. T. Lopes, A. F. de Souza, and T. Oliveira-Santos, "Deep learning-based large-scale automatic satellite crosswalk classification," *IEEE Geosci. Remote Sens. Lett.*, vol. 14, no. 9, pp. 1513–1517, Sep. 2017.

[33] S. Kurath, R. D. Gupta, and S. Keller, "OSMDeepOD-object detection on orthophotos with and for VGI," *GI Forum*, vol. 2, no. 2, pp. 173–188, 2017.

[34] M. A. Malbog, "Mask R-CNN for pedestrian crosswalk detection and instance segmentation," in *Proc. IEEE 6th Int. Conf. Eng. Technol. Appl. Sci. (ICETAS)*, Dec. 2019, pp. 1–5.

[35] K. Yang, R. Cheng, L. M. Bergasa, E. Romera, K. Wang, and N. Long, "Intersection perception through real-time semantic segmentation to assist navigation of visually impaired pedestrians," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2018, pp. 1034–1039.

[36] S. Zimmermann-Janschitz, *The Application of Geographic Information Systems to Support Wayfinding for People with Visual Impairments or Blindness*. London, U.K.: IntechOpen, 2019.

[37] K. Hara, S. Azenkot, M. Campbell, C. L. Bennett, V. Le, S. Pannella, R. Moore, K. Minckler, R. H. Ng, and J. E. Froehlich, "Improving public transit accessibility for blind riders by crowdsourcing bus stop landmark locations with Google street view: An extended analysis," *ACM Trans. Accessible Comput.*, vol. 6, no. 2, pp. 1–23, Mar. 2015, doi: 10.1145/2717513.

[38] P. Cáceres, A. Sierra-Alonso, B. Vela, J. M. Cavero, M. A. Garrido, and C. E. Cuesta, "Adding semantics to enrich public transport and accessibility data from the web," *Open J. Web Technol.*, vol. 7, no. 1, pp. 1–18, 2020.

[39] W. M. Elmannai and K. M. Elleithy, "A highly accurate and reliable data fusion framework for guiding the visually impaired," *IEEE Access*, vol. 6, pp. 33029–33054, 2018.

[40] Q. Chen, L. Wu, Z. Chen, P. Lin, S. Cheng, and Z. Wu, "Smartphone based outdoor navigation and obstacle avoidance system for the visually impaired," in *Multi-Disciplinary Trends in Artificial Intelligence*. Kuala Lumpur, Malaysia: Springer, Nov. 2019, pp. 26–37.

[41] V. Gintner, J. Balata, J. Boksansky, and Z. Mikovec, "Improving reverse geocoding: Localization of blind pedestrians using conversational UI," in *Proc. 8th IEEE Int. Conf. Cogn. Infocommun. (CogInfoCom)*, Sep. 2017, pp. 145–150.

[42] V. Kaushalya, K. Premarathne, H. Shadir, P. Krithika, and S. Fernando, "'AKSHI': Automated help aid for visually impaired people using obstacle detection and GPS technology," *Int. J. Sci. Res. Publications*, vol. 6, no. 11, p. 110, Nov. 2016.

[43] R. Velázquez, E. Pissaloux, P. Rodrigo, M. Carrasco, N. I. Giannoccaro, and A. Lay-Ekuakille, "An outdoor navigation system for blind pedestrians using GPS and tactile-foot feedback," *Appl. Sci.*, vol. 8, no. 4, p. 578, Apr. 2018.

[44] A. J. Spiers and A. M. Dollar, "Outdoor pedestrian navigation assistance with a shape-changing haptic interface and comparison with a vibrotactile device," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 34–40.

[45] V. V. Meshram, K. Patil, V. A. Meshram, and F. C. Shu, "An astute assistive device for mobility and object recognition for visually impaired people," *IEEE Trans. Human-Mach. Syst.*, vol. 49, no. 5, pp. 449–460, Oct. 2019.

[46] J. Bai, Z. Liu, Y. Lin, Y. Li, S. Lian, and D. Liu, "Wearable travel aid for environment perception and navigation of visually impaired people," *Electronics*, vol. 8, no. 6, p. 697, Jun. 2019.

[47] R. Cheng, W. Hu, H. Chen, Y. Fang, K. Wang, Z. Xu, and J. Bai, "Hierarchical visual localization for visually impaired people using multimodal images," *Expert Syst. Appl.*, vol. 165, Mar. 2021, Art. no. 113743. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957417420305674

[48] S. Lin, R. Cheng, K. Wang, and K. Yang, "Visual localizer: Outdoor localization based on ConvNet descriptor and global optimization for visually impaired pedestrians," *Sensors*, vol. 18, no. 8, p. 2476, Jul. 2018. [Online]. Available: https://www.mdpi.com/1424-8220/18/8/2476

[49] Y. Fang, K. Yang, R. Cheng, L. Sun, and K. Wang, "A panoramic localizer based on coarse-to-fine descriptors for navigation assistance," *Sensors*, vol. 20, no. 15, p. 4177, Jul. 2020.

[50] R. Cheng, K. Wang, J. Bai, and Z. Xu, ''Unifying visual localization and scene recognition for people with visual impairment,'' *IEEE Access*, vol. 8, pp. 64284–64296, 2020.

[51] A. Cohen and S. Dalyot, ''Route planning for blind pedestrians using OpenStreetMap,'' *Environ. Planning B, Urban Anal. City Sci.*, vol. 48, no. 6, pp. 1511–1526, Jul. 2021.

[52] A. P. Bravo and A. Giret, ''Recommender system of walking or public transportation routes for disabled users,'' in *Highlights of Practical Applications of Agents, Multi-Agent Systems, and Complexity: The PAAMS Collection*. Toledo, Spain: Springer, Jun. 2018, pp. 392–403.

[53] I. F. B. Hairuman and O.-M. Foong, ''OCR signage recognition with skew & slant correction for visually impaired people,'' in *Proc. 11th Int. Conf. Hybrid Intell. Syst. (HIS)*, Dec. 2011, pp. 306–310.

[54] P. Devi, B. Saranya, B. Abinayaa, G. Kiruthikamani, and N. Geethapriya, ''Wearable aid for assisting the blind,'' *methods*, vol. 3, 2016.

[55] Y. Bazi, H. Alhichri, N. Alajlan, and F. Melgani, ''Scene description for visually impaired people with multi-label convolutional SVM networks,'' *Appl. Sci.*, vol. 9, no. 23, p. 5062, Nov. 2019.

[56] A. A. Mishra, C. Madhurima, S. M. R. Gautham, J. James, and D. Annapurna, ''Environment descriptor for the visually impaired,'' in *Proc. Int. Conf. Adv. Comput., Commun. Informat. (ICACCI)*, Sep. 2018, pp. 1720–1724.

[57] E. Cardillo, V. Di Mattia, G. Manfredi, P. Russo, A. De Leo, A. Caddemi, and G. Cerri, ''An electromagnetic sensor prototype to assist visually impaired and blind people in autonomous walking,'' *IEEE Sensors J.*, vol. 18, no. 6, pp. 2568–2576, Mar. 2018.

[58] W.-J. Chang, L.-B. Chen, M.-C. Chen, J.-P. Su, C.-Y. Sie, and C.-H. Yang, ''Design and implementation of an intelligent assistive system for visually impaired people for aerial obstacle avoidance and fall detection,'' *IEEE Sensors J.*, vol. 20, no. 17, pp. 10199–10210, Sep. 2020.

[59] M. M. Islam, M. S. Sadi, and T. Bräunl, ''Automated walking guide to enhance the mobility of visually impaired people,'' *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 3, pp. 485–496, Aug. 2020.

[60] S. Shadi, S. Hadi, M. A. Nazari, and W. Hardt, ''Outdoor navigation for visually impaired based on deep learning,'' in *Proc. CEUR Workshop*, vol. 2514, 2019, pp. 397–406.

[61] P.-J. Duh, Y.-C. Sung, L.-Y.-F. Chiang, Y.-J. Chang, and K.-W. Chen, ''V-eye: A vision-based navigation system for the visually impaired,'' *IEEE Trans. Multimedia*, vol. 23, pp. 1567–1580, 2021.

[62] R. C. Joshi, S. Yadav, M. K. Dutta, and C. M. Travieso-Gonzalez, ''Efficient multi-object detection and smart navigation using artificial intelligence for visually impaired people,'' *Entropy*, vol. 22, no. 9, p. 941, Aug. 2020.

[63] (Jan. 2023). *Maptic*. [Online]. Available: https://www.core77.com/projects/68198/Maptic-Tactile-Navigation-for-the-Visually-Impaired

[64] (Jan. 2023). *Microsoft Soundscape*. [Online]. Available: https://www.microsoft.com/en-us/research/product/soundscape/

[65] (Jan. 2023). *SmartCane*. [Online]. Available: http://edition.cnn.com/2014/06/20/tech/innovation/sonar-sticks-use-ultrasound-blind/index.html

[66] (Jan. 2023). *WeWalkCane*. [Online]. Available: https://wewalk.io/en/product

[67] (Jan. 2023). *Horus*. [Online]. Available: https://www.prnewswire.com/news-releases/horus-technology-launches-early-access-program-for-ai-powered-wearable-for-the-blind-rebrands-company-as-eyra-300351430.html

[68] (Jan. 2023). *Ray Electronic Mobility Aid for the Blind*. [Online]. Available: https://www.maxiaids.com/ray-electronic-mobility-aid-for-the-blind

[69] (Jan. 2023). *UltraCane*. [Online]. Available: https://www.ultracane.com/

[70] (Jan. 2023). *BlindSquare*. [Online]. Available: https://www.blindsquare.com/

[71] (Jan. 2023). *EnvisionGlasses*. [Online]. Available: https://www.letsenvision.com/blog/envision-announces-ai-powered-smart-glasses-for-the-blind-and-visually-impaired

[72] (Jan. 2023). *EyeSee*. [Online]. Available: https://mashable.com/2017/09/14/smart-helmet-visually-impaired/?europe=true

[73] (Jan. 2023). *NEAR by Explorer*. [Online]. Available: https://mashable.com/2017/09/14/smart-helmet-visually-impaired/?europe=true

[74] (Jan. 2023). *The Seeing Eye GPS*. [Online]. Available: http://www.senderogroup.com/products/seeingeyegps/index.html

[75] (Jan. 2023). *pathVu Navigation*. [Online]. Available: http://www.pathvu.com

[76] (Jan. 2023). *Step Hear*. [Online]. Available: https://www.step-hear.com/

[77] (Jan. 2023). *Lazarillo APP*. [Online]. Available: https://lazarillo.app/

[78] (Jan. 2023). *Lazzus*. [Online]. Available: http://www.lazzus.com/

[79] (Jan. 2023). *Sunu Band*. [Online]. Available: https://www.sunu.com/en/index

[80] (Jan. 2023). *Ariadne GPS*. [Online]. Available: https://apps.apple.com/us/app/id441063072

[81] (Jan. 2023). *BrainPort*. [Online]. Available: https://www.wicab.com/brainport-vision-pro

[82] M. A. Williams, C. Galbraith, S. K. Kane, and A. Hurst, '''Just let the cane hit it': How the blind and sighted see navigation differently,'' in *Proc. 16th Int. ACM SIGACCESS Conf. Comput. Accessibility (ASSETS)*. New York, NY, USA: Association for Computing Machinery, 2014, pp. 217–224, doi: 10.1145/2661334.2661380.

[83] P.-A. Quinones, T. Greene, R. Yang, and M. Newman, ''Supporting visually impaired navigation: A needs-finding study,'' in *Proc. CHI Extended Abstr. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2011, pp. 1645–1650, doi: 10.1145/1979742.1979822.

[84] S. R. A. W. Alwi and M. N. Ahmad, ''Survey on outdoor navigation system needs for blind people,'' in *Proc. IEEE Student Conf. Res. Develop.*, Dec. 2013, pp. 144–148.

[85] A. Nagraj, R. Kuber, F. Hamidi, and R. S. G. Prasad, ''Investigating the navigational habits of people who are blind in India,'' in *Proc. 23rd Int. ACM SIGACCESS Conf. Comput. Accessibility (ASSETS)*. New York, NY, USA: Association for Computing Machinery, Oct. 2021, pp. 1–10, doi: 10.1145/3441852.3471203.

[86] N. Banovic, R. L. Franz, K. N. Truong, J. Mankoff, and A. K. Dey, ''Uncovering information needs for independent spatial learning for users who are visually impaired,'' in *Proc. 15th Int. ACM SIGACCESS Conf. Comput. Accessibility*. New York, NY, USA: Association for Computing Machinery, Oct. 2013, pp. 1–8, doi: 10.1145/2513383.2513445.

[87] S. Azenkot, S. Prasain, A. Borning, E. Fortuna, R. E. Ladner, and J. O. Wobbrock, ''Enhancing independence and safety for blind and deaf-blind public transit riders,'' in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2011, pp. 3247–3256, doi: 10.1145/1978942.1979424.

[88] R. N. Brewer and V. Kameswaran, ''Understanding trust, transportation, and accessibility through ridesharing,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2019, pp. 1–11, doi: 10.1145/3290605.3300425.

[89] S. Lee, R. Yu, J. Xie, S. M. Billah, and J. M. Carroll, ''Opportunities for human-AI collaboration in remote sighted assistance,'' in *Proc. 27th Int. Conf. Intell. User Interfaces (IUI)*. New York, NY, USA: Association for Computing Machinery, Mar. 2022, pp. 63–78, doi: 10.1145/3490099.3511113.

[90] A. Miyake, M. Hirao, M. Goto, C. Takayama, M. Watanabe, and H. Minami, ''A navigation method for visually impaired people: Easy to imagine the structure of the stairs,'' in *Proc. 22nd Int. ACM SIGACCESS Conf. Comput. Accessibility*, Oct. 2020, pp. 1–4.

[91] V. Kameswaran, A. J. Fiannaca, M. Kneisel, A. Karlson, E. Cutrell, and M. Ringel Morris, ''Understanding in-situ use of commonly available navigation technologies by people with visual impairments,'' in *Proc. 22nd Int. ACM SIGACCESS Conf. Comput. Accessibility*. New York, NY, USA: Association for Computing Machinery, Oct. 2020, pp. 1–12, doi: 10.1145/3373625.3416995.

[92] M. Hersh, ''Mental maps and the use of sensory information by blind and partially sighted people,'' *ACM Trans. Accessible Comput.*, vol. 13, no. 2, pp. 1–32, Apr. 2020, doi: 10.1145/3375279.

[93] M. Bandukda, C. Holloway, A. Singh, G. Barbareschi, and N. Berthouze, ''Opportunities for supporting self-efficacy through orientation & mobility training technologies for blind and partially sighted people,'' in *Proc. 23rd Int. ACM SIGACCESS Conf. Comput. Accessibility*. New York, NY, USA: Association for Computing Machinery, Oct. 2021, pp. 1–13, doi: 10.1145/3441852.3471224.

[94] A. Arditi and Y. Tian, ''User interface preferences in the design of a camera-based navigation and wayfinding aid,'' *J. Vis. Impairment Blindness*, vol. 107, no. 2, pp. 118–129, Mar. 2013.

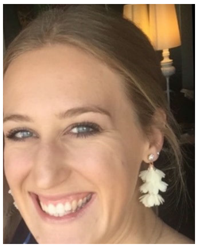
[95] L. Zeng, ''A survey: Outdoor mobility experiences by the visually impaired,'' in *Mensch und Computer 2015—Workshopband*, A. Weisbecker, M. Burmester, and A. Schmidt, Eds. Berlin, Germany: De Gruyter, 2015, pp. 391–398, doi: 10.1515/9783110443905-056.

[96] M. Avila and L. Zeng, "A survey of outdoor travel for visually impaired people who live in Latin–American region," in *Proc. 10th Int. Conf. Pervasive Technol. Rel. Assistive Environ.* New York, NY, USA: Association for Computing Machinery, Jun. 2017, pp. 9–12, doi: 10.1145/3056540.3064953.
[97] S. Shingte and R. Patil, "A passenger bus alert and accident system for blind person navigational," *Int. J. Sci. Res. Sci. Technol.*, vol. 4, no. 8, pp. 282–288, 2018.
[98] G. H. Flores and R. Manduchi, "A public transit assistant for blind bus passengers," *IEEE Pervasive Comput.*, vol. 17, no. 1, pp. 49–59, Jan. 2018.
[99] C. Yu, Y. Li, T.-Y. Huang, W.-A. Hsieh, S.-Y. Lee, I.-H. Yeh, G. K. Lin, N.-H. Yu, H.-H. Tang, and Y.-J. Chang, "BusMyFriend: Designing a bus reservation service for people with visual impairments in Taipei," in *Proc. Companion Publication ACM Designing Interact. Syst. Conf.* New York, NY, USA: Association for Computing Machinery, Jul. 2020, pp. 91–96, doi: 10.1145/3393914.3395879.
[100] Y. Sáez, J. Muñoz, F. Canto, A. García, and H. Montes, "Assisting visually impaired people in the public transport system through RF-communication and embedded systems," *Sensors*, vol. 19, no. 6, p. 1282, Mar. 2019.
[101] J. Guerreiro, D. Ahmetovic, D. Sato, K. Kitani, and C. Asakawa, "Airport accessibility and navigation assistance for people with visual impairments," in *Proc. CHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2019, pp. 1–14, doi: 10.1145/3290605.3300246.
[102] W. R. Wiener, R. L. Welsh, and B. B. Blasch, *Foundations of Orientation and Mobility*, vol. 1. Arlington, VA, USA: American Foundation for the Blind, 2010.
[103] P. Péruch, F. Gaunet, C. Thinus-Blanc, and J. Loomis, "Understanding and learning virtual spaces," in *Cognitive Mapping*. Evanston, IL, USA: Routledge, 2018, pp. 108–124.
[104] R. Ruggieri, M. Ruggeri, G. Vinci, and S. Poponi, "Electric mobility in a smart city: European overview," *Energies*, vol. 14, no. 2, p. 315, Jan. 2021.
[105] M. Markiewicz and M. Skomorowski, "Public transport information system for visually impaired and blind people," in *Transport Systems Telematics*. Katowice, Poland: Springer, Oct. 2010, pp. 271–277.
[106] S. K. Kane, C. Jayant, J. O. Wobbrock, and R. E. Ladner, "Freedom to roam: A study of mobile device adoption and accessibility for people with visual and motor disabilities," in *Proc. 11th Int. ACM SIGACCESS Conf. Comput. Accessibility*, Oct. 2009, pp. 115–122.

FATMA EL-ZAHRAA EL-TAHER received the bachelor's and Master of Science degrees from the Department of Computer and System Engineering, Faculty of Engineering, Al-Azhar University, Egypt. She has worked as a Teaching Assistant with the School of Computer Science. Currently, she is a Ph.D. Researcher and a Teaching Assistant with the School of Computer Science, Technological University Dublin. Her research interests include computer vision, machine/deep learning, and navigation systems.

LUIS MIRALLES-PECHUÁN received the Ph.D. degree, in 2012, on creating new approaches within the online advertising world. He worked as a full-time Researcher/a Lecturer at University Panamericana, Mexico, for more than three years. During his Ph.D. degree, he got familiar with ML and he has published a good number of papers on topics related to how to apply ML to online advertising. After finishing his Ph.D. degree, he worked at postdoctoral levels at CeADAR, UCD, and there, he published in the Digital Forensic Conference and they won the prize for the best student paper. He is currently an Assistant Lecturer with TU Dublin. His favorite topic is how to apply reinforcement learning to fight the COVID-19 pandemic and to plan the containing levels considering both public health and the economy.

JANE COURTNEY received the B.E., M.Eng.Sc., and Ph.D. degrees. She is also a Lecturer and a Researcher with the School of Electrical & Electronic Engineering, TU Dublin. She has over 20 years of experience in computer vision, image processing and analysis, biomedical engineering, and power systems. She was the Chair of the Irish Machine Vision and Image Processing Conference 2019. She is also a Consultant Trainer in advanced computer vision and the Team Leader of the Electricity Training Centre projects in the developing world. She is also a MIEI.



KRISTINA MILLAR is currently a Clinical Scientist, working with people with visual impairment at the National Council for the Blind, Ireland's National Agency, for supporting people with visual impairment.

CHANTELLE SMITH is currently the National Access and Mobility Manager with the National Council for the Blind, Ireland National Agency, for supporting people with visual impairment. She has extensive experience working on the mobility requirements of vulnerable users, she worked as an Orientation and Mobility Specialist with Vision Australia.

SUSAN MCKEEVER (Senior Member, IEEE) is currently a Senior Lecturer with the School of Computer Science, Technological University Dublin. Her research interests include the domain of applied machine learning, with a particular emphasis on using technologies for societal benefit, including health, accessibility, and smart cities. She has published widely in these domains.