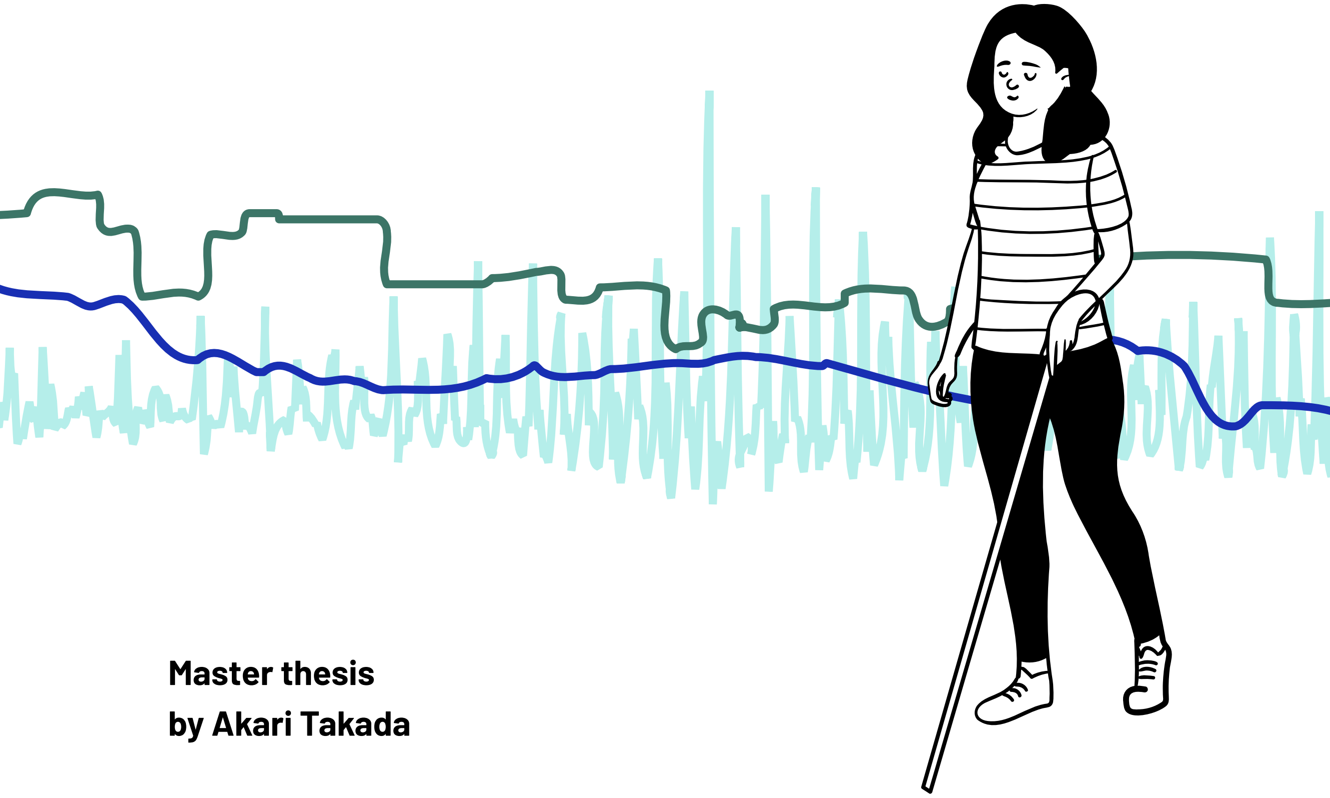
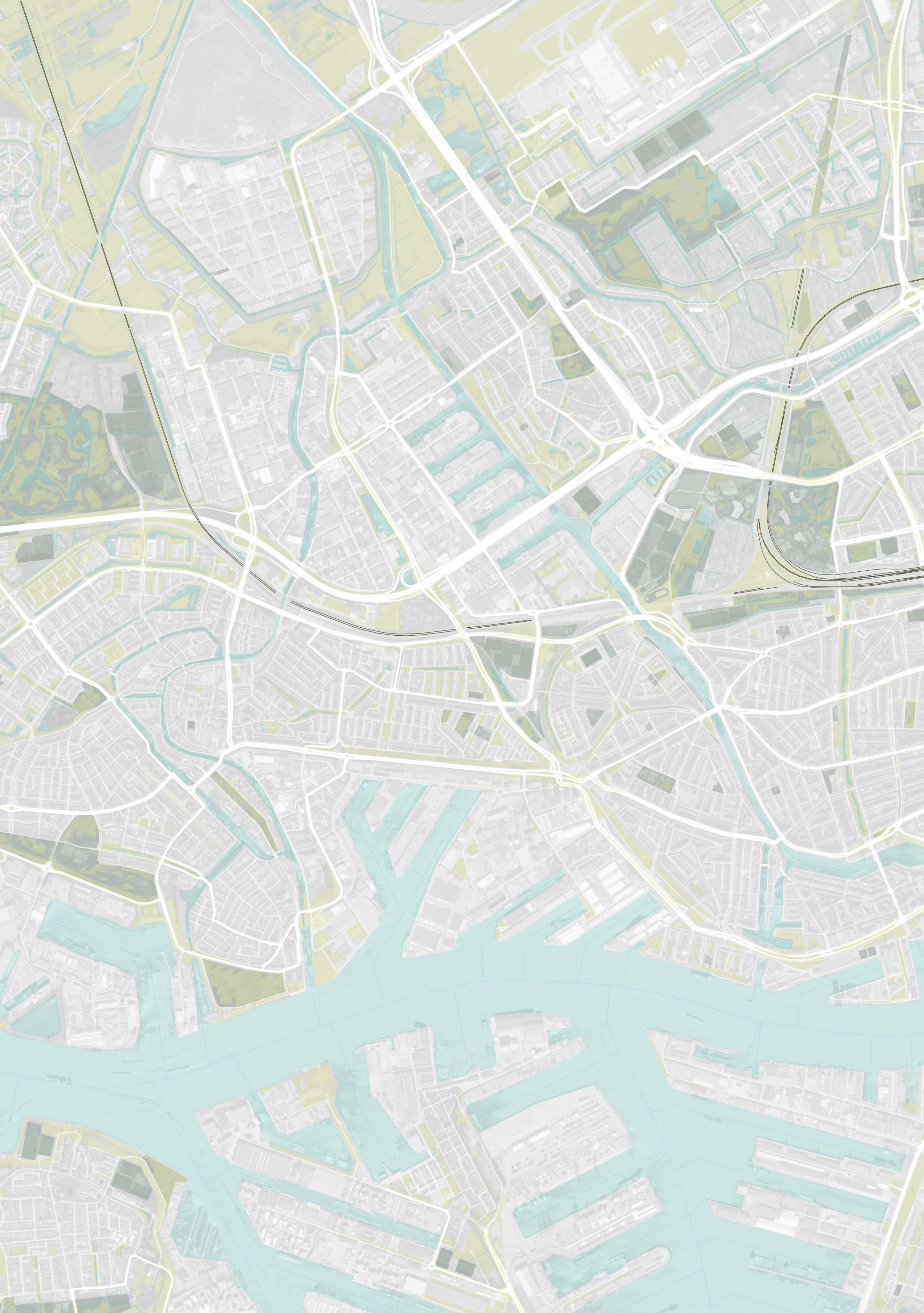
NavAware

Data-centric design of a user-aware navigation agent for blind mobility



Master thesis

by Akari Takada



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Master Thesis

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Acknowledgments

Il decided to come to Delft in the summer of 2020 to pursue my passion for design. Moving to a country that I had never visited before amid the pandemic was a very risky decision to make, but it certainly was not the wrong decision. Two years have passed and my journey in the Netherlands has proved to be a life-changing experience. What made my experience in the Netherlands special is all the wonderful people I have met. So many people have supported me over these two years and this thesis is no different. I would not have been able to do this on my own.

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Last but not least, I would like to thank my family for supporting my decision to come to the Netherlands and pursue my passion for design. This amazing journey I've had in the Netherlands would not have been possible without you.

Nomenclature

AI	Artificial intelligence
BI	Business Intelligence
DCL	Data Capture Lab
ETA	Electronic Travel Aids
HREC	Human Research Ethics Committee
IAPB	International Agency for the Prevention of Blindness
IDE	Integrated Development Environment
ML	Machine learning
O&M	Orientation and mobility
OSC	Open Sound Control
P	Participant
POI	Points of interest
PVI	People with vision impairments
UDP	Universal Datagram Protocol
WHO	World Health Organization

Abstract

With the rise of digital technologies including artificial intelligence, machine learning, and sensor technologies, all the products we use every day are increasingly becoming 'intelligent'. Machines, objects, and tools are slowly evolving into robots, objects-with-intent (Rozendaal et al., 2019), and agents. At the same time, their capabilities are also increasing. These capabilities come from their ability to process large amounts of data. In this digital era, how can designers create user-centric solutions by leveraging the strengths of these digitally-enabled products at an early stage in the design process?

This thesis explores this topic in the context of pedestrian mobility. More specifically, outdoor mobility for people with vision impairments. When people with vision impairments travel, they must process an extensive amount of spatial information without relying on their vision. How can an agent partner with these users to make this process less demanding and thus, make it easier for people with vision impairments to travel independently?

Combining these two visions, this thesis focuses on uncovering the problem areas, information needs, and desires of PVIs traveling outdoors by leveraging behavioral data. Two main user studies, both involving different types of behavioral data have been explored.

Based on the exploratory research, in which physiological data was collected, two behavioral states, 'following' and 'reorienting', were identified. These two states also reflected the PVI's mental state, moments of ease, and moments of uncertainty. This inspired the initial idea for a user-aware navigation agent, which could announce different types of data depending on whether the user was 'following' a route or 'reorienting' on the route.

In the evaluative research, the agent's capability to detect the two states was tested by training a machine learning algorithm. In addition, a second evaluative user study was conducted to test the hypothesis of the information needs in the 'following' and 'reorienting ' states. The study setup was designed to generate a new type of behavioral data, which consists of the location users requested additional information. Thus, the user needs were quantified.

This kind of behavioral data; one that embeds rich information about the user needs, becomes the building block of future prototypes of the user-aware navigation agent. Those iterations will then produce more data that embed further insights. This positive feedback cycle will be key to keeping the PVIs constantly in the product development loop and hopefully, result in a navigation agent that allows PVIs to easily travel safely and independently.

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ZONE
CASINO

Chapter 1

Introduction

In Chapter 1, the background, key concepts, and research aims of the project are introduced. While this project aims to contribute to the mobility and independence of people with vision impairments, it also serves as a case study to explore data-centric design methods and human-agent partnerships, which are the main topics explored in the Data-centric Design Lab and Expressive Intelligence Lab at the Delft University of Technology.

1.1

Background

> **In this thesis, the potential for human-agent partnerships in the context of blind mobility is explored through a data-centric design approach. In this section, the background and basic principles in these three topics, blind mobility, human-agent partnerships, and data-centric design are introduced. The scope within these three topics are also clarified.**

1.1.1

Blind mobility

Mobility, or traveling safely and efficiently (Goldschmidt, 2018), plays a central role in daily life. Whether it is indoors or outdoors, our lives would be highly restrictive if we could only stay in one place. Therefore, being able to independently travel is an important aspect to maintain one's livelihood.

> **Mobility** – The act of traveling safely and efficiently (Goldschmidt, 2018)

> **Travel** – Moving through space

As the infographic "The bandwidth of our senses" created by Danish physicist Tor Nørretranders conveys (Figure 1.1), vision is a powerful sense with the widest bandwidth when compared to the other senses. Vision impairments, which limit this visual information, can therefore pose challenges when traveling.

It does not come as a surprise that, in a survey conducted by Douglas et al. (2006) in the United Kingdom with 1,960 participants, 394 of them mentioned issues with 'travel, transport, and mobility' when asked 'about things in relation to your visual impairment that are very important'. This was the most reoccurring topic, followed by 'independent living skills' mentioned by 209 participants

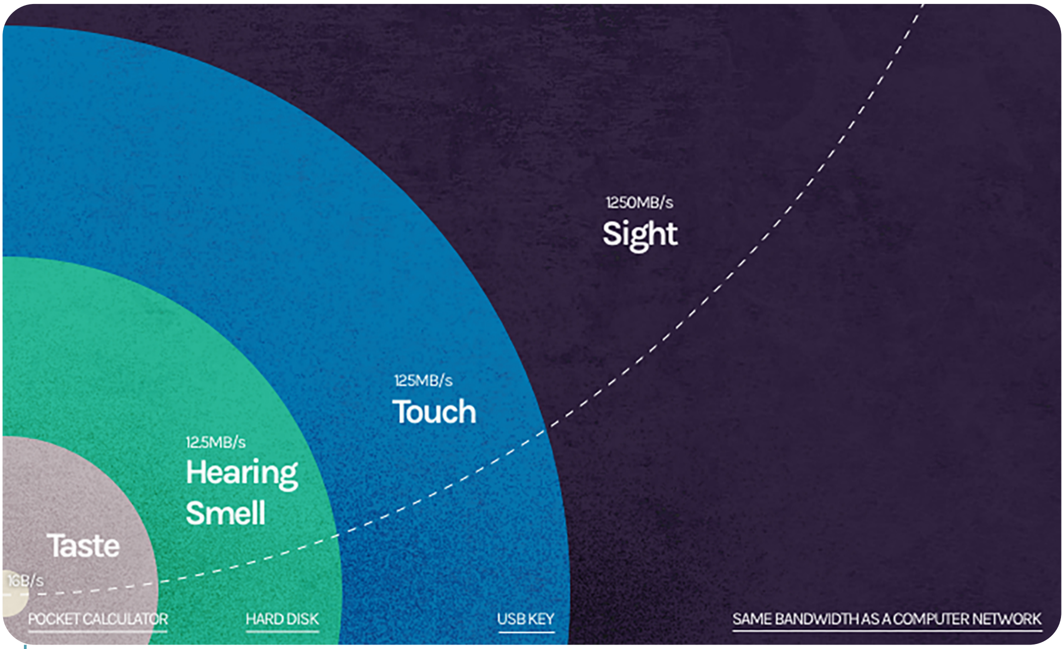


Figure 1.1 Infographic "The bandwidth of our senses" created by Danish physicist Tor Nørretranders. From Richard (2015).

and 'family issues' mentioned by 152 participants (Douglas et al., 2006).

Other than human guides, guide dogs, and white canes, people with vision impairments (PVIs) use electronic travel aids (ETAs), which are white canes enabled with sensor technology, and smartphone applications (apps) for assistance during travel. A combination of these tools helps users during the several activities involved when traveling from A to B. These activities include journey planning, indoor travel, outdoor travel, public transport, and last-mile navigation. Out of these activities, this thesis focuses on outdoor travel.

Creating an app or ETA that empowers PVIs to travel independently is a major challenge. Furthermore, many previously developed apps and devices have not been successful when it comes to user adoption. Many of these projects start with a technology that could be applied to help PVIs in mobility. However, it is essential to take a step back and conduct a proper analysis of user needs and usability issues in depth (Real & Araujo, 2019).

Accordingly, this thesis also starts by exploring the user needs and information needs of PVIs navigating an outdoor route.

1.1.2

Human-agent partnerships

The initial idea for this thesis is that an agent, which is increasingly being implemented to simplify the user interaction of products and services that deal with a lot of information, could also benefit PVIs in mobility. This thesis serves as a step towards such an agent that partners with PVIs for outdoor navigation.

An agent is an artifact that is autonomous, reactive, proactive, and social (Wooldridge & Jennings, 1995). This means that the agent acts without human intervention, can sense and respond to the user and environment, takes initiative to complete a goal, and can communicate with other agents and humans (Wooldridge & Jennings, 1995). These qualities are illustrated in Figure 1.2.

Although all aspects are important when conceptualizing an agent, this thesis especially focuses on the ‘reactive’ aspect of the agent. Understanding the limits of sensing the user and experimenting with how an agent can respond is essential for further developing the human-agent partnership.

The most common agent we see in our daily lives these days are conversational agents, such as Siri. Siri can access the endless amount of information on the internet, which is the environment, and sense the user by accessing calendars, contacts, and other personalized information. With this information, Siri generates customized suggestions that are more useful or relevant to the user. Of course, it can also communicate with the user through conversations.

Rozendaal et al. (2020) proposed a tool-agent spectrum, shown in Figure 1.3 that to analyze how people experience designed artifacts and explain how their roles change. It also clarifies how agents differ from tools. While tools are more conducive or con-

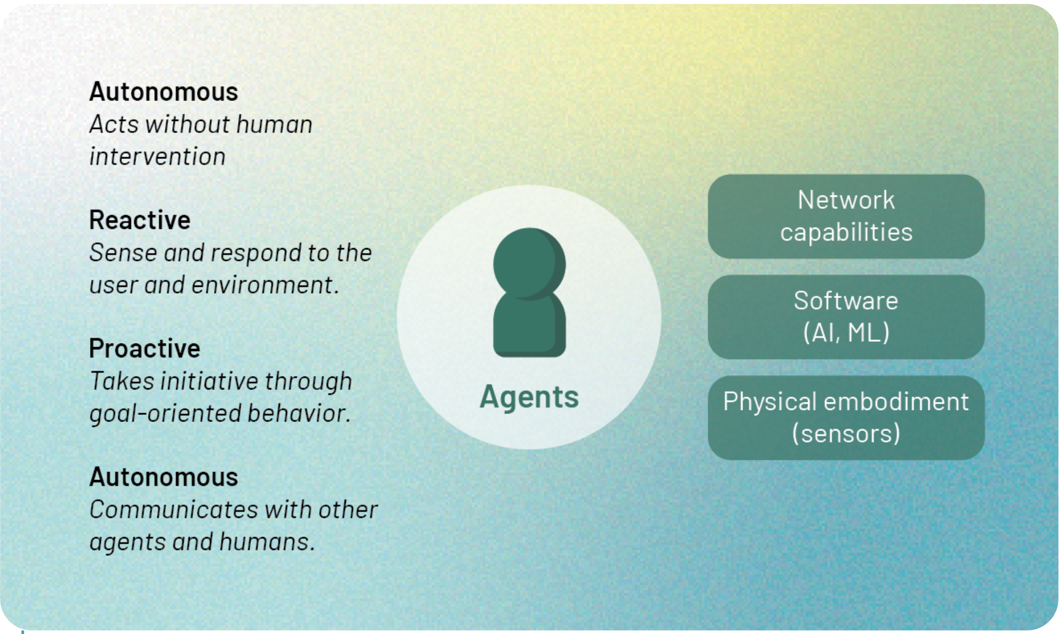


Figure 1.2 Qualities of an agent as defined by Wooldridge & Jennings (1995).

tributive to the intention of the user, agents appear to have intentions of their own. As an example, Rozendaal et al. (2020) introduce BagSight, a backpack that tightens its straps when it detects light. Users described that this behavior made it seem that BagSight wanted to go somewhere, and thus had intentions of its own.

Furthermore, Cila (2022) recently introduced guidelines that break down the collaborative qualities that make agents successful partners, using human-human partnerships as an inspiration. To foster a successful partnership, the agent and user must commit to a joint activity, mutually respond to each other, and support each other throughout the activity (Cila, 2022). Within these three aspects, seven qualities are identified. These qualities are introduced in Figure 1.4.

In this thesis, human-agent partnerships are discussed using these two frameworks as a basis.

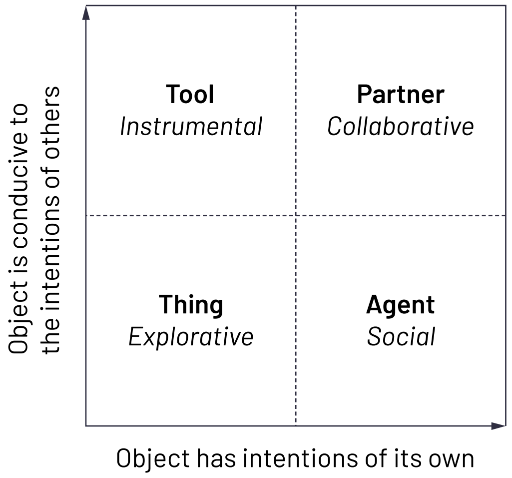


Figure 1.3 The tool-agent spectrum. From Rozendaal et al. (2020).

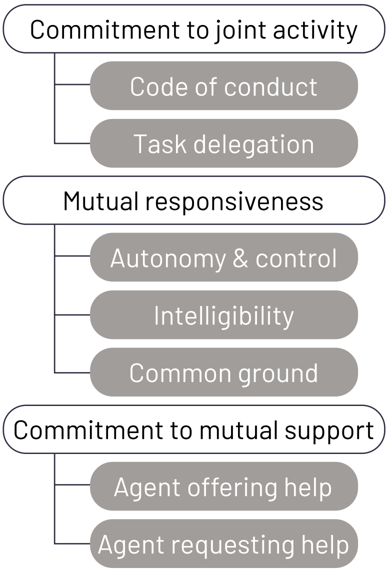


Figure 1.4 Collaboration qualities in human-agent partnerships proposed by Cila (2022).

1.1.3

Data-centric design

There are many methods that designers use to research and uncover latent user needs, such as ethnographic research or co-creation. Behavioral data contains rich information about user experience that is less commonly used in the design process. However, it is already frequently used in some fields such as website development and Business Intelligence (BI). For example, mouse movement and clicks are used to analyze user behavior on a website. Furthermore, in BI, companies use consumer analytics to understand user preferences, realize performance gaps, and detect market trends (IBM, 2021).

With the rise of human-sensing technologies, behavioral data in the physical world is becoming more accessible. Smartwatches and fitness trackers are prime examples of this trend. With such technologies, people track habits and routines such as screen time, sleeping patterns, burned calories, and much more. In addition, digital technologies such as cloud computing, artificial intelligence, and machine learning are increasingly making products and services 'smart'. Agents are also an example of a 'smart' product.

These technologies and trends for 'smart' products are also impacting the design process. This is because 'smart' products generate data (Cantamessa et al., 2020). Cantamessa et al. (2020) examine and demonstrate how the design process will be influenced through two diagrams shown in Figure 1.5.

There are two main differences in this new data-centric design process. First, designers are not meant to design completed artifacts, but instead, a 'seed design'. This 'seed design' actively contributes to the design process by generating data that is analyzed to provide new insights and feedback. Secondly, new tools, such as data analytic tools need to be developed to foster the shift to a data-centric design process.

This thesis takes a data-centric design approach to uncover the PVI's needs when navigating outdoors. In other words, this thesis serves as a case study and hopefully, the methods and tools used throughout the thesis will serve as material to further develop future data-centric design methodologies.

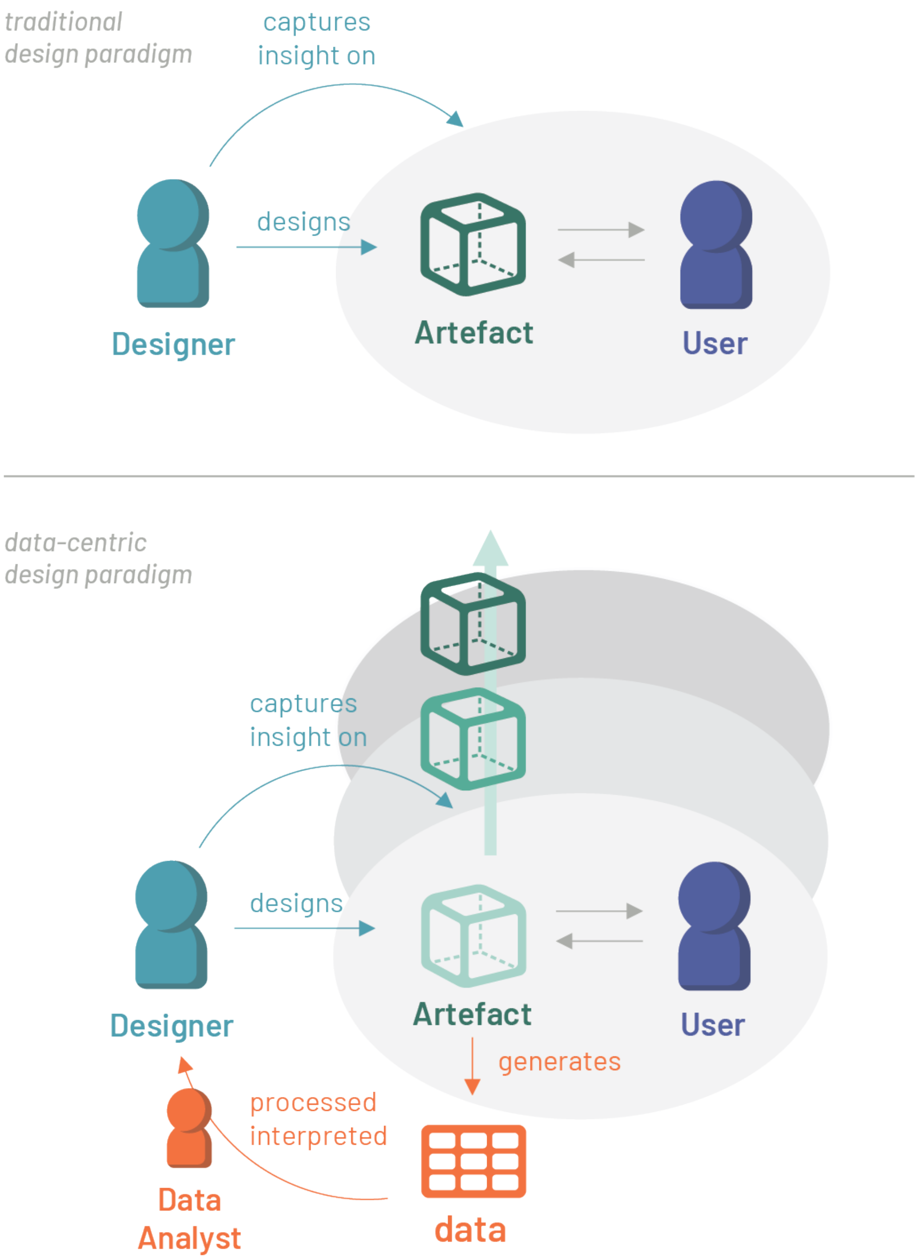


Figure 1.5 The new data-centric paradigm (bottom) compared to the old paradigm (top). Adapted from Cantamessa et al. (2020).

1.2

The Project

> **Within the scope defined in the previous section, the research aims are formulated. This is followed by an overview of the steps in the data-centric design process.**

1.2.1

Research aims

The long-term vision of this project is to conceptualize an agent for PVIs in mobility. Even after narrowing the scope to outdoor travel, different situations occur in a journey from A to B, and accordingly, the user needs also change. For an agent to successfully partner with users, these situations and user needs must be understood.

Therefore, the following research aims were formulated:

1. **Uncover problem areas that occur on a route**
2. **Define situations that reflect problem areas**
3. **Evaluate the capability of agents to detect these situations**
4. **Clarify information needs in the identified situations**

Figure 1.6 Three key perspectives: the agent, the designer, and the user.

This is done through a data-centric design approach, more specifically, by involving behavioral data in all stages of the design process. This approach suited the topic of the thesis because not only does the behavioral data provide rich information about user needs, but it also reflects the information agents have access to. This allows me to explore the project through three perspectives as shown in Figure 1.6: the agent, the designer, and the user.

1.2.2
Overview

The structure of this thesis reflects the process and steps taken to fulfill the research aims. This process is visualized in Figure 1.7s.

First, in Chapter 2, the current situation of PVIs traveling outdoors in the Netherlands is investigated through literature research to gain a general understanding of the topic.

In Chapter 3, exploratory research is conducted to address the first research aim: 'uncover situations on a route where problems occur'. Behavioral data is already collected at this stage, mainly as a design material to uncover latent user needs. It also provides a benchmark for data that the agent could access. Using the behavioral data, the second research aim, 'define situations that reflect problem areas', is addressed. The chapter is concluded with a preliminary idea for a user-aware navigation agent.

In Chapter 4, two evaluative studies are conducted to assess the feasibility and desirability of a user-aware navigation agent. First, the sensing capabilities of the agent are investigated to address the third research aim: 'evaluate the capability of agents to detect these situations'. Second, an interactive Wizard-of-Oz prototype of the agent is used to address the final research aim: 'Clarify information needs in the identified situations'.

Finally, in Chapter 5, the thesis is concluded with future recommendations for further developing a user-aware navigation agent for blind mobility. Reflections on the imagined human-agent partnership and the data-centric design processes are also discussed based on the findings from the research conducted in Chapter 3 and 4.

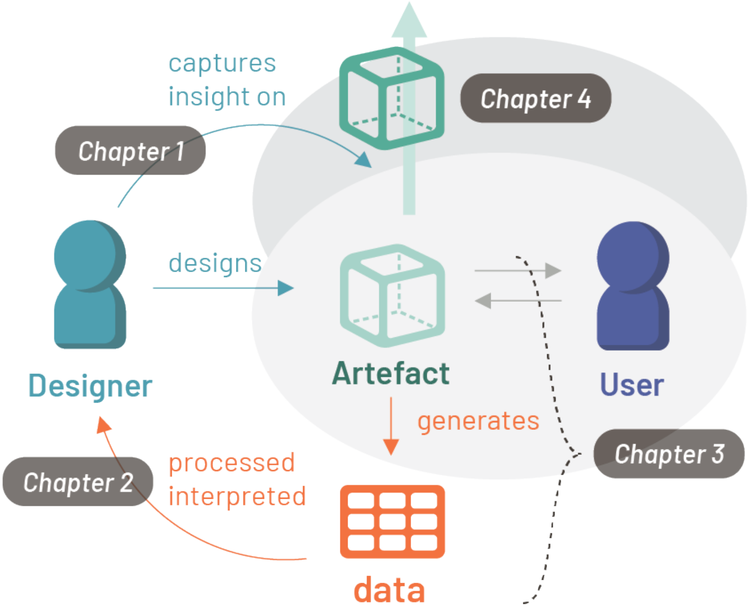


Figure 1.7 Overview of the process.


10.2
Hier uw reclame
Of aan een andere mast?
0800-1999
huureenstadsklok.nl
CHECK

Chapter 2

Literature review

> In Chapter 2, the current situation of traveling with a vision impairment is explained. Topics on vision impairment and mobility training are discussed to understand how people learn to travel without relying on vision. Furthermore, tools for mobility are analyzed to uncover partnerships that unfold in this context. Important terminology that is essential to understanding the upcoming chapters is also defined.

2.1

Vision impairments and mobility

> **A common misconception that many people have is that blind individuals do not see anything, like when one's eyes are closed. However, this is not the case. Some people can still perceive light even if their visual impairment falls under the 'blind' category. As demonstrated in this example, fundamental knowledge of vision impairment and the training users undergo to gain or regain mobility is essential to eliminate any existing misconceptions.**

2.1.1

Vision impairments

Prevalence in the Netherlands

According to the International Agency for the Prevention of Blindness (IAPB) (Bourne, 2020), 1.1 out of 7.8 billion people worldwide had a vision impairment in 2020. Specifically in the Netherlands, 0.87 out of 17.1 million are affected by a vision impairment (Bourne, 2020). These numbers are expected to rise due to the aging population (Bourne, 2020).

Table 2.1 Vision impairment categories.

Distance vision impairment		
Mild	Visual acuity worse than 6/12 to 6/18	
Moderate	Visual acuity worse than 6/18 to 6/60	Low vision
Severe	Visual acuity worse than 6/60 to 3/60	
Blindness	Visual acuity worse than 3/60	Blind
Near vision impairment		
Near	Visual acuity worse than N6 or M.08 at 40cm	

Definitions

Vision impairments are classified into near and distance vision impairments in the International Classification of Diseases 11 (Khoury et al., 2017), which is defined by the World Health Organization (WHO) and is further broken down into categories shown in Table 2.1. This thesis targets the user group with vision impairments categorized as low vision or blind.

Measurements

One of the most common measurements of vision impairment is visual acuity, which "estimates the level of finest detail that can be detected or identified" (Bennett et al., 2019). If one's visual acuity is 6/12, it means that the individual needs to be 6m away to see clearly what a person with normal vision can see from 12m. As shown in Figure 2.1, even if a vision impairment falls under the category of blindness, the individual may be able to perceive light.

Although visual acuity is a common measurement for the level of vision impairment, it does not successfully express the breadth of vision impairments that exist. Other common measurements for visual function include visual field, contrast sensitivity, color, depth, and motion perception (Bennett et al., 2019).

Causes

These factors are greatly affected by what caused the vision impairment. In 2008, the main causes of blindness and low vision in the Netherlands included macular degeneration, cataract, refractive errors, glaucoma, and diabetic retinopathy (Limburg & Keunen, 2009). Figure 2.2 demonstrates how the cause of the vision impairment affects how an individual sees.

It is important to note that the simulation images, shown in Figure 2.1 and Figure 2.2, are mere examples. The various measurements and conditions introduced above

Figure 2.1 Simulated images of visual acuity generated through the Visual Acuity Tool (Bayer, 2021). From Bayer (2021).

Figure 2.2 Simulated images of common eye conditions that cause low vision or blindness. Adapted from Optelec International (n.d.).

help categorize one's visual function. Nevertheless, no individual sees the same way as another, and it is challenging to define a vision impairment. Therefore, when interacting with users who have a vision impairment, understanding their residual vision in combination with their measurements and conditions is crucial.

Timing: Congenital, early, and late

Besides the level of vision impairment, the age that which the vision impairment occurs can influence one's spatial cognition strategies, which is especially important to consider in blind individuals. This is because congenitally blind individuals, who were born completely blind, have no visual experience, while those that are early or late blind, who developed a vision impairment after birth, do.

For example, Pasqualotto et al. (2013) found that congenitally blind individuals prefer an 'egocentric', while late blind and blindfolded sighted individuals prefer an 'allocentric' reference frame. In an egocentric reference frame, the location of an object is expressed by referencing the body, while in an allocentric reference frame, the location of an object is expressed by referencing other objects (Hersh & Johnson, 2008; Pasqualotto et al., 2013). In addition, Wan et al. (2010) found that congenital and early blind individuals have an enhanced auditory perception, while late blind individuals do not.

> **Egocentric referencing space** –
> Expressing the location of an object by referencing the body (Hersh & Johnson, 2008; Pasqualotto et al., 2013)

> **Allocentric referencing space** –
> Expressing the location of an object by referencing other objects (Hersh & Johnson, 2008; Pasqualotto et al., 2013)

2.1.2

Tasks in mobility

Mobility and travel

Regardless of whether you have a vision impairment, there are many tasks involved in mobility. Mobility generally occurs in two different spaces: near space and far space. According to (Hersh & Johnson, 2008), near space refers to "the space immediately around the person's body", while far space refers to "the distant geographical space".

Often, mobility in near space is referred to as micro navigation and mobility in far space is referred to as macro navigation (Katz et al., 2012), however in this thesis, the former will be called near-space mobility and the latter will be called far-space mobility, in favor of defining navigation as an activity done only in far-space.

> **Near space** – The space immediately around the person's body (Hersh & Johnson, 2008)

> **Far space** – The distant geographical space (Hersh & Johnson, 2008)

Since sighted individuals can rely on their vision for spatial information, near-space mobility is a more natural process, compared to those who cannot rely on their vision. Brambring's travel model, shown in Figure 2.3, provides an overview of the tasks that are involved when blind people travel (Brambring, 1985, as cited in Hersh & Johnson, 2008).

I further elaborated upon Brambring's travel model by categorizing the tasks into near-space and far-space mobility and adding specific subtasks. Figure 2.4 shows the modified travel model. The full diagram can be found in Appendix B.

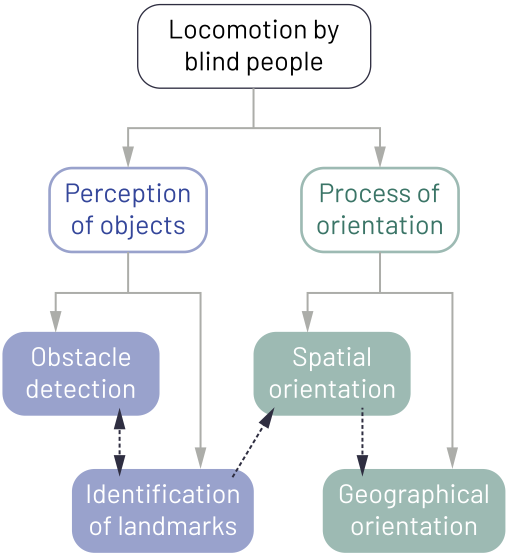


Figure 2.3 Brambring's travel model. Adapted from Hersh & Johnson (2008).

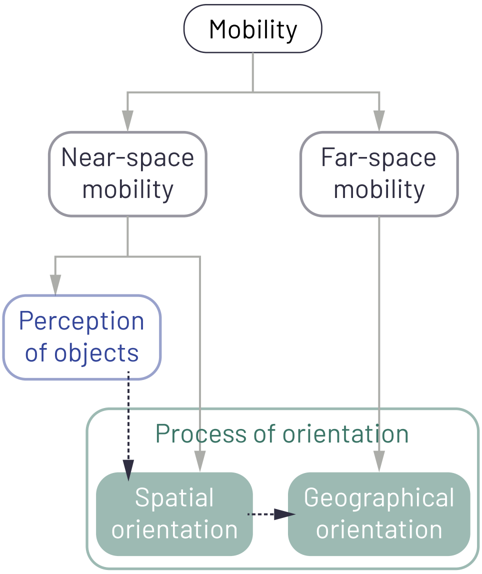


Figure 2.4 Brambring's travel model with additional details on near-space mobility, far-space mobility, and subtasks.

Figure 2.5 Example scenario of near-space mobility. Adapted from Next Sense (n.d.).

Near-space mobility

Near-space mobility consists of two main tasks: perception of objects and spatial orientation. Figure 2.5 shows a scenario with specific examples of what a traveler might consider in near-space mobility.

In this context, 'object' is a broad term that refers to everything from buildings to textures of the ground and people passing by. The objects can be perceived not only using tactual senses through the white cane but also using residual vision and hearing. These objects can be further classified into hazards, obstacles, clues, and landmarks (Swobodzinski & Raubal, 2009).

Hazards are objects that hinder the safety and/or efficiency of travel and cannot be detected by mobility aids or senses (Swobodzinski & Raubal, 2009). For example, chest or head height objects, potholes in the ground, and quiet vehicles on the road.

> **Hazards** – Objects that hinder the safety and/or efficiency of travel and cannot be detected by the primary mobility aids or senses.

Similarly, obstacles are objects that hinder the safety and/or the efficiency of travel but can be detected using mobility aids or senses. This includes trees, poles, and parked vehicles.

> **Obstacles** – Objects that hinder the safety and/or the efficiency of travel but can be detected using mobility aids or senses.

On the other hand, clues and landmarks are objects that help with the safety and/or efficiency of travel. The only difference is that landmarks are memorized by travelers and are usually in a permanent configuration, while clues are spontaneous encounters.

> **Clues** – Objects that help with the safety and/or efficiency of travel, more specifically, with spatial orientation.

> **Landmark** – Memorized objects that help with the safety and/or efficiency of travel, more specifically, with spatial and geographic orientation.

It is important to note that these objects are not mutually exclusive. For example, a pole that was initially an obstacle could be used to determine the distance left on a segment, and thus become a landmark after repeating the route several times.

Furthermore, clues and landmarks are closely related to spatial orientation, or "the ability to maintain a position in the immediate environment of the traveler" (Hersh & Johnson, 2008). Knowing your position on the path, minimizing veering, and safely crossing the road are all tasks that are relevant to spatial orientation.

Clues and landmarks help with these tasks. For example, a grass line or the direction of traffic is a commonly used clue that provides a reference for walking straight or along a path. In the case of a familiar route, landmarks such as a permanent object that makes constant noise or a nearby bench could also help maintain a position on a route. Throughout this thesis, spatial orientation is used interchangeably with orientation.

> **Spatial orientation (orientation)** – The ability to maintain a position in the immediate environment of the traveler (Hersh & Johnson, 2008).

Far-space mobility

In far-space mobility, there is one main task: geographical orientation. Geographic orientation is "the ability to determine a position in the geographical space of the entire journey" (Hersh & Johnson, 2008). All the considerations that are made to get from point A to B are part of far-space mobility, for example, following a path and knowing when to turn next. Figure 2.6 shows a scenario with specific examples of what a traveler might consider in far-space mobility. Often, learned landmarks serve as clues for the geographical orientation process. Throughout this thesis, geographical orientation is used interchangeably with navigation.

> **Geographical orientation (navigation)** – The ability to determine a position in the geographical space of the entire journey (Hersh & Johnson, 2008).

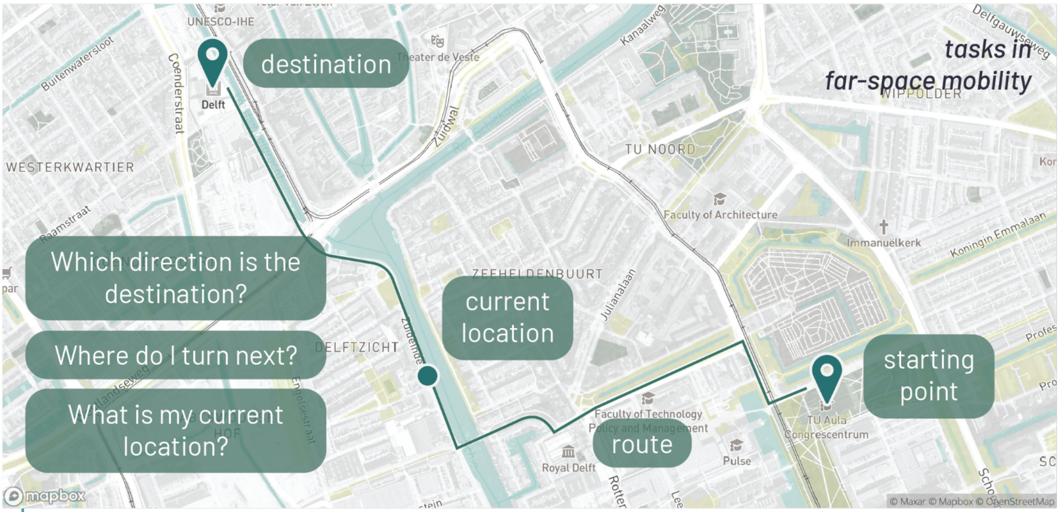


Figure 2.6 Example scenario of far-space mobility. Adapted from Mapbox.

2.1.3

Training for mobility

Purpose of O&M training

People with vision impairments often undergo orientation and mobility training, or O&M training, to gain or regain skills for independent travel. The purpose of O&M training is "to prepare the person to travel in a variety of environments, both familiar and unfamiliar, and to increase the skills of moving in the environment in a safe and efficient way" (Goldschmidt, 2018).

Although there are basic principles and techniques taught in O&M training, no two curriculums are the same. Sessions are usually carried out on a one-on-one basis and O&M instructors customize the training content after assessing the individual's condition, needs, and learning style (Swobodzinski & Raubal, 2009). Therefore, O&M training differs greatly depending on if you have any residual vision.

O&M training is often conducted when one acquires a vision impairment condition. However, it is also conducted when the living environment drastically changes, for example, when an individual moves to a new house or gets a new job.

Techniques for spatial orientation

A logical but important O&M principle is that students are taught to maximize any residual sense, including residual vision (*Orientation and Mobility Skills*, n.d.). This is also where training for individuals who have some form of functional vision differs from completely blind individuals (Goldschmidt, 2018). To gain spatial orientation, students practice the following (Goldschmidt, 2018).

- Train the residual senses to gather information about the surroundings
- Learn how to use landmarks and clues
- Create and use cognitive maps or a mental image of the environment or route

Pre-cane techniques

Before learning how to use mobility aids such as white canes and guide dogs, students learn fundamental techniques that apply to both indoor and outdoor travel.

Students learn the following techniques.

- **Self-protection techniques** – The student places their forearm in front to absorb shock and prevent injuries (Goldschmidt, 2018; Michael Gleeson, 2018).
- **Sighted guide techniques** – The student holds just above the elbow of a sighted guide, who is half a step in front of them, and senses the guide's movements to travel. This technique is also used when an O&M instructor communicates information about environmental clues or landmarks (Goldschmidt, 2018).
- **Trailing technique** – The student uses their fingers to follow something that allows them to travel in a straight line (e.g. walls, handrails, etc.) (Goldschmidt, 2018).

Mobility aids: White cane

Traditional mobility aids such as white canes and guide dogs assist with one's near-space mobility.

There are several types of white canes people with vision impairments use. Together with the O&M instructor, the student chooses the cane that works best for their needs. These canes differ in length, shape, and color.

In terms of length, there are mainly three types of canes: the symbol, guide, and long cane (Marrone, 2020).

- **Symbol cane** – This is the shortest cane that is about 70 cm to 100 cm in length. As the name suggests, the main purpose of this cane is to notify others that the person has a vision impairment. Therefore, it does not provide any protection.
- **Guide cane** – This cane is longer than the symbol cane and it is long enough to touch the floor. It is usually held across the body to detect obstacles beforehand.
- **Long cane** – The longest and most well-known cane. The user usually sweeps or taps the cane from side to side to detect obstacles and gather information about the environment. It provides the most protection and is usually used by blind individuals.

The main limitation of a guide cane or a long cane is that it cannot detect overhanging obstacles and even with ground-level obstacles, small objects are easily missed. In fact, in a study conducted by Manduchi & Kurniawan (2011), 40% of 300 blind individuals experienced accidents several times a year, while 13% experienced accidents more than once a month.

Mobility aids: Guide dogs

Guide dogs are also a common mobility aid, used mainly by low-vision individuals. Usually, people with vision impairments undergo training with a cane before learning how to travel with a guide dog. The main difference between using a cane versus using a guide dog is explained well through this quote.

> “ **a cane is [for] obstacle detection, a [guide] dog is [for] obstacle avoidance.**
>
> ***- A participant from a study conducted by Williams et al. (2013)***

As explained in the quote, guide dogs are trained for obstacle avoidance. They make it easier to maintain a line of direction, which allows easier travel in unfamiliar places where the obstacles are unknown (Wiggett-Barnard & Steel, 2008), or in open spaces where there are fewer clues for orientation (Goldschmidt, 2018). They are also skilled at guiding someone through a crowd of people (Portch, 2018). One guide dog user also mentioned that “walking is automatic” with a guide dog (Timmermans, 2021). Guide dogs also provide companionship. The effect of this partnership is further discussed in section 2.3.

However, there are some limitations of a guide dog. Guide dogs easily get disturbed when they encounter, for example, another animal. The public is also attracted to guide dogs while they are working. These interactions with the public make guide dogs tired and it reduces their performance when guiding a person (Wiggett-Barnard & Steel, 2008). Another limitation is that there are places where dogs are not allowed, which restricts the users’ options for travel (Wiggett-Barnard & Steel, 2008).

Techniques for outdoor travel

Using these mobility aids, participants learn techniques to travel first in a more controlled indoor environment and then outdoors (Goldschmidt, 2018). Below are examples of common skills people with vision impairments learn during their training (Goldschmidt, 2018; Michael Gleeson, 2018).

- Traveling on a sidewalk
- Understanding intersection types
- Crossing the street
- Traveling in a residential area
- Traveling in busy commercial or business areas
- Soliciting advice from the public
- Using public transport
- Using escalators, elevators, stairs, and revolving doors

2.1.4

Main takeaways

- The categories and measurements that define vision impairments do not successfully express the breadth of vision impairments that exist.
- People with vision impairments categorized as ‘blind’, sometimes have residual vision (e.g. light perception).
- Besides vision impairment conditions, the age at which the vision impairment occurs (congenital or early/late) is an important factor that characterizes how a PVI understands space.
- Whether you have a vision impairment or not, mobility consists of tasks in near space and far space.
- Traditional mobility aids (white canes and guide dogs) help with near-space mobility tasks. White canes are used for obstacle detection, while guide dogs are used for obstacle avoidance.
- Navigation apps are usually used for far-space mobility tasks.
- The main limitation of using a white cane is that it cannot detect waist or head-level objects.
- The main limitation of a guide dog is that dogs are inconsistent at times when they are distracted, become tired, or are near retirement.
- PVIs undergo O&M training to gain fundamental techniques for traveling in safely and efficiently in any environment.
- PVIs are taught to maximize the use of any residual vision.

2.2

Existing solutions

Significant advancements in sensor technology and computing power have opened doors to more high-tech tools for navigation, such as electronic travel aids and smartphone apps. Unfortunately, many of these tools have not been adopted by the target group, for a variety of reasons, including misalignments with user needs and high costs. This section introduces the range of existing tools PVIs use when traveling outdoors.

2.2.1

Electronic travel aids

The most common ETAs are devices that can be attached to white canes and often use radar and sonar technologies to detect above-waist obstacles. The I-Cane (*Home | I-Cane*, 2018) and WeWalk (*WeWALK*, 2020) are examples of electronic white canes that have this function. These canes also come with additional functions of even apps that help with navigation. However, the major advantage they have over apps is their ability to sense obstacles. More recently, a team at Stanford developed a robotic white cane that has self-navigating abilities (Slade et al., 2021).

However, although advancements in technology have enabled canes with additional functions, these technologies are not widely accepted. These technology-first solutions often miss the mark on practical matters such as user needs, overall cost, and complexity (Cuturi et al., 2016). Therefore, the majority of PVIs use traditional mobility aids (e.g. white canes and guide dogs) to travel.

2.2.2

Smartphone apps

Compared to ETAs, smartphone apps are more widely used. This is because a large percentage of the PVIs have adopted smartphones, even though smartphones have a vision-heavy interface. Accessibility functions allow PVIs to use these devices through the built-in voice-over function. Figure 2.7 shows the percentage of PVIs in each age group that uses smartphones (blue) and computers (orange) (Real & Araujo, 2019).

Like ETAs, the cost and usability of apps limit the adoption rate of some apps. However, compared to ETAs, no additional hardware is needed, and users can try different apps through one device. There are a variety of apps, each providing different kinds of information, that are used when PVIs travel outdoors. Although it is hard to navigate through this sea of information, the smartphone has helped PVIs access more information via the internet, just like it has for anyone.

Apps for navigation

The essential route information is provided through navigation apps such as Google Maps and Apple Maps. Just like sighted individuals, PVIs also rely on mainstream navigation apps to obtain route information. Even though these apps provide navigation instructions designed for cars, these apps are used the most since they are pre-installed on smartphones.

There are also apps for navigation that provide instructions using sound and tactile feedback. For example, Soundscape (Microsoft, 2022) and waveOut (Dreamwaves, 2022) both use spatial audio to guide a user through a route, rather than descriptions of the distance and street. Bartiméus is also developing an indoor navigation app that uses audio cues for navigation (*Indoor navigation app*, 2022). These types of apps allow users to navigate just by following the sound.

Some devices provide navigation instructions through vibrations. The naviBelt is a belt with 16 vibration motors and gives you tactile feedback around your waist

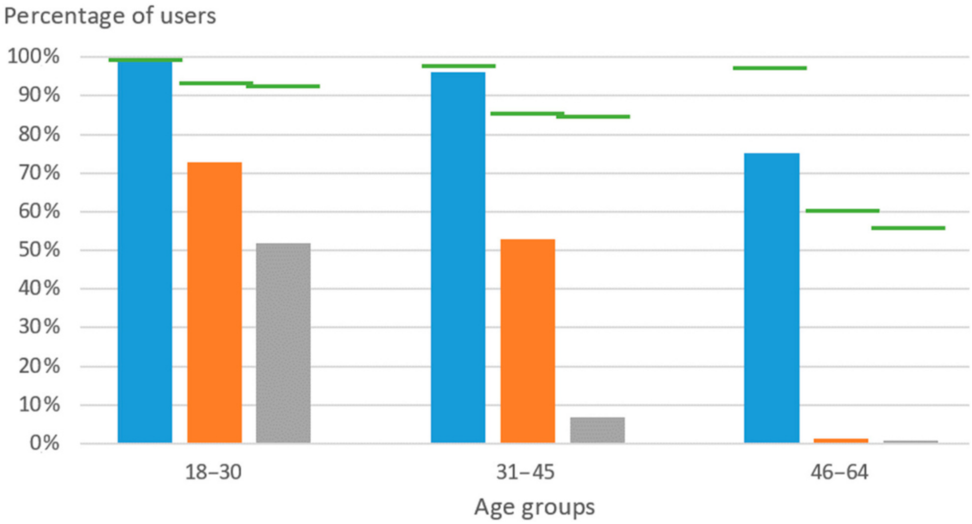


Figure 2.7 Percentage of VIPs in Spain that use smartphones (blue) and computers (orange). From Real & Araujo (2019).

(*FeelSpace*, 2022). The feelSpace app is used with this belt to communicate the direction of the destination. The Wayband takes a slightly different approach. This band is worn on the arm, and it vibrates when one veers off the path. Instead of the vibrations indicating the direction, the vibrations create a virtual corridor around the path (*Wayband*, 2022).

Apps for points of interest (POI)

Mainstream navigation apps are often used in combination with apps that provide points of interest (POI) information. Soundscape and waveOut also provide information about POIs, but the most known apps for obtaining POIs include BlindSquare (MIPsoft, 2022) and Lazarillo (Espinoza, 2022). Both apps provide POIs that are split into categories. The POI information of the chosen categories is announced as the user walks along a route unless the pause function is activated. Users also have the option to create POI with these apps.

Apps for orientation

The previously mentioned apps also have some additional features that help with spatial orientation. For example, Soundscape announces upcoming intersections, street names, and the direction the streets run. It also announces the streets you are crossing. With BlindSquare, users occasionally hear the distance and clockface direction of the destination. This app can also announce the nearest crossing and address.

2.2.3

Main takeaways

- Advancements in sensor technology and computing power resulted in the development of electronic travel aids and smartphone apps.
- User acceptance rates remain especially for electronic travel aids due to mismatches in user needs, high cost, complex use, and need for additional hardware.
- A high percentage of PVIs have adopted the smartphone, although the touch screen is a highly visual interface.
- Although there is a higher acceptance rate for smartphone apps, mismatches in user needs, high cost, and complex use are still common issues.
- Currently, built-in map applications (e.g. Google Maps) are usually used in combination with apps that provide information on POIs (e.g. BlindSquare, Lazarillo) and orientation when PVIs travel.
- Recently, many navigation apps use spatial audio sound cues and vibrations to guide a PVI on a route.

Chapter 2 Literature review

2.3

Existing partnerships

A common method for ideating new human-agent partnerships is by investigating human-human partnerships (Cila, 2022). This section aims to analyze existing partnerships in the context of blind mobility to understand how users collaborate with other people, guide dogs, and tools. This brings insights on what kind of partnerships work, or do not work.

2.3.1

Partnerships with existing solutions

The partnerships PVIs establish when using the white cane, guide dog, and a navigation app is analyzed using the tool-agent spectrum introduced in Figure 1.3 and the collaboration qualities of human-agent partnerships shown in Figure 1.4. Figure 2.8 shows these solutions mapped on the tool-agent spectrum.

White cane-to-PVI

In the tool-agent spectrum introduced in Figure #tool-agent-spectrum, the white cane is a ‘tool’ used for near-space mobility. Williams et al. (2014) explain the relationship between the user and the cane well. She explains that as eyes catch the light that hits the objects, white cane users perceive the tactile and auditory sensation from the cane that hits the objects (Williams et al., 2014). This portrays that the white cane is a tool that is an extension of one’s senses. Of course, the cane does not have any agentic features, as it does not have any ‘autonomy and control’.

Guide dog-to-PVI

Rozendaal et al. (2020) conducted a study that investigates the hybrid quality that guide dogs have, shifting between a tool, agent, and partner. As a tool, a guide dog, like a white cane, is perceived as an extension of one's senses (Rozendaal et al., 2020). It is an instrument that avoids obstacles. Since they are animals, they also have intentions that have nothing to do with travel (e.g. play, eat, or rest).

The partnership users have with guide dogs is analyzed using the guideline proposed by Cila (2022). First, there is a 'code of conduct', or norms that both the user and guide dog understand. These include the following:

- The harness means that the dog is on duty
- Guide dogs should walk two steps ahead of the user without constantly pulling them
- The user is a human that is taller than the guide dog

Not to mention, the guide dog is also trained to understand the norms of human society (Portch, 2018). There is also a clear 'task delegation': users are responsible for knowing which way to go, while guide dogs are responsible for avoiding obstacles and negotiating potentially dangerous situations safely. In short, users are responsible for far-space mobility while the guide dog is responsible for near-space navigation.

The level of 'autonomy and control' that the guide dog has is dynamic depending on the situation. This is of course related to the task delegations. In most situations, the user has control and gives commands to the guide dog.

> **“ The dog is taking the lead; he is physically in charge, but the user has the mental lead.**
>
> **- A *participant from a study conducted by* Rozendaal *et al.* (2020)**

However, in a dangerous situation, the guide dog takes control. For example, the dog will stop even if the user gives a command to proceed if it is dangerous to cross the street. The communication between the user and the guide dog throughout the journey is established through commands such as 'stay', 'sit', and ' find sidewalk' and through the pulling sensation of the harness. This serves as the 'common ground'.

Finally, the unique companionship between the user and guide dog is usually established because the guide dog is a living animal.

> **“ It's a big creature with needs and with hair that it sheds... it causes quite a bit of 'schlep', which one needs to cater for.**
>
> **- A *participant from a study conducted by* *Wiggett-Barnard & Steel* (2008)**

The responsibility to take care of the dog can be perceived as a negative or positive aspect of owning a guide dog. Either way, in this partnership, this is when the 'agent requests help' from the user and if it has a positive impact on the user, this relationship fosters a partnership.

The above highlights how the partnership between the user and guide dog is successful. However, there are also moments when this partnership fails. This is also because a guide dog is an animal. After a long day, when the dog is near retirement, or if people encounter the guide dog while it is working, the guide dog becomes fatigued. This hinders the guide dog's ability to pay attention and perform as expected by the user (Portch, 2018; Timmermans, 2021).

Navigation app-to-PVI

Like the white cane, a navigation app is a tool in the tool-agent spectrum. The only difference is that it is a tool for far-space mobility. It is also not perceived as an extension of the senses, but rather a 'puzzle' the users must solve in their minds.

> **“ I’m constantly solving a puzzle in my mind.**
>
> **- P3 (*Participant from user study conducted in this thesis*)**

One reason for this could be that navigation apps have a lot of ‘autonomy and control’. Even though users have the options to choose what categories of information the app announces on the route, navigation apps are made to automatically announce information, leaving little room for users to control the information they want.

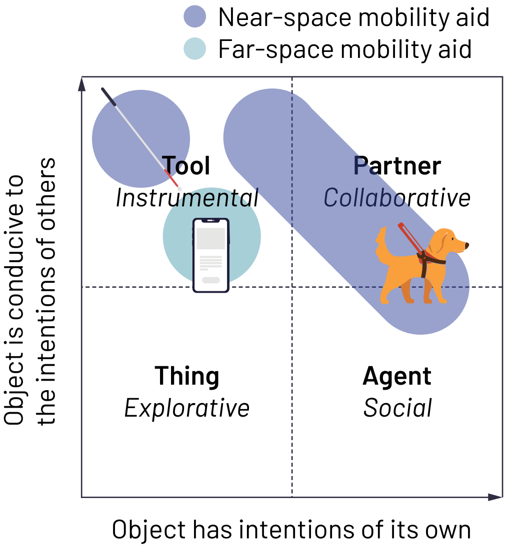


Figure 2.8 Existing solutions mapped on the tool-agent spectrum.

2.3.2

Partnerships with people

Sighted-to-PVI

Williams et al. (2014) investigated how blind participants navigate to a destination with help from a sighted companion. The sighted guide method was not used. This meant that the sighted companion could only give verbal directions to the PVI.

Many of the groups encountered problems, especially towards the beginning. This shed light on many misconceptions sighted people have about traveling with limited or no sight. In other words, the ‘code of conduct’ and norms were not established.

> **“ Never trust sighted people.**
>
> **- *Participant from study conducted by Williams et al.* (2014)**

The main misconceptions included assuming it is easy to walk straight in an open space and assuming that boundaries should be avoided because they are a hazard (Williams et al., 2014). In reality, it is extremely difficult to walk straight without something to follow. Therefore, boundaries are very important to maintain this line of direction. Ambiguous phrases such as ‘here’ and announcing directions too early also led to some misunderstandings in the study (Gupta et al., 2020; Williams et al., 2014).

PVI-to-PVI

When PVIs gather information about a route for an upcoming travel plan, they also often consult friends who also have a vision impairment (Hersh, 2020; Quinones et al., 2011). Balata (2018) conducted a series of studies that investigated collaborative navigation between PVIs. In one study, a trained PVI navigator assisted another PVI to navigate the route remotely through verbal communication (Balata et al., 2015).

Unlike sighted-to-PVI collaboration, both PVIs know what kind of landmarks and clues are useful for navigation. Therefore, there is no mismatch in the underlying biases or 'code of conduct'. The 'task delegation' is also clear. The navigator provides navigation directions and relevant environmental descriptions, while the traveler gathers information about their surroundings and communicates his/her position and orientation.

The instructions from the navigator included many environmental descriptions that help with spatial orientation, such as checking if buildings or traffic are on a certain side of the traveler, describing textures of the street, and using unique objects such as rubber mats to confirm a location (Balata et al., 2015). On the other hand, similarities in the environment, temporary changes in the environment, landmark confusion, and recovery after walking off route caused problems (Balata et al., 2015).

2.3.3

Main takeaways

- A white cane is a tool, while a guide dog is an agent for near-space mobility, while navigation apps are unintuitive tools for far-space mobility with still room for improvement.
- Sighted-to-PVI partnerships are not successful at times due to underlying biases that cause misalignment in the 'code of conduct' or norms.
- Common misconceptions sighted individuals have is that it is easy to walk straight in open spaces. Although in reality, such environments are more challenging.
- PVI-to-PVI partnerships are more successful since there is no misalignment in the 'code of conduct'. There is a mutual understanding of useful landmarks and clues.


TOOLSTATION

Chapter 3
Exploratory research

In Chapter 3, exploratory research is conducted to address the first research aim: 'uncover situations on a route where problems occur'. Factors that influence information needs during outdoor travel are analyzed by combining insights from literature and user interviews. After looking at the 'big picture', specific problems that arise on an unfamiliar route from A to B are investigated through a navigation task. Results were analyzed by combining qualitative and quantitative data on user experience. Based on the results, the second research aim, 'define situations that reflect problem areas', is addressed. The chapter is concluded with a preliminary idea for a user-aware navigation agent.

3.1

Factors that influence travel

We all travel for a variety of reasons: going out to get groceries, meeting a friend in the city center, or exploring a new city. Although all scenarios involve outdoor travel, the information needed to complete the journey is completely different due to the varying degrees of familiarity and interest. The goal of this section is to understand how these factors influence navigation strategies and information needs during outdoor travel. This was done by combining literature with results from interviews conducted with three PVIs who participated in the first user study explained in section 3.2.

How do familiarity and interest levels influence information needs?

3.1.1

Familiarity level

Familiar route

The familiarity level drastically changes how a PVI navigates a route. On a familiar route most PVIs can navigate using only their primary mobility aid (e.g. white canes and guide dogs)(Quinones et al., 2011).

> **“ it becomes automatic, when we have done a route several times we know it ... it becomes routine.**
>
> **- *A participant from a study conducted by* Hersh (2020)**

They do this by memorizing clues and landmarks they can detect with their residual senses. These clues and landmarks help participants verify where they are on a route (Quinones et al., 2011). In other words, the clues and landmarks detected in their immediate surroundings (near-space) are directly connected to the route (far-space). With the help of these clues and landmarks, PVIs create very detailed mental maps of locations they frequently visit (Balata, 2018; Quinones et al., 2011).

Nevertheless, problems still occur on familiar routes. For example, the weather, changes in the environment without prior notice, construction points, and lost landmarks are all causes of confusion for

PVIs even if it is a familiar route (Quinones et al., 2011; Williams et al., 2013).

Unfamiliar route

Compared to familiar routes, unfamiliar routes require more energy to navigate, and many PVIs are not as comfortable traveling in a new environment by themselves (Hersh, 2020). Therefore, many PVIs prefer being accompanied by a friend or using private transportation services when traveling to new places (Hersh, 2020; Quinones et al., 2011).

If that is not possible, people gather information before traveling from the internet, friends who have been to the area, and sometimes even simulate the route at home (Hersh, 2020). In addition, they gather information on the route by using navigation apps and strangers (Hersh, 2020; Quinones et al., 2011). However, apps are not always accurate and information from sighted strangers often includes information that is not useful. P2 mentioned video calling family members, who can virtually guide him to a destination as well.

It is important to note that not being able to arrange accompaniment or reserve time to gather information beforehand does not prevent PVIs from traveling to unfamiliar places. There are also of course cases where routes can be self-taught.

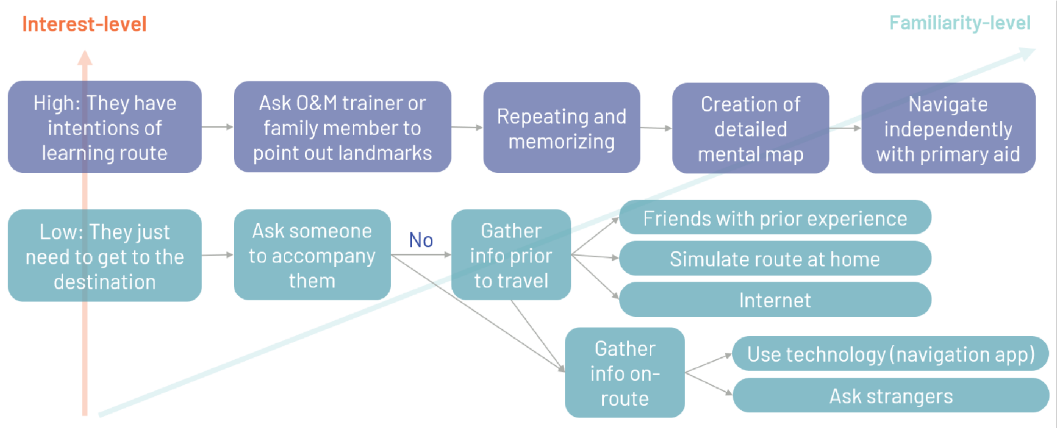


Figure 3.1 The process and strategies for navigating routes in situations with varying interest levels and familiarity levels.

3.1.2

Interest level

The level of interest someone has in a route is determined by whether the traveler has an intention of learning and memorizing the route. Another possible scenario when someone has a high interest is when they want to explore an area. However, this seems to be a rare scenario. P1 mentioned that even when you travel to explore a new city or area, a destination of some sort is chosen beforehand (e.g. café, shop).

Naturally, PVIs have a high interest in routes they are likely to repeat. On the other hand, one-time routes are not worth putting in the effort to memorize (Hersh, 2020). If a PVI has an intention of learning a route, they ask a family member or O&M trainer to point out landmarks and clues they can use (Hersh, 2020; Quinones et al., 2011).

Through repetitions, PVIs concentrate and put in the effort to memorize the route through the learned landmarks and cues. P3 mentioned creating voice memos or written notes as well to help with this process. This repetition and constant updating of a mental map eventually allow PVIs to navigate the route independently using only their primary mobility aid.

3.1.3

Personality

Although the general process and strategies for navigating routes in various situations are introduced, no two PVIs are the same. This is highlighted in the research conducted by Williams et al. (2013) that involved 30 interviews with PVIs living in the United States of America.

Through the study, Williams et al. (2013) identified 5 major personality dimensions that characterize how PVIs travel: exploration attitude, resilience to ask for help, technology reliance, technology adoption, and mobility aid. On top of these traits, one's willingness to take risks also affects decisions (Williams et al., 2013).

These dimensions determine the choices PVIs take in each of the situations. For example, one PVI might decide to cancel a trip if they cannot find someone who can accompany them on the trip, while another PVI who is skilled at using navigation apps would not even think about finding a companion for the trip.

3.1.4

Main takeaways

How do familiarity and interest levels influence information needs?

- On familiar routes, landmarks and clues are memorized well enough to create a mental map. In other words, information gathered in near space is directly linked to the route in far space.
- On first-time routes, regardless of interest level, PVIs prefer to be accompanied by friends and family or an O&M trainer. However, not being able to organize accompaniment does not stop PVIs from traveling to unfamiliar areas.
- The approach for navigation change drastically when a PVI intends to learn a route (high interest) or if they only intend on passing by (low interest). Therefore, one should be chosen to further scope the project.
- PVIs usually do not travel without a clear destination even when they intend to explore an area.
- Exploration attitude, resilience to ask for help, technology reliance, technology adoption, type of mobility aid, and willingness to take risks are dimensions that characterize travel behavior.

3.2

Participatory data storytelling

> **Based on the findings from the previous section, we dive into a specific context: unfamiliar routes of low interest. As opposed to the previous section that demonstrated how information needs to change in a long period of a couple of weeks, this section aims to uncover how information needs to change in a shorter period of about half an hour when an individual travels from point A to B. Accordingly, the following research questions were formulated.**

What are the problem areas that occur when navigating an unknown urban area?

What information is needed to overcome these problems when navigating unknown areas?

What can an agent sense from the user?

3.2.1

Study design

Route selection

The study was conducted in an urban area since these areas are often dense and include more mobility challenges within a short distance. These areas are also more accessible by public transport, which makes it possible for people living further away to participate in the study. As the largest cities in the Netherlands are also where a relatively large number of VIPs live, the Hague, Rotterdam, and Utrecht were considered as locations for the study.

The chosen route starts at Rotterdam Blaak station and ends at a nearby café called 'Joy Espresso and More', as shown in Figure 3.2.

Out of three possible routes assessed by an O&M trainer at Bartiméus, this route was selected because it included the most urban mobility challenges in the shortest distance. This would help keep the navigation task short.

Common urban mobility challenges include avoiding obstacles (e.g. overhead or waist-level obstructions, parked vehicles, etc.), detecting ground-level changes (e.g. stairs that go down, narrow or irregular sidewalks, etc.), understanding street crossings (e.g. lack of audio output or traffic lights, lack of curved sidewalks, etc.), adapting to light variation, navigating through open space where there is a lack of clues, navigating through busy areas, and finding the exact location of the destination (e.g. door of the destination, bus stops, etc.) (Saitis & Kalimeri, 2016; Williams et al., 2013; Zeng, 2015).

Figure 3.2 Chosen route from Rotterdam Blaak station to a nearby café 'Joy Espresso and More'. Adapted from Mapbox.

Navigation system prototype: setup

In this study, the navigation system was acted out by the researcher. As shown in Figure 3.3, the researcher walked slightly behind the user to verbally announce instructions.

This choice was made for a few reasons. First, Google Maps, which is the most widely used app amongst VIPs, does not recognize that there is a path under the tunnel. Therefore, the automatically generated route does not include the tunnel, which was an important mobility challenge requiring participants to adapt to sudden light variations.

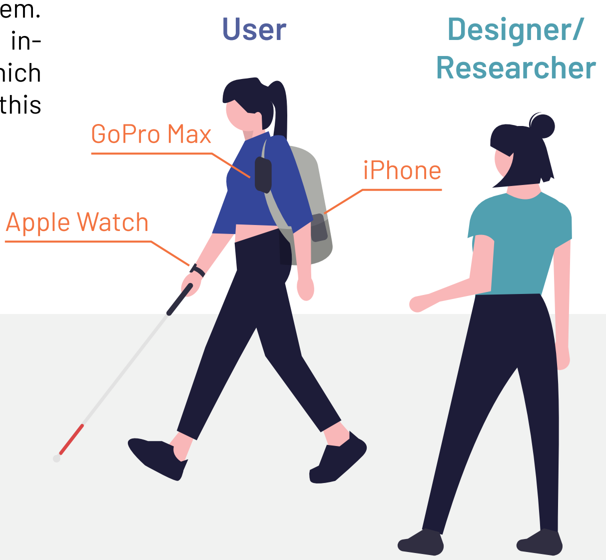
Second, different participants use different mobility aids and apps to navigate unfamiliar routes. This means that the participants would receive different information in a variety of modalities, such as verbal cues, audio signals, and vibrations. Therefore, the information the participants use will be hard to control and capture.

Finally, this provides the option for the users to ask questions to the navigation system. This would help uncover specific information needs of the participants, which is one of the research questions in this study.

Navigation system prototype: information

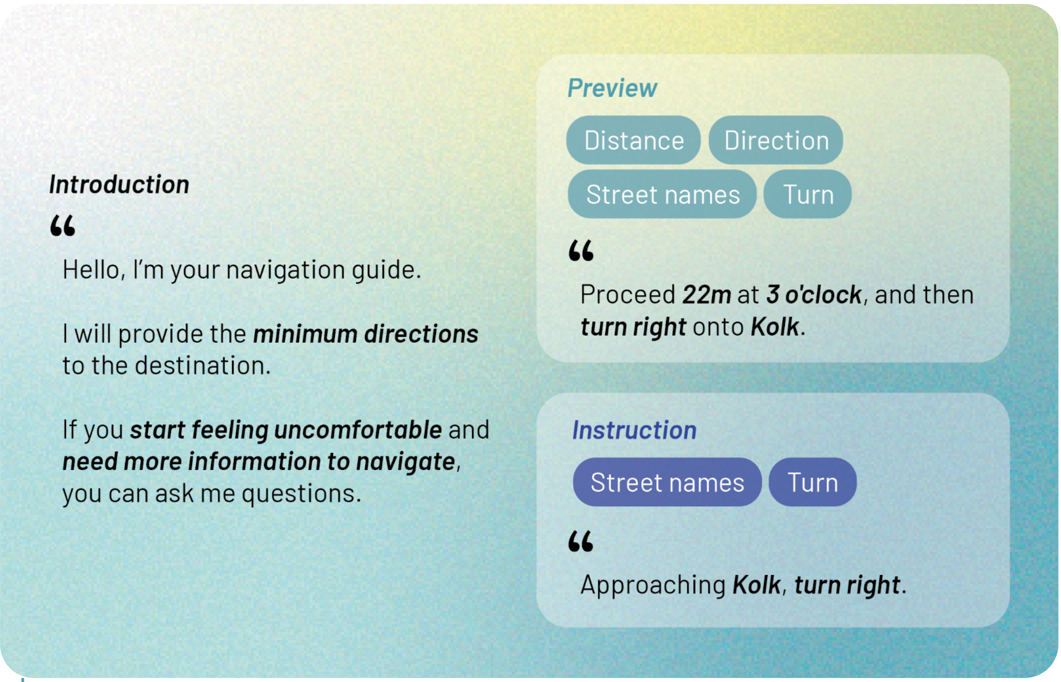
Accordingly, the information announced to the users was planned out. To encourage users to ask questions, the information was intentionally kept to a minimum. The instructions, which are sentences that integrate one or more information types, were designed to mimic mainstream navigation apps such as Google Maps. This consisted of street names, distances, and turning points. These types of information were also used in the instructions announced by navigation apps specialized for VIPs such as BlindSquare, Lazarillo, and Soundscapes. In addition to this information, the direction was announced in clockface (e.g. 2 o'clock).

Figure 3.4 shows the structure of the instructions. For each segment, a preview of the instruction was announced at the beginning of the segment, and instruction was announced right before the segment changed. Figure 3.5 shows all the instructions and where they were announced on the route.



navigation instructions are announced by the researcher

Figure 3.3 The setup of the first navigation system prototype.



“Hello, I’m your navigation guide.

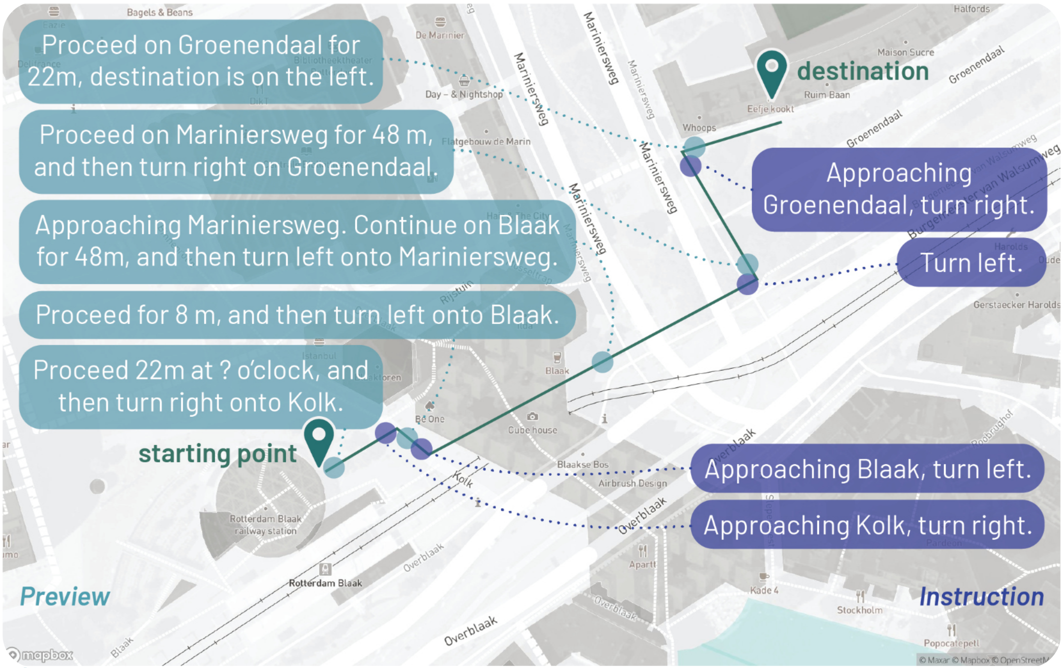
I will provide the ***minimum directions*** to the destination.

If you ***start feeling uncomfortable*** and ***need more information to navigate***, you can ask me questions.

“Proceed ***22m*** at ***3 o'clock***, and then ***turn right*** onto ***Kolk***.

“Approaching ***Kolk***, ***turn right***.

Figure 3.4 Structure of the announced instructions.



Proceed on Groenendaal for 22m, destination is on the left.

Proceed on Mariniersweg for 48 m, and then turn right on Groenendaal.

Approaching Mariniersweg. Continue on Blaak for 48m, and then turn left onto Mariniersweg.

Proceed for 8 m, and then turn left onto Blaak.

Proceed 22m at ? o'clock, and then turn right onto Kolk.

Approaching Groenendaal, turn right.

Turn left.

Approaching Blaak, turn left.

Approaching Kolk, turn right.

Figure 3.5 All the announced instructions on the route. Adapted from Mapbox.

Data selection

The general approach to finding relevant behavioral data that relates to the user experience is by first gathering as many types of data as possible, and gradually discarding ones that are not significant through the iterations. Therefore, I started by brainstorming the different types of data that can be collected through electronic devices and prototyping kits.

Table 3.1 shows the ‘behavioral’ data chosen from the initial list. This includes, travel speed, body orientation, body movements, cane movements, and heart rate. Along with this data, ‘context” data, which includes location, environmental features, and environmental sounds, were selected. This data will be necessary to give context to the ‘behavioral’ data during the analysis.

The main criterion for the selection was to keep the number of devices placed on the participant to a minimum to avoid making the study setup too complex. The final selection of devices, included an iPhone, an Apple Watch, and GoPro.

Table 3.1 data selected for this study and additional ‘context’ data necessary for analysis.

Device	Behavior type	Sensor
iPhone	Travel speed	Accelerometer
	Body orientation	Magnometer
	Body movement	Accelerometer
Apple Watch	Cane movement	Accelerometer
		Gyroscope
	Stress and emotion	Heart rate
Device	**Context type**	**Sensor**
iPhone	Location	GPS
GoPro	Environment features	Camera
	Environment sounds	Microphone

Table 3.2 Overview of participant demographics, vision impairment details, and travel habits.

#	Demographics		Vision impairment				Travel in unfamiliar areas	
	Age	Gender	Type	Timing	Residual vision	Mobility aid	Frequency	Comfort level
P1	30-34	Male	Low vision	6 months	Tunnel vision <5 degree, visual acuity 2% only in right eye	Symbol cane	Daily	Somewhat comfortable
P2	30-34	Male	Blind	Birth	None	White cane	Seasonal	Very uncomfortable
P3	25-29	Female	Blind	Birth	None	White cane	Monthly	Somewhat uncomfortable

3.2.2

Methods

Participants

Three participants were recruited for this study. One participant was recruited from an emailing list of VIPs in the Netherlands accessed through Bartiméus, and two participants were recruited through snowball sampling. Table 3.2 shows an overview of the participant demographics, vision impairment details, and travel habits that were collected in an initial questionnaire through a phone call or online via Microsoft forms.

There were two main criteria for selecting participants. First, participants who had undergone O&M training were selected to ensure they have the basic skills to stay safe outdoors. Second, participants who use a guide dog for navigation were not selected, since the information needs would vary greatly, as explained in Chapter 1. Of course, it was also important that the participant was willing to navigate an unfamiliar route in an urban area on their own. The vision impairment type or degree was not included as a criterion because this does not determine the participant's willingness to navigate an unfamiliar route and to avoid limiting the number of participants that may be interested.

The study was conducted in English for P1 and P3 since the participants were comfortable speaking in English. For P2, the study was conducted in Dutch with the help of a Dutch-speaking interpreter.

Ethical considerations

This study was reviewed and approved by the Human Research Ethics Committee (HREC) at Delft University of Technology (submission ID: 2144). Participants read through a detailed study description and gave informed consent beforehand (see Appendix C). Furthermore, the study description and explicit consent points were reviewed on the day of the navigation task to ensure that participants are well informed. During the navigation task, an extra, sighted researcher walked in the proximity of the participants to ensure their safety.

Procedure

As shown in Figure 3.6, the main activity of this study consists of the navigation task, post-navigation interview, and follow-up interview. The navigation task and post-navigation interview were conducted according to a user manual shown in Appendix D.

The navigation task took place in the Rotterdam Blaak area. After a short introduction to the study, the devices for data collection were placed on the participants. The video camera (GoPro Max) was mounted on the strap of a backpack, the iPhone was placed in the right pocket of the same backpack, and the Apple Watch was worn on the wrist of the arm the participants use to hold the cane.

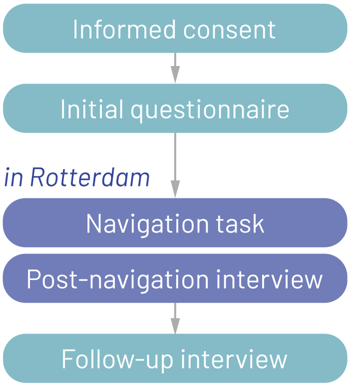


Figure 3.6 Overview of procedures.

For the data collection, the GoPro was set to '360 mode' to capture a 180-degree view of the environment in front of the participant. On the iPhone and Apple Watch, an app called SensorLog (Bernd Thomas, 2022), which was downloaded beforehand, was opened and started to log data from the sensors inside of the respective devices with a sampling frequency of 30 Hz. A 'walking' workout was also started on the Apple Watch, to ensure that the heart rate sensor keeps measuring the participant's heart rate, for the entire duration of the navigation task.

The participant was asked to navigate from Rotterdam Blaak station to the door of the café 'Joy Espresso and More' with the minimal instructions provided by the navigation system, which was acted out by the researcher. In addition, the following phrase was announced before the task to all the participants. "Hello, I'm your navigation guide. I will provide the minimum directions to the destination. If you start feeling uncomfortable and need more information to navigate, you can ask me questions." During the navigation task, the navigation system intervened only if the participants veered off route for more than 20m or if there was a dangerous situation (e.g. walking onto a street or tram line, encountering an object that participants could not detect with their cane, etc.).

The follow-up interview took place at 'Joy Espresso or More' or at Rotterdam Central Library, depending on how busy the café was. The purpose of the interview was to capture the user's thought process and emotions during the task. In this thesis, this is called experience annotation. To do this, the researcher played the GoPro video footage on a PC and gave verbal descriptions to help the participants' recall what happened during the navigation task. The audio was outputted through a speaker so that the participants could also hear the video. The participants were asked to signal the researcher to stop the footage if they recalled a thought or emotion. The researcher also stopped the footage when something significant happened.

> **Experience annotation** – Annotating a stream of data with the subjective experience of the user.

The experience annotation task was followed by a separate interview. The results are introduced in section 3.1.

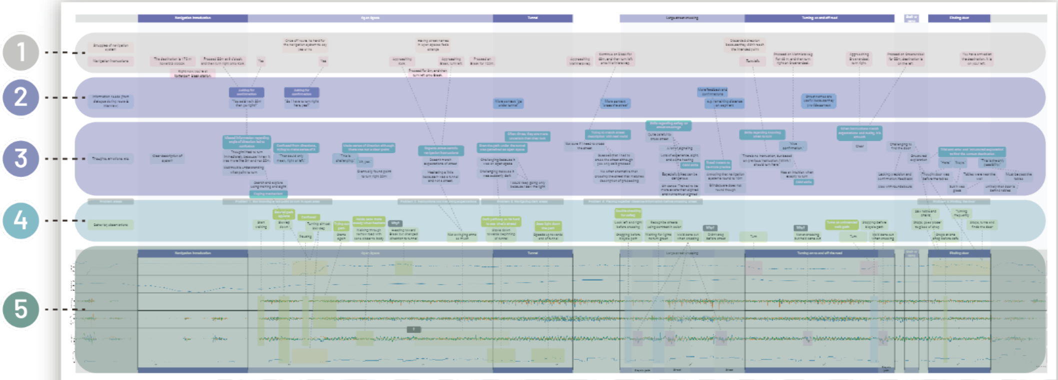
The final follow-up interview was conducted through a phone call after the collected data was reviewed, using methods explained in the next section. The purpose of the interview was to make sure that the researcher's interpretation was aligned with what the participants experienced. The assumptions made while exploring the data were also discussed with the participants. This fostered collaboration in the data analysis process. Both interviews were recorded.

Data analysis method

The behavioral time-series data collected from the iPhone and Apple Watch was first cleaned and visualized using the pandas and matplotlib libraries in python. To make it easier to go through this data, the behavioral data was resampled and imported into the Data Capture Lab (DCL) tool (SensiML, 2022), which is a desktop app that can sync time-series data with a video file. The user interface also allows the researcher to zoom and scroll through, making it easier to explore the time-series data.

Figure 3.7 shows how the collected data from the navigation task was mapped out for each participant.

Furthermore, a thematic analysis was conducted with the transcribed experience annotation interview data to identify reoccurring themes. The quotes or paraphrased notes in the journey map were coded and



① Navigation instructions
② **Information needs** *Questions on-route and experience annotation*
③ **Thoughts and emotions** *Experience annotation*
④ **Observed behaviors** *Realtime and video footage observations*
⑤ **Behavioral data** *Sensors in iPhone and Apple Watch*

Figure 3.7 Example journey maps used for analysis.

further clustered into themes. These clusters were further placed on a graph with two axes to find further relations between the identified themes. The y-axis provides the source of the information: information provided by the navigation system versus information the users gathered themselves. The x-axis provides how the information is used: information used for near-space mobility versus information used for far-space mobility.

3.2.3

Results & findings

Journey map

Detailed journey maps were created for each participant and are shown in Appendix E.

Here, the problems and other interesting episodes are compiled to demonstrate the journey that the participants underwent.

The problems are also classified depending on the intensity. Major problems were incidents that caused the participant to go off route or took significant time to tackle. Minor problems were incidents when the participants needed to focus more on the situation or were momentarily confused. Other episodes that provided some additional findings are also introduced.

It is important to note that although the word ‘problem’ is used in this thesis, to the participants, they are not necessarily perceived as ‘problems’.

> **“ It's not really problematic, but they are moments that you really have to pay attention.**
>
> **– P2**

> **Major problems — Incidents that caused the participant to go off the route or took significant time to tackle.**

> **Minor problems — Incidents when the participants needed to focus more on the situation or were momentarily confused.**

> **Other episodes — Other interesting incidents that demonstrate insights on how PVIs travel**

Open space

Problem 1, major, P1
Not knowing exact point to turn in the open area

Incident: Participant simply missed the clockface directions in the beggining.

Coping method: Structured exploration to see options and eliminating them using residual vision and past experience.

Problem 2, minor, P1
Streets in open spaces not matching expectations

Incident: The announced street name caused confusion because it was an open space and there were no apparent streets.

Coping method: Confused but continued in the general direction.

Episode 1, P2
Misidentifying a small step in the open area with a drop-off on a sidewalk

Incident: This misunderstanding worked in the participants' favor since they used this clue to turn right, just as the instructions stated.

Insight: The incident demonstrates that PVIs constantly try to match instructions to what they can sense.

Problem 3, major, P3
Forgetting the route instructions while finding something to follow

Cause: After orienting in the correct direction, P3 started looking for something to follow and as a resulted headed in the wrong direction.

Coping method: Trial-and-error process. In this case, P3 veered too far off, therefore researchers intervened and explained directions once more.

Tunnel

Episode 2, P1
Slowing down in the tunnel and following the light

Incident: Initially uncertain if going through the tunnel is necessary.

Insight: An episode that highlights use of residual vision for navigation.

Problem 4, major, P2
Disoriented due to object in front of the tunnel

Incident: Immediately stops after encountering a bike near the entrance of the tunnel.

Coping method: Asked researcher about the correct direction.

Problem 5, other, P3
Confusion caused by mistake in navigation instructions

Incident: The wrong directions were announced accidentally.

Coping method: Momentarily stop to clarify the mistake and the correct directions.

Episode 3, P3
Looking for something to follow after sensing a change in the environment

Incident: P3 detected the tunnel as she entered and actively started searching for the wall. After finding the wall, P3 asked if she was headed the right direction and the distance left on the segment.

Insight: The incident demonstrates that PVIs can detect changes in environment and uses it to determine if there might be something to follow. But afterwards, needs confirmation about navigation instructions.

Street crossing

Problem 6, minor, P1 P2

Detecting and seeking confirmation before crossing street

Incident: Both P1 and P2 detected the street crossing on their own and were uncertain if crossing the street is necessary.

Coping method: P1 guessed correctly to cross the street based on the instructions to proceed. P2 asked the researcher.

Problem 7, major, P2

Knowingly turning left early to avoid crossing street

Incident: At this point before the street crossing, participants are told to proceed for 48m and then turn left. P2 found a curve on the sidewalk and followed it to turn left even though he knew it was too early.

Coping method: He proceeded on this route until completely veering off the route. Researchers intervened and gave additional instructions to return to the route.

Problem 8, major, P3

Not being able to find the exact location of the street crossing

Incident: When exiting the tunnel, P3 veered to the left since the wall they were following in the tunnel was on the left hand side. Therefore, they were slightly to the left of the zebra crossing.

Coping method: Since it was a safety concern, researcher instructed P3 to veer to the right.

Problem 9, minor, P3

Disoriented due to tree planted on the pedestrian island

Incident: After encountering a tree on the pedestrian path, P3 got disoriented.

Coping method: P3 confirmed her current location and direction to proceed.

Problem 10, major, P3

Almost crossing the street on a red light

Incident: Since the intersection was quite big, there were several street crossings with sound indicators in the vicinity. P3 misinterpreted the sounds and started to walk on a red light.

Coping method: Researcher intervened to stop P3 immediately.

Sidewalk

Problem 11, minor, P1
Mistakes caused by 'previews' of the instruction

Incident: P1 turned early on to a wide pedestrian island instead of crossing the bike path since the previews mentioned taking a left turn.

Coping method: Researchers did not intervene since the pedestrian island was very wide.

Problem 12, major, P2
Failing to detect a pole in front and almost running into it

Incident: P2's white cane missed the pole on the sidewalk.

Coping method: Researcher intervened to stop P2 immediately.

Problem 13, minor, P3
Veering frequently to find something to follow

Incident: After the environment changed, P3 seeked for clue to follow. In the process, they navigated around a few of the planted trees.

Coping method: Trial-and-error process, eventually found the drop-off of the sidewalk.

Problem 14, minor, P3
Confusion caused by 'previews' of the instruction

Incident: Lengthy instructions with the current street and the street in the next segment caused confusion. made P3 confused about the current location.

Coping method: Researchers clarified the current location.

Episode 4, P2
Assuming environment from uneven road

Incident: Due to uneven roads caused by the roots of the trees, P2 assumed they were walking in an alley.

Insight: Demonstrates how PVIs are constantly guessing their surroundings based on what they sense.

Stairs/ramp
Finding door

Episode 5, P2
Detecting stairs and automatically finding the handrails

Incident: When P2 encountered the stairs, he first detected a step. He then tapped and dragged his cane around until he eventually understood that there were stairs with handrails. He then automatically held his cane with his left, and the handrails on his right hand to climb up the stairs.

Insight: Demonstrates how O&M skills are used in a real-life scenario. Especially the time and extra step needed to understand the situation before being able to rely on O&M skills.

Problem 15, minor, P1 P2 P3
Finding the exact location of the door to the café

Incident: All participants took their time to find the location of the door, which was expected.

Coping method: Since the instructions mentioned the destination on the left side, all participants actively searched the left side along the buildings. This is also a skill taught in O&M training.

The journey map showed specific situations that each participant encountered in chronological order. Contrary to the journey map, the thematic analysis shed light on the common issues that occurred across participants. The analysis resulted in nine large clusters.

Problem areas

The specific problems that occurred on the route are introduced through the journey map summaries. Through the thematic analysis four main themes that caused the problems were identified.

Confusion due to expectations about the navigation system

P1 expected any roads with a 'street name' to have cars and a sidewalk. This expectation confused P1 when they encountered a street in the open area, that did not look like a street. On the other hand, an environment that was not next to streets with cars, such as the tunnel, was considered an open area. Concerning expectations, all participants knew that the reliance on GPS is not that high and did not expect it to be completely reliable.

High-dependency on received and gathered information

Nevertheless, all participants relied heavily on the instructions given by the navigation system. All participants mentioned trying their best to execute the instructions as well as possible.

The process of making sense of and following navigation instructions goes well if instructions match real-world scenarios. For example, when the navigation system mentions a turn, a drop-off in front or curve in the sidewalk serves as a clue to turn. However, in some cases, participants also made some wrong assumptions to feel that they had completed the instruction. For example, P2 misidentified a small step in the open area with a drop-off on a sidewalk. P1 also found a 'clear' turning point in the open area, although it was not the correct turning point that the navigation intended.

P2 and P3, who had no residual vision also had a great dependency on structures they can follow. For example, P2 kept following the sidewalk drop-off even though he knew it was wrong. This is because having structures to follow helps them with their orientation and walking straight. It is also how

they usually travel on familiar routes. Therefore, they get a sense of ease and safety when they have something to follow. At times, especially with P3, they lost track of instructions while trying to find a structure to follow.

Having trouble recalling instructions

Despite information being kept to a minimum, it was hard for participants to keep track of it. Sometimes, participants were simply not able to catch all the information. In other cases, they forgot the previous instruction since they were focused on their near-space mobility, for instance, when they encountered an object and were navigating around it.

The 'Preview' instructions also caused some confusion, perhaps because there were too many instructions given at once. For example, when the navigation announced, “Proceed on Mariniersweg for 48 m, and then turn right on Groenendaal.”, the participant got confused and asked, “So Mariniersweg is not here?”. ‘Preview’ instructions also led to participants turning too fast. For example, after the instruction “Proceed on Blaak for 48m and then turn left on to Mariniersweg.” was announced, P2 turned left before crossing the street and P1 turned left before crossing the final bike path.

Encountering an obstacle on the route

Especially for P2 and P3, problems occurred when they encountered objects on the path, especially bikes and scooters. When they detected something in front of them, participants immediately doubted that they are on the correct path and as mentioned before, became busy with near-space mobility and navigating around the object.

Gathered information and additional information needs

The information provided by the navigation mostly helps participants with far-space mobility, while participants gather information for near-space mobility using skills obtained during O&M training.

Using provided instructions regardless of their intuitiveness

All participants preferred clock face directions ('? o'clock'), as it is more precise than 'right' or 'left'.

There were some personal differences regarding the distance information that was announced in meters. This preference depended on the ability to estimate real-life distance and know the exact meters. P1, who usually travels unfamiliar routes wanted even more precision in the instructions regarding distance in meters. P2 and P3, who usually do not travel unfamiliar routes as often found instructions regarding distance in meters to be unintuitive. One participant even disregarded the information towards the end.

Regardless of their preference, all participants used the distance in one way or the other. For example, they used it to determine whether to cross the street or not, to estimate when to turn, and to estimate the remaining distance on the segment.

Street names were also helpful to participants because they provide context and were used to recall specific situations on the route.

Relying on O&M skills for environment understanding and safety

As seen in other studies, participants leverage information from all senses to gather information about their surroundings. For example, P3 heard the tunnel. It is also important to note that P1 used his residual vision, despite a low visual acuity and field of vision, to identify bike paths and zebra crossings.

Participants are also constantly piecing together clues and guessing what kind of environment they are in. For example, Participant 2 thought that the café was located on a terrace when he noticed there were stairs on the route and assumed being in an alley or small sidewalk when he felt the uneven road.

Moments, when they relied on their O&M skills, were also evident. First, participants gathered clues and once they detected the type of obstacle, they automatically use strategies learned in O&M training. This was prevalent during the last mile navigation, street crossing, and stairs. Figure 3.8 illustrates this process.

During last mile navigation through structured exploration, participant 1, who had some residual vision, found the door of the café through a trial-and-error exploration process also making use of their sight. Regardless of residual vision, participants explained that they usually follow the building line on the side the destination is and eventually detect the door. Before a street crossing, all participants listened to traffic, lifted their cane, and waved it in the air to signal others, then started walking. Also, when P2 encountered the stairs, he automatically looked for handrails as soon as he detected the stairs.

Needing more confirmation and information on street structures

All participants were uncertain and wanted to know if they needed to cross the street beforehand. This information is especially important to ensure the safety of participants and help them feel at ease. The information also contributes to the participant's knowledge of their surroundings and context. However, feeling this sense of safety sometimes was the cause of going off route.

Similarly, information regarding common obstacles and structures (e.g. stairs, tunnel) were also requested. This information not only provides information on their safety but also provides rich information for participants to look for. For example, if there is a bridge on the route, the participant can anticipate that there is water nearby and an inclined surface. P3 also mentioned knowing these structures could help when asking other people. Finally, since these structures are on the route, it could help participants confirm that they intuitively are

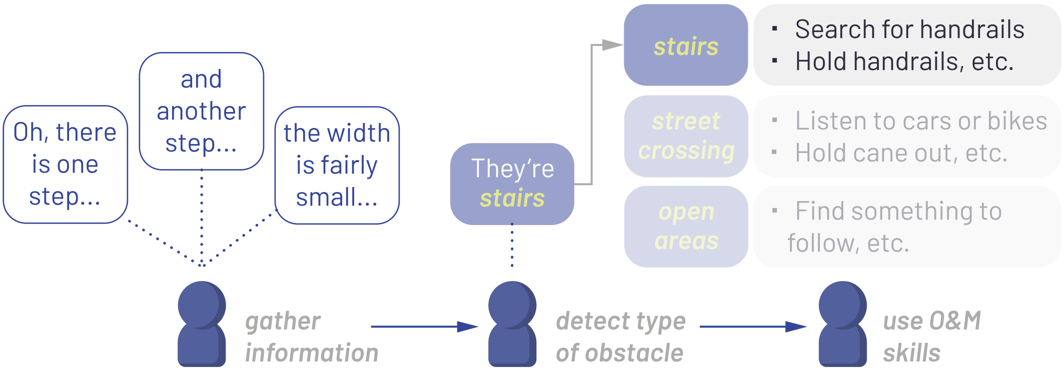


Figure 3.8 Illustration of how VIPs use learned O&M skills on the route.

on track, thus assisting with the far-space navigation.

Participants also asked about the current instruction and the progress they made on the segment. As expected, having more frequent confirmation regarding their location and the direction they are headed was especially important.

Mentality

The last two themes reflected the mentality of the participants when navigating.

Falling back on trial-and-error when encountering problems

The main coping method when a participant encountered a problem was trial-and-error. They search for their options and if they cannot narrow the options based on the navigation instructions, they followed one of the options until told otherwise. One participant also mentioned having trouble determining if she should ask the navigation system or try to figure it out on her own. This explains why many of the participants were relatively passive when it came to asking questions.

Prioritizing safety

In O&M training, safety is a priority, and this is a mentality that all participants have. Even common situations, such as crossing a street, is a high-risk activity. Whether participants are comfortable taking risks depends on how much experience one has with traveling in unfamiliar areas. For example, P1, who travels to unfamiliar areas daily, crossed the street without asking, while P2 and P3 crossed the street only after knowing they had to cross.

Data correlates

Many behaviors showed up in the time-series data. For example, moments when participants encountered objects in front, detected objects on the side of the path, held the cane upright, held the cane out, and waved their cane in the air.

However, two large categories of data were observed: data with rhythmic patterns and data with no patterns. The rhythmic data resulted from ‘walking’ movements, while the random data resulted from movements when participants were navigating around objects or trying to figure out which direction to go in.

Limitations

One limitation of the study was that the participants had varying degrees of vision impairments. This was due to the limited access to participants. In addition, the task did not capture a navigation task in a completely natural environment, in which the participants use their tools to navigate outside. Therefore, compared to the navigation app, the location accuracy was higher than in a natural environment.

3.2.3

Main takeaways

What are the problem areas that occur when navigating an unknown urban area?

- PVIs became disoriented due to encounters with obstacles (e.g. parked vehicles) or by following a clue for too long
- PVIs needed more information before proceeding when they encountered a common street structure (e.g. streets and stairs).
- PVIs were uncertain about which way to head due to confusing instructions (e.g. streets in an open area), poorly timed instructions (e.g. previews), or missed instructions.
- PVIs forgot which way to head after actively looking for clues that could help them identify turning points (e.g. curves) or provide a line of direction (e.g. walls).

What information is needed to overcome these problems when navigating unknown areas?

- All participants wanted to know if crossing the road is necessary.
- All participants needed more frequent confirmation through, for example, repetition of instructions.
- Although participants detected types of common street structures (e.g. tunnels and stairs), they preferred to receive information about it beforehand. This is because these moments are potential moments of danger and safety is of utmost importance to participants.
- PVIs are very used to the trial-and-error process, therefore attempted to solve problems on their own. This is why many of them did not ask many questions.

What can an agent sense from the user?

- Two large categories of data were observed: data with rhythmic patterns that captured ‘walking’ movements and data with random patterns that captured movements when participants were navigating around objects or trying to figure out which direction to go in.

3.3

Design direction

> **Based on the findings from the participatory data storytelling, two behaviors that reflect the user's mental state are identified. This serves as the basis for the preliminary idea of a user-aware navigation agent. Furthermore, specific hypotheses about problem areas and information needs of PVIs navigating unfamiliar outdoor areas are formulated.**

What are the behaviors that reflect the traveler's mental state?

How can an agent help?

3.3.1

Problem statement

When traveling outdoors in an unfamiliar area, PVIs must simultaneously manage far-space and near-space tasks. This proved to be mentally demanding. It also does not help that the navigation instructions for far-space mobility, such as the distance information, are unintuitive and hard to estimate. The real challenge is to bridge the gap between near-space and far-space mobility. This is already done on familiar routes, where the landmarks and clues correlate with the position on a route. However, this connection is made through repetition. How can we achieve this in an unfamiliar area?

3.3.2

Two situations

Figure 3.9 shows the main behaviors of the PVIs identified through observations, along with the transitions between these behaviors. The two main behaviors that also reflect the PVIs mental process were when PVIs were walking or proceeding, versus when they were exploring their immediate surroundings. These two behaviors will be called 'following' and 'reorienting'.

'Following' the route

When PVIs navigate an unfamiliar route, they are never 100% confident that they are following the route. However, whenever they have an idea of which way is correct, they walk in that direction and wait for confirmation from the navigation app (e.g. distance on the segment becomes shorter, the next instruction is announced) or wait until the navigation system tells them they have veered off the route.

In either case, they are more focused on 'following' the route precisely using the navigation instructions that were given to them. In other words, they are more focused on far-space mobility tasks.

As the data correlates showed, since the traveler is walking in this state, the sensor data captured periodic data with many rhythmic patterns.

'Reorienting' on route

While PVIs are following a route, there were moments that triggered them to stop following the route and start gathering information from their surroundings.

These moments occurred in the problem areas that were identified in the first user study. First, when PVIs became disoriented due to encounters with obstacles (e.g. parked vehicles) or by following a clue for too long. Second, when they encountered a common street structure (e.g. streets and stairs) and needed more information before proceeding. Third, when they were uncertain about which way to head due to confusing instructions (e.g. streets in an open

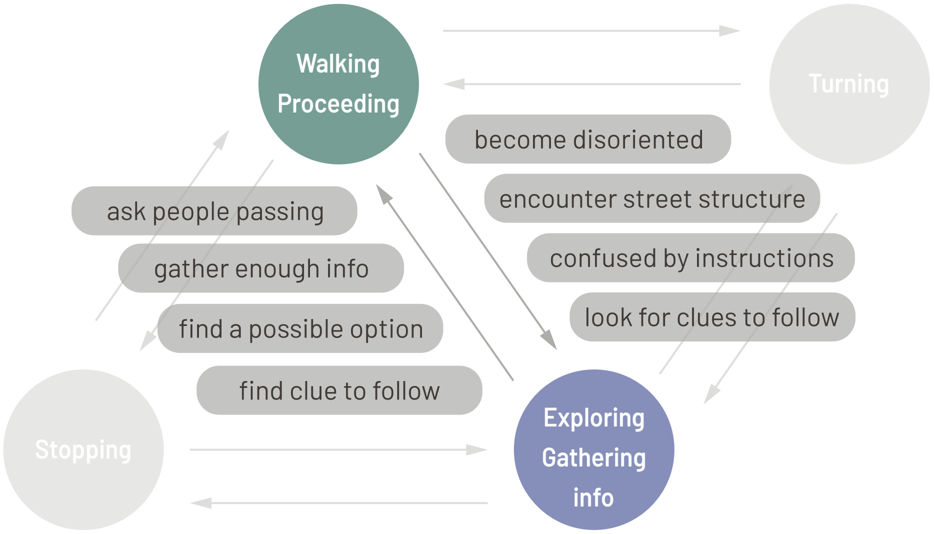


Figure 3.9 Main behaviors identified on the route, along with the transitions.

area), poorly timed instructions (e.g. previews), or missed instructions. Finally, when they were actively looking for clues that could help them identify turning points (e.g. curves) or provide a line of direction (e.g. walls).

In these cases, PVIs were more focused on understanding their immediate surroundings, or with near-space mobility tasks. To do this, PVIs often slow down, change their body orientation frequently, and use residual senses (e.g. tactile feedback through the cane). After exploring their immediate surroundings, PVIs must 'reorient' on the route to get back on track with the navigation. Participants often needed a reminder of which direction they should be heading in.

In general, moments when PVIs 'reorient' on a route are also moments of uncertainty compared to when they were 'following' a route. This was reflected in the data as random movements, especially in the body orientation data.

3.3.3

The concept

The idea for the 'seed design' is visualized in Figure 3.10. If an agent can detect the 'following' and 'reorienting' behaviors, it can also provide the most necessary information in that situation.

More specifically, when the user is busy thinking about 'following' the route for far-space mobility, the agent could assist with near-space mobility by giving environmental descriptions, clues to maintain a line of direction, and announcing objects they might encounter.

On the other hand, when a PVI is busy with near-space mobility tasks and needs to 'reorient' on a route, the agent could remind the user of the direction they should be heading. This way, the PVI can focus on near-space mobility for as long as they want and not worry about forgetting the directions.

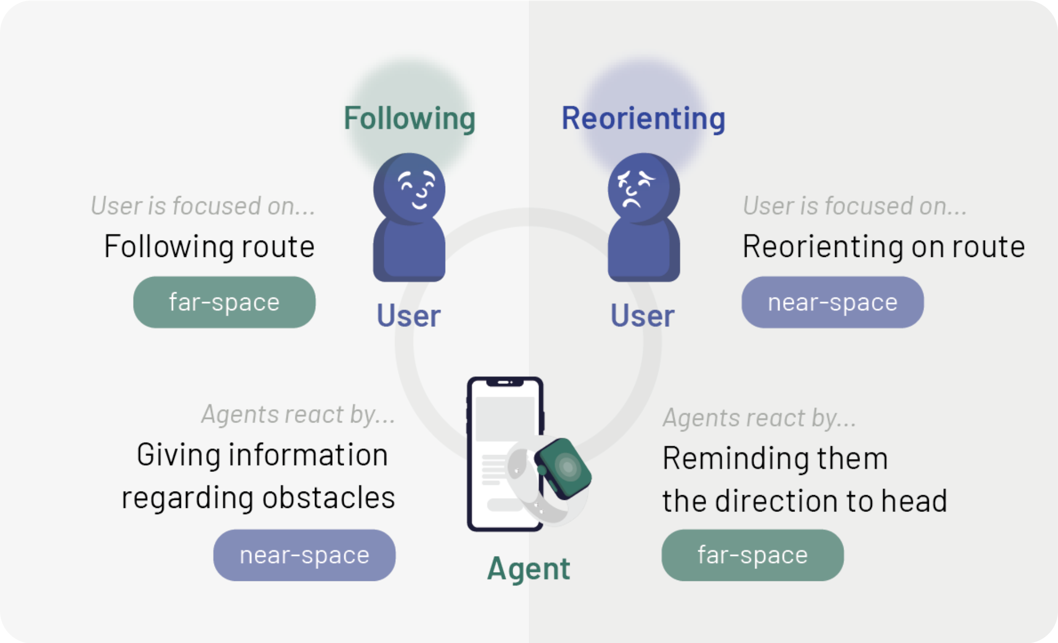


Figure 3.10 The initial idea of the user-aware navigation agent.

3.3.4

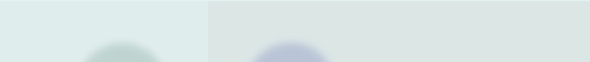
Main takeaways

What are the behaviors that reflect the traveler's mental state?

- Outdoor navigation is challenging and unintuitive for users mainly because the information on far-space mobility provided by the navigation app is hard to link to information gathered in near-space mobility.
- Two distinct situations that reflect the user's state on the route were identified through the behavioral data.
- These two states are called 'following' and 'reorienting' because they reflect moments when users are 'following' a route and 'reorienting' on the route.

How can an agent help?

- The PVI's mind is usually occupied with far-space mobility when 'following' the route and occupied with near-space mobility when 'reorienting' on the route.
- The hypothesis is that an agent that assists with near-space mobility when PVIs are 'following' a route and assists with far-space mobility when 'reorienting' on a route would help make navigating a lot easier.




Rivo
Outdoor Walk
2:49
Pause
End
New
Lock
waliteit in uw leven

Chapter 4
Evaluative research

In Chapter 4, the idea for a user-aware navigation agent is evaluated through the perspective of the agent and user, namely the feasibility and desirability. For technical feasibility, abilities to sense the user through machine learning (ML) algorithms and the ability to sense the environment through existing data on the internet are considered. The desirability is investigated through a navigation task using a wizard-of-oz puppet prototype of the concept.

4.1

Capabilities of the agent

One of the largest advantages of an agent partnering with people with vision impairments is that agents can sense the user and the environment. In this section, we investigate how well an agent can detect the 'following' and 'reorienting' behaviors of a user and what sensors are necessary to do this. In addition, the agent's ability to provide environmental descriptions that could help link information for far-space and near-space mobility is also discussed.

How well can an agent detect 'following' and 'reorienting' behaviors?

How many devices are needed to detect 'following' and 'reorienting' behaviors?

What are the key data that characterize 'following' and 'reorienting' behaviors?

What kind of information is available or could be generated to provide more context?

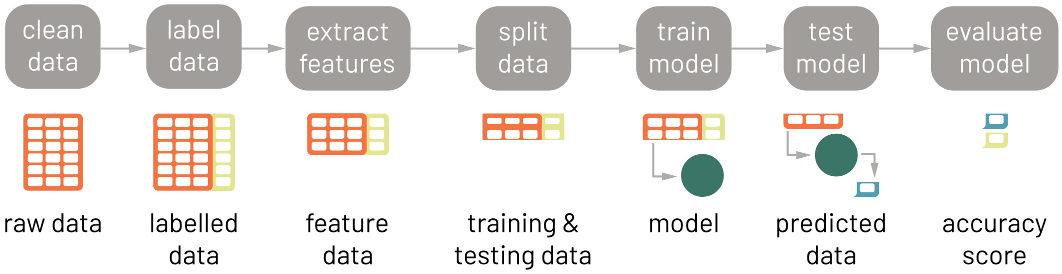


Figure 4.1 Procedures to train and evaluate the ML algorithm.

4.1.1

Sensing the user

Training an ML algorithm

To see how well an agent can detect 'following' and 'orienting' behaviors, an ML algorithm was trained to categorize windows, or short chunks, of time-series data. Since there is not a lot of behavioral data available, separate algorithms were trained for each participant. This makes it easier for the algorithm to classify behaviors since the data will contain more consistent patterns. Behavioral data from the second user study, introduced in section 4.3, were used.

Figure 4.1 shows an overview of the steps that were taken to train and evaluate the algorithm. All procedures were done in python using the sklearn, matplotlib, and pandas libraries. First, the raw data is cleaned, filtered, and labeled. The data was cleaned by discarding data from before and after the navigation task. Also, the body orientation data was altered to eliminate sudden changes from 360 degrees to 0 degrees and vice versus.

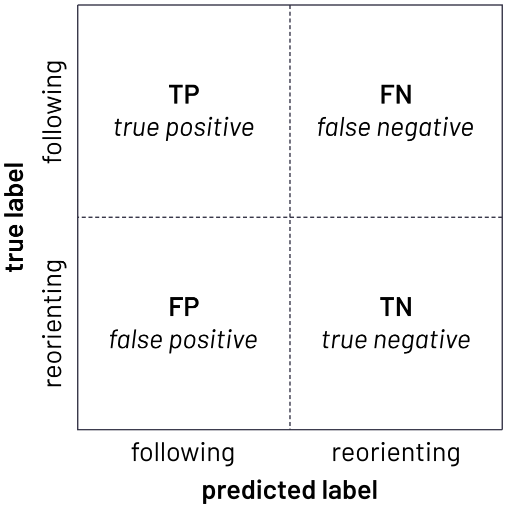
The data were filtered by choosing data types that seemed to correlate with the respective behavior states. These are listed in Table 4.1. Finally, the data was labeled by reviewing and observing the video footage from the navigation task.

Table 4.1 Data and features used to train the algorithm.

Device	Behavior type	Sensor	Extracted features	#
iPhone	Travel speed	Accelerometer	mean, maximum, minimum	3
	Body orientation	**Magnometer**	mean, **difference**, FFT maximum, FFT maximum index	4
	Body movement	Accelerometer (x)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Accelerometer (y)	maximum, minimum, **difference**, **FFT maximum**, FFT maximum index	5
		Accelerometer (z)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
Apple Watch	Cane movement	Accelerometer (x)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Accelerometer (y)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Accelerometer (z)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Gyroscope (x)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Gyroscope (y)	maximum, minimum, difference, FFT maximum, FFT maximum index	5
		Gyroscope (z)	maximum, minimum, difference, FFT maximum, FFT maximum index	5

Next, the features are extracted from each window of time-series data. To capture the rhythmic patterns when one is walking, the window sizes were set to incorporate 5 steps. Considering the sampling frequency of 30Hz and the amount of time it took for one step (about 0.6 seconds for most participants), the window size was set to 100. The step size was set to half of the window size to increase the number of features in the limited dataset. For each window, 52 features mentioned in Table 4.1 were extracted. The label that occurred most was chosen as the label for the window.

This dataset is then split into the training and testing datasets using the train_test_split function. More specifically, the data were randomly split into half, while ensuring there is an equal number of 'reorienting' and 'following' data in both training and testing datasets. A logistic regression model was trained using the training dataset. Finally, the performance of the algorithm is evaluated by inputting the testing dataset into the trained algorithm and comparing the predicted labels with the true labels.



true label \ predicted label	following	reorienting
following	**TP** *true positive*	**FN** *false negative*
reorienting	**FP** *false positive*	**TN** *true negative*

Figure 4.2 Explanation of a confusion matrix.

Initial results

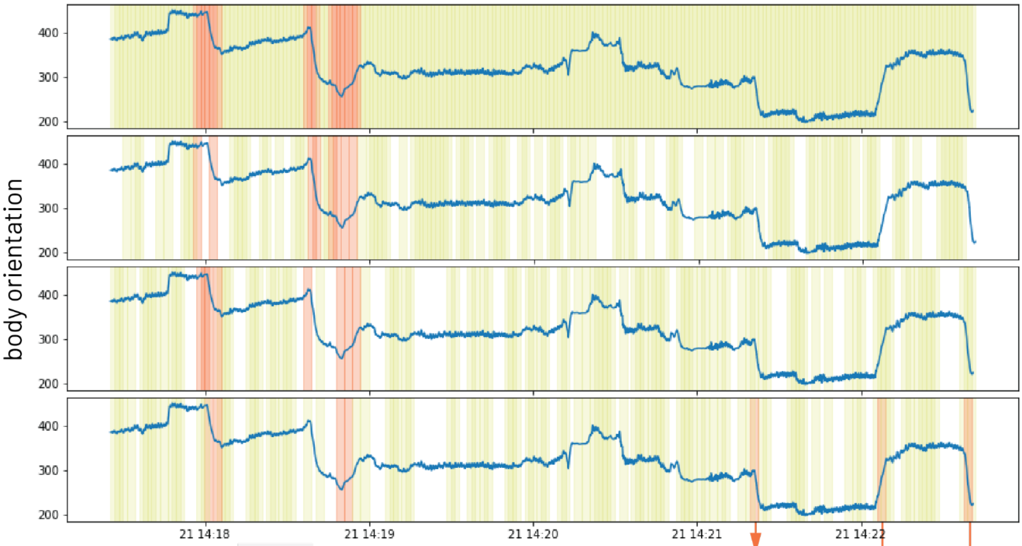
The accuracy of a model is usually evaluated using an accuracy score and confusion matrix. The accuracy score expresses how many windows were correctly classified. In the confusion matrix, as shown in Figure 4.2, the x-axis consists of the 'true' labels, while the y-axis consists of the 'predicted' labels. Each cell in the matrix shows the number of windows that fall into each category. If a model is perfect, the cells that are not located on the top left to bottom right diagonal, namely the false positive and false negatives, should all be 0.

The accuracy of a model highly depends on the data it was trained with. Therefore, five sets of training and testing datasets were created randomly using the random_state parameter in the train_test_split function. For each dataset, a model was trained and evaluated. This was done for each of the three participants.

The resulting accuracy score and the specificity are shown in Table 4.2. The sensitivity is not indicated because the values were high, ranging from 0.94 to 1.0, which implies that the 'following' windows can be classified with high accuracy. This is because there is more data labeled 'following' in the datasets that were used.

The accuracy score is calculated by (TP + TN)/(TP + TN + FP + FN), and the specificity calculated by TN/(TP + FN), where TP, TN, FP, and FN denote true positive, true negative, false positive, and false negative, respectively. In short, the specificity of the 'reorienting' label expresses how many windows labeled 'reorienting' were classified correctly.

Furthermore, to understand where mistakes were made, the labels were visualized. Figure 4.3 shows the confusion matrix and the trained, predicted, and true labels visualized on the body orientation data.



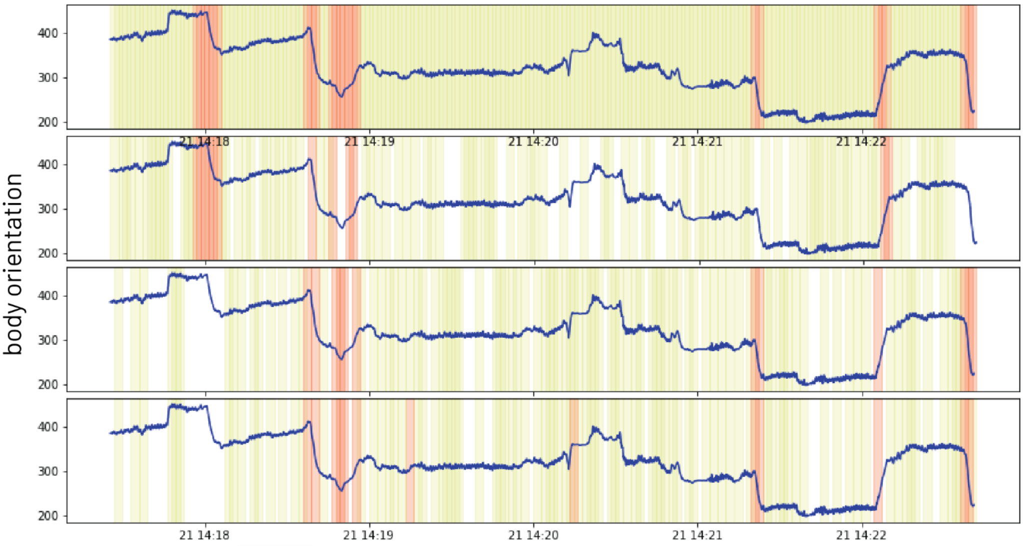
following | F	94	3
reorienting | R	4	4
	F	R

turning left on to Mariniersweg

turning right on to Groenendaal

turning left to find the destination

Figure 4.3 Confusion matrix and the trained, predicted, and true labels visualized on the body orientation data.



following | F	91	2
reorienting | R	1	11
	F	R

Figure 4.4 Confusion matrix and the trained, predicted, and true labels visualized on the body orientation data after labels were edited..

The highlighted areas correspond to when P4 is turning left onto Mariniersweg, turning right onto Groenendaal, and turning left to find the door. This is interesting because although travelers are 'following' the route when they turn on a segment, they are also 'reorienting' and finding the next direction the route continues. This misinterpretation was present in all three participants.

Labeling 'turning' as 'reorienting'

From the initial results, it was evident that moments when users 'turn' in between segments were also recognized as a moment of 'reorienting'. Therefore, the 'reorienting' labels were edited to include moments when one turns on and off a street.

Again, five sets of training and testing datasets were created randomly using the random_state parameter in the train_test_split function. The same random_state values were used. For each dataset, a model was trained and evaluated. This was done for each of the three participants. The resulting accuracy score and specificity are shown in Table 4.3.

The average accuracy score increased by 0.1 for P4 and P6 and remained the same for P5. However, for all participants, the specificity increased. This shows that more 'reorienting' windows were classified correctly after relabeling 'turning' behavior as 'reorienting'. In addition, the specificity for P5 is higher than the other two participants. P5 took the most time to complete the route and therefore, there were a lot of moments of 'reorienting'. This resulted in more training data, which likely caused the specificity to be higher. This also shows that more training data will help increase the accuracy of the model.

Furthermore, Figure 4.4 shows the confusion matrix and the trained, predicted, and true labels visualized on the body orientation data. As expected, moments when P4 'turns' on the route are classified as 'reorienting'.

These results imply that in the agent's perspective, the behavior when someone 'turns' between segments is comparable to when one is 'reorienting' on a route. According to the results, an agent can classify 'following' and 'reorienting' behaviors at 90% to 95% accuracy. However, 'reorienting' moments include moments when one is 'turning' on to the next segment. This information could be discarded by combining the classification results with route information that includes when a traveler is expected to turn. This way, an agent can sense moments where users are 'reorienting' during each segment.

Table 4.2 Resulting accuracy score and specificity of the trained model.

random_state		6	10	46	59	63	mean
P4	**Accuracy**	0.93	0.90	0.92	0.94	0.93	**0.93**
	Specificity	0.25	0.50	0.50	0.25	0.50	**0.40**
P5	**Accuracy**	0.89	0.90	0.91	0.87	0.89	**0.89**
	Specificity	0.75	0.82	0.75	0.67	0.69	**0.74**
P6	**Accuracy**	0.88	0.89	0.92	0.93	0.93	**0.91**
	Specificity	0.27	0.27	0.27	0.64	0.55	**0.40**

Table 4.3 Results after the labels were edited to include 'turns' as a 'reorienting' behavior..

random_state		6	10	46	59	63	mean
P4	**Accuracy**	0.96	0.91	0.95	0.93	0.94	**0.94**
	Specificity	0.67	0.50	0.67	0.67	0.67	**0.64**
P5	**Accuracy**	0.92	0.91	0.89	0.89	0.89	**0.90**
	Specificity	0.88	0.85	0.84	0.84	0.78	**0.84**
P6	**Accuracy**	0.89	0.94	0.93	0.91	0.89	**0.91**
	Specificity	0.36	0.64	0.57	0.57	0.57	**0.54**

Limiting the number of devices

With the current data selection used to train the machine learning algorithm, shown in Table 4.1, both the iPhone and Apple watch are necessary. In a case where only the iPhone is available, how would the accuracy score change? To answer this question, the features created from the Apple watch data were discarded. This resulted in 21 features.

Again, five sets of training and testing datasets were created randomly using the random_state parameter in the train_test_split function. The same random_state values were used. For each dataset, a model was trained and evaluated. This was done for each of the three participants. The resulting accuracy score and specificity are shown in Table 4.4.

The accuracy of the model stayed the same for P4 and P6, while it increased by 0.2 for P5. The specificity increased for P4 and P5, while it decreased for P6. Therefore, only using features from the iPhone data had varying effects depending on the participant and the results are not conclusive. However, overall, the accuracy of the model did not decrease drastically.

The features of the accelerometer and gyroscope of the Apple Watch reflected the rhythmic movements of the cane. The accuracy and specificity may not have been affected because similar rhythmic movements are captured through the accelerometer of the iPhone when one walks. Therefore, the Apple Watch data enforced some behaviors that characterized 'reorienting' behavior, but it was not extremely essential to train the model.

This conclusion also implies that there is a possibility that data from non-cane users could be used to train an algorithm that classifies 'following' and 'reorienting' behaviors.

Limiting the number of features

Finally, the minimum number of features that improve the model drastically were investigated. This shows what behavioral traits characterize the 'reorienting' behavior. This was done through a trial-and-error process. The two most important features to train the model were the 'amplitude of the true heading' and the 'maximum amplitude of the iPhone accelerometer (y-axis)' in the frequency domain'. A third feature that is not as impactful but important, was the 'amplitude of the iPhone accelerometer (y-axis)'.

The 'amplitude of the true heading' and 'amplitude of the iPhone accelerometer (y-axis) is then calculated by subtracting the minimum value from the maximum value in the window. The 'maximum amplitude of the

Table 4.4 Results when the model is trained only with data from the iPhone.

random_state		6	10	46	59	63	mean
P4	Accuracy	0.96	0.92	0.96	0.93	0.93	**0.94**
	Specificity	0.75	0.58	0.67	0.75	0.58	**0.67**
P5	Accuracy	0.93	0.93	0.91	0.91	0.90	**0.92**
	Specificity	0.85	0.85	0.82	0.85	0.79	**0.83**
P6	Accuracy	0.88	0.92	0.93	0.92	0.92	**0.91**
	Specificity	0.29	0.43	0.50	0.50	0.57	**0.46**

Table 4.5 Results when the model is trained only with the three most important features.

random_state		6	10	46	59	63	mean
P4	Accuracy	0.95	0.92	0.93	0.93	0.95	**0.94**
	Specificity	0.58	0.42	0.42	0.75	0.67	**0.57**
P5	Accuracy	0.91	0.91	0.92	0.90	0.91	**0.91**
	Specificity	0.79	0.79	0.79	0.78	0.78	**0.79**
P6	Accuracy	0.89	0.93	0.94	0.93	0.91	**0.92**
	Specificity	0.29	0.43	0.50	0.43	0.43	**0.42**

iPhone accelerometer (y-axis) in the frequency domain' is calculated by converting the time-series data from a time domain to a frequency domain using Fast Fourier Transform (FFT) and finding the maximum value.

In short, the 'amplitude of the true heading' reflects the body orientation and how much it increased or decreased in each window. The 'maximum amplitude of the iPhone accelerometer (y-axis) in the frequency domain' reflects how much rhythmic movements occurred. The y-axis was used since based on the orientation of the phone, the y-axis captures the most movements. Finally, the 'amplitude of the iPhone accelerometer (y-axis)' is a feature that reflects the travel speed. Although the iPhone was able to directly record 'travel speed' data, the sampling frequency was low and there also was a tendency for a time lag. Therefore, the 'amplitude of the iPhone accelerometer (y-axis)' was used instead.

Again, five sets of training and testing datasets were created randomly using the random_state parameter in the train_test_split function. The same random_state values were used. For each dataset, a model was trained and evaluated. This was done for each of the three participants. The resulting accuracy score and the specificity are shown in Table 4.5.

Similar data that reflect these behaviors could produce similar results. However, from these results, data that reflects the body orientation, rhythmic movements when walking, and travel speed, seem to be important metrics that characterize 'reorienting' behavior.

4.1.2

Sensing the environment

The first user study unveiled that PVIs are constantly trying to connect the street and distance information with the information they collect through O&M skills all while juggling near-space and far-space mobility tasks. For navigation agents to be more useful, they must provide more contextual information that PVIs can confirm using their residual senses. This contextual information should help both near-space and far-space mobility tasks.

The importance of contextual information in varying levels of abstraction has been pointed out in literature as well. In a study by Banovic et al. (2013), users mentioned gathering high-level information, or more general information, that is gathered through friends or even on city tours, about an area they are planning to travel to. This study refers to highly abstract environmental descriptions. Also, in a successful partnership between a sighted and PVI, the sighted companion gave a brief description of the environment every time they were in a new environment (Williams et al., 2014). This is an example of environmental descriptions at a lower level of abstraction.

To get a clear picture of what contextual information a navigation agent could provide, four information types with varying levels of abstraction are identified: general area descriptions, environmental descriptions, common street structures, and hazards.

General area description

General area descriptions refer to information if an area is historic, touristic, residential, etc. This information is highly abstract, and it is most useful when planning a trip to an area. This kind of information can be obtained through open source maps, which are map databases that can be edited by anyone. A good example is Hoodmaps (*Rotterdam Neighborhood Map*, n.d.), which categorizes areas under six labels: 'suits', 'rich', 'hip', 'tourist', 'student', and 'normie'. Another example is OpenStreetMap, which includes categorizations such as 'retail area', 'industrial area', 'commercial area', and 'school or university'.

Environmental descriptions

Environmental descriptions refer to the type of space around a traveler. For example, open areas, sidewalks, pedestrian islands, green areas, buildings, etc. This information is not specific enough to characterize the route and therefore does not help with geographic orientation. However, this information could help anticipate clues PVIs can use or obstacles they might encounter, which could assist in spatial orientation.

Some of this information regarding green spaces and open areas already exist in, for example, OpenStreetMaps and Google maps. However, environments that are specific to pedestrians such as sidewalks and pedestrian islands are still under development. There are projects such as OpenSidewalks (Taskar Center for Accessible Technology (TCAT), n.d.), that is taking an open source approach to creating data with details about the pedestrian paths, such as width, surface composition, and inclination. Google is also working on an update to include accurately scaled road widths, pathways, and steps in parks, sidewalks, street crossings, and pedestrian islands by using AI and ML algorithms on street maps, satellite, and aerial images (Google Maps Help, n.d.; Khoury, 2021).

Common street structures

'Common street structures' are information about common obstacles such as street crossings, stairs, tunnels, bridges, etc. that users will encounter on a chosen route. The abstraction level is lower than environmental descriptions because 'common street structures' are specific to a specified route. This information bridges the gap between far-space and near-space mobility. In other words, it gives information about the entire route, while giving information that users can also confirm through their senses. Furthermore, it clarifies obstacles they must overcome to reach the destination.

Information regarding 'common street structures' are not used in current navigation systems yet, but databases are under development through open source projects and by Google.

Hazards

'Hazards' are information about overhead obstructions and potholes in the ground. This kind of information requires high precision and has a high tendency to change. Although it is important information even on unfamiliar routes for safety reasons, information is hard to obtain through satellite images and street views. A system in which PVIs and O&M instructors can annotate specific areas on a route and a highly accurate GPS is needed to create such a database.

4.1.3

Main takeaways

How well can an agent detect 'following' and 'reorienting' behaviors senso

- An ML algorithm trained using 51 features from 2 devices (iPhone and Apple Watch) and 4 sensors can detect the two states with an accuracy of 89-93%, however, the algorithm was only able to classify 40%-74% of 'reorienting' labels correctly.
- This algorithm miscategorized moments when participants were 'turning' in between segments as 'reorienting' rather than 'following'.
- After labels were edited to include 'turns' as moments of 'reorientating', the accuracy score increased to 90-94% and the algorithm was able to classify 54%-84% of 'reorienting' labels correctly.
- Generally speaking, more data on 'reorienting' moments is needed for the ML algorithm to be able to classify 'reorienting' labels with higher accuracy.

How many devices are needed to detect 'following' and 'reorienting' behaviors?

- An ML algorithm trained using 21 features from one device (iPhone) and 2 sensors can detect the two states with an accuracy of 91-94% and the algorithm was able to classify 46%-83% of 'reorienting' labels correctly.
- The accuracy score implies that the iPhone could be sufficient for detecting these two states.

What are the key data that characterize 'following' and 'reorienting' behaviors?

- An ML algorithm trained using 3 features from one device (iPhone) and 2 sensors can detect the two states with an accuracy of 91-94% and the algorithm was able to classify 42%-79% of 'reorienting' labels correctly.
- The accuracy score implies that body orientation, rhythmic movements when walking, and travel speed are three features that characterize 'following' and 'reorienting' behaviors most.

What kind of information is available or could be generated to provide more context?

- Four types of contextual information, 'general area description', 'environment descriptions', 'common street structures', and 'hazards' are defined according to their abstraction level.
- Information on 'general area description' and some information on 'environment descriptions' exist in current map databases (e.g. OpenStreetMaps, Google Maps).
- Information on 'environment descriptions' and 'common street structures' that are specific to pedestrian navigation is under development through open source projects (e.g. OpenSidewalks) and by Google.
- Information on 'hazards', which require high precision and have a high tendency to change, is challenging to create. A system in which PVIs and O&M instructors can annotate specific areas on a route and a highly accurate GPS is needed to create such data.

4.2

Participatory Data Creation

> **Keeping the agent's capabilities in mind, this section explains how a second user study was conducted to verify the hypothesis that PVIs prefer information that helps with near-space mobility when they are 'following' a route and prefer information that helps get them back on track with far-space mobility when 'reorienting' on a route. This hypothesis was tested through an interactive wizard-of-oz puppet prototype that not only pushed information but allowed PVIs to pull information when needed.**

How do information needs change when they are 'following' route' vs 'reorienting' on the route?

Is there information that users prefer to have control over? What information do the users want to be automated?

4.2.1

Study design

Route selection

The same route as the one introduced in section 3.2.1, which starts at Rotterdam Blaak station and ends at a nearby café called 'Joy Espresso and More', was used for this study. The starting point was slightly changed to increase the distance participants travel in the open space, which is one of the areas where participants 'reorient' the most. The slightly altered route is shown in 4.5.

Navigation system prototype: setup

In the previous study, the navigation system was acted out by the researcher. In this iteration, the navigation system prototype ran on an iPhone which was controlled by an iPad that the researcher operates. The iPhone that the user operates will be called the 'puppet', and the iPad that the researcher operates will be called the 'controller'.

As shown in Figure 4.6, the researcher operated the controller 5 to 10 meters from the participant during the task.

This setup was chosen for reasons. First, a person can give away many different clues just by walking and talking next to the participant. For example, the direction that the voice is coming from, and the sound of the footsteps can give clues about which way to head. Second, a smartphone-based interface better simulates a real-life scenario where an individual is using a navigation app.

Finally, a smartphone-based interface provides an opportunity for simple interactions between the user and the navigation system. More specifically, the user can communicate to the navigation system through a gesture or a button press, as opposed to a verbal question. The idea was to make it easier for users to request information since many participants in the first user study were constantly debating in their minds whether they should figure out a situation themselves or ask the researcher.

The prototype was made using a python IDE that runs on iOS called Pythonista (omz:software, 2022). This app was downloaded on both the puppet (iPhone) and controller (iPad). The controller (iPad) was connected to the puppet (iPhone) through its hotspot and messages were sent to and from the devices through the OSC protocol via UDP sockets. The python code on each device was set up to fulfill the functions shown in Table 4.6.

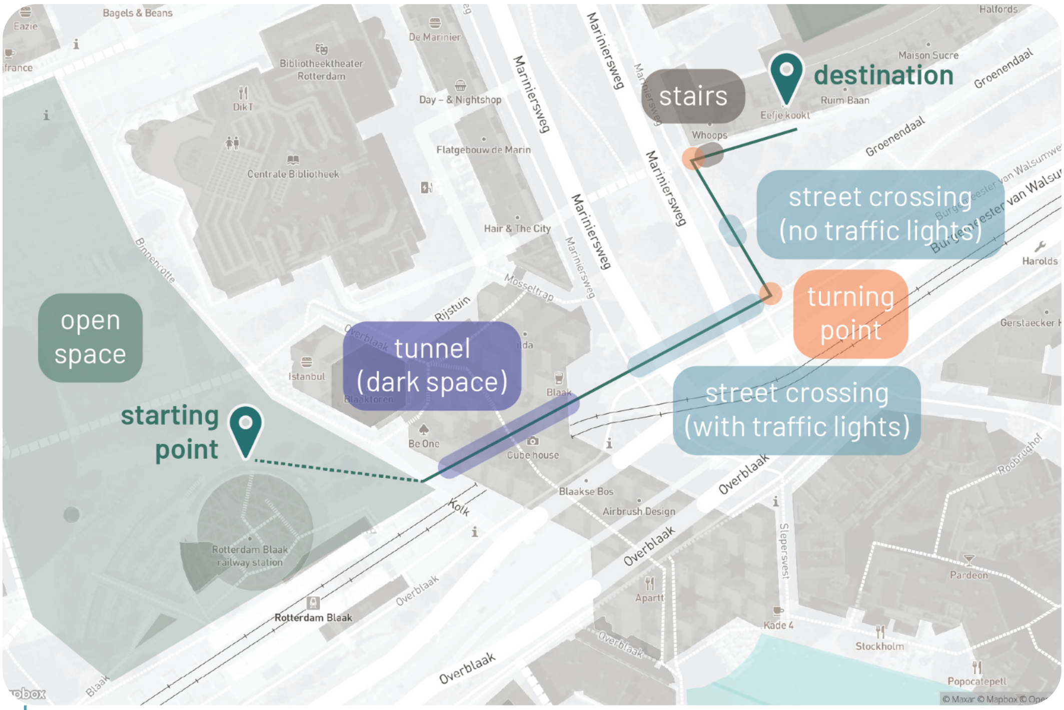


Figure 4.5 Slightly altered route from Rotterdam Blaak station to a nearby café 'Joy Espresso and More'. Adapted from Mapbox.

In addition, a UI for the controller was created, as shown in Figure 4.7. The information types and instructions are further explained in the upcoming section. The python script on the iPad also was coded to create a log of each piece of information that was pushed and pulled by the participant.

Navigation system prototype: information

The instructions and information that the navigation system provides were created through an iterative ideation process based on some guiding principles, or a list of requirements, that led to a series of design decisions. Both principles and design decisions were motivated by literature and insights from the previous user study.

Important to note is that a major difference compared to the first user study was that there are two types of information to design: pushed and pulled information. Pushed information is automatically announced to the users, while pulled information is announced only when the users request it. In this case, the users will pull information through the two buttons.

> **Pushed information** – Information that is automatically announced by the users.

> **Pulled information** – Information that is announced when users request them.

The following principles were formulated and served as requirements for the prototype.

- The instructions should be tailored to a situation where PVIs travel in a low-interest, unfamiliar area.
- Navigation with the prototype should be easy to learn and must not include more than two types of pulled information.

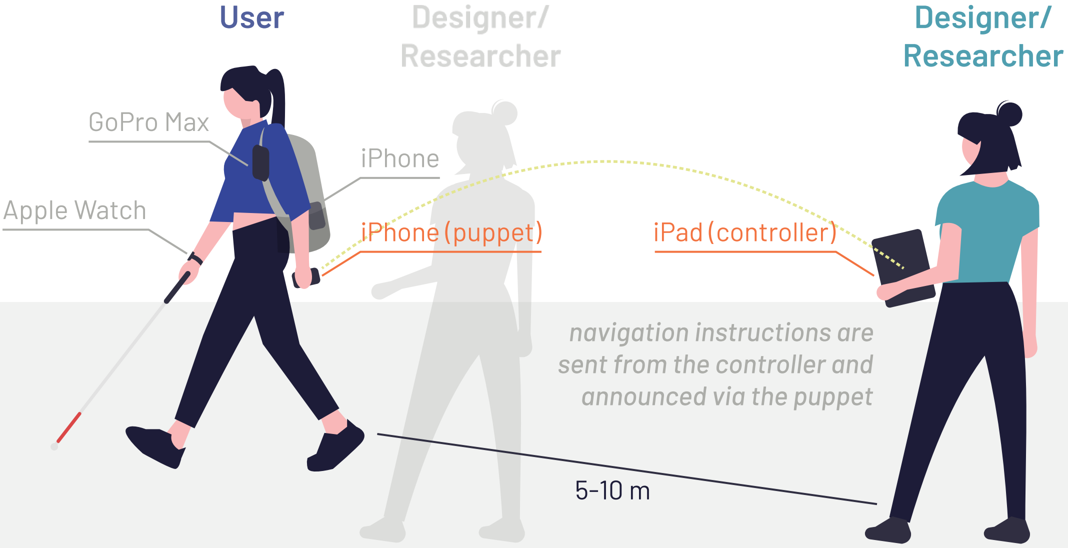
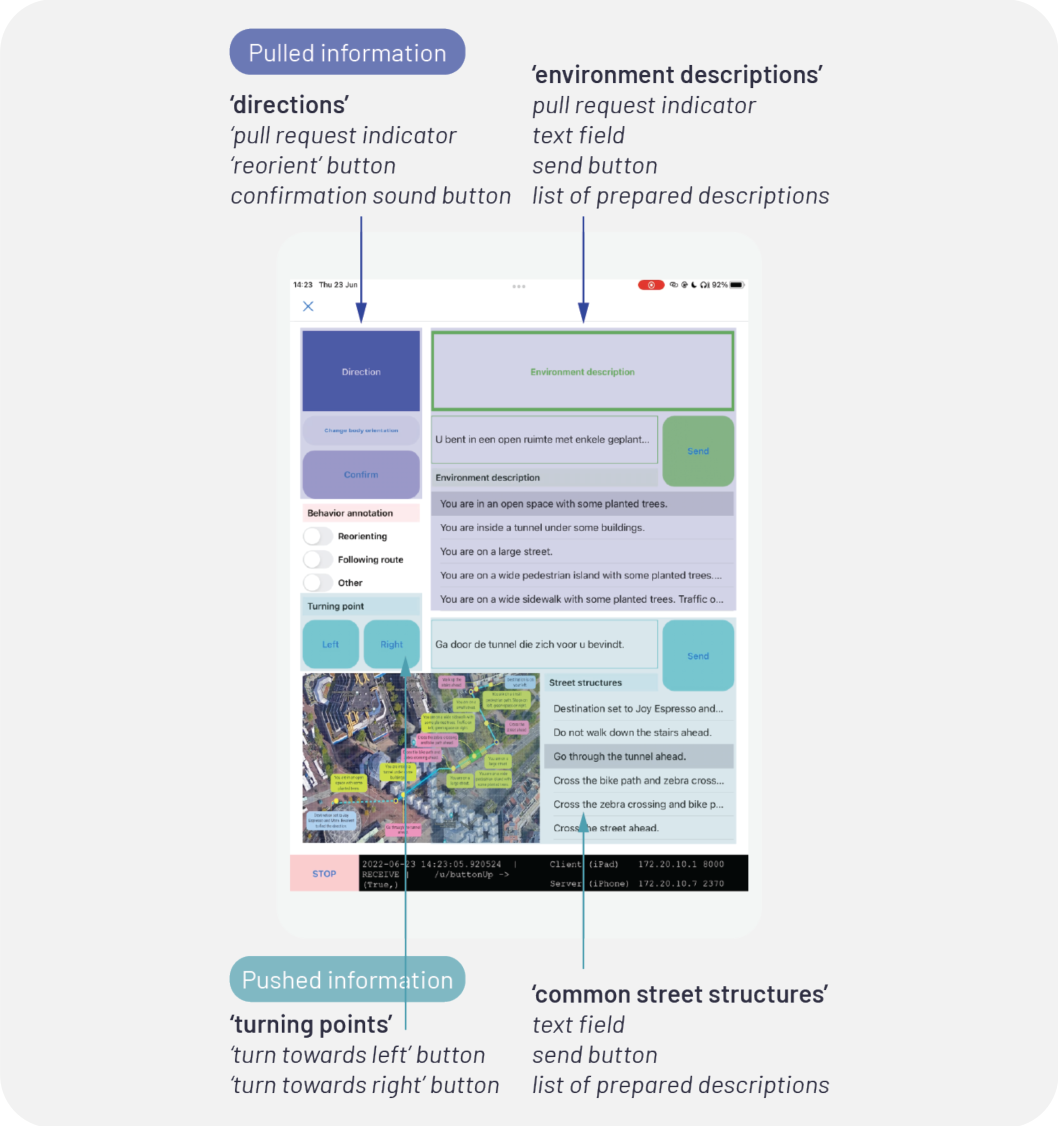


Figure 4.6 The setup of the second navigation system prototype.

Table 4.6 functions enabled on the puppet and controller through Pythonista.

User's device, puppet, iPhone			User's device, puppet, iPhone	
type	function		type	function
output	text-to-speech	⟵	input	choose and input text
output	play notification sounds	⟵	input	button to play sounds
input	buttons (2 volume buttons)	⟶	output	indication of button press



Pulled information

‘directions’
‘pull request indicator
‘reorient’ button
confirmation sound button

‘environment descriptions’
pull request indicator
text field
send button
list of prepared descriptions

U bent in een open ruimte met enkele geplant...

You are in an open space with some planted trees.
You are inside a tunnel under some buildings.
You are on a large street.
You are on a wide pedestrian island with some planted trees....
You are on a wide sidewalk with some planted trees. Traffic o...

Ga door de tunnel die zich voor u bevindt.

Destination set to Joy Espresso and...
Do not walk down the stairs ahead.
Go through the tunnel ahead.
Cross the bike path and zebra cross...
Cross the zebra crossing and bike p...
Cross the street ahead.

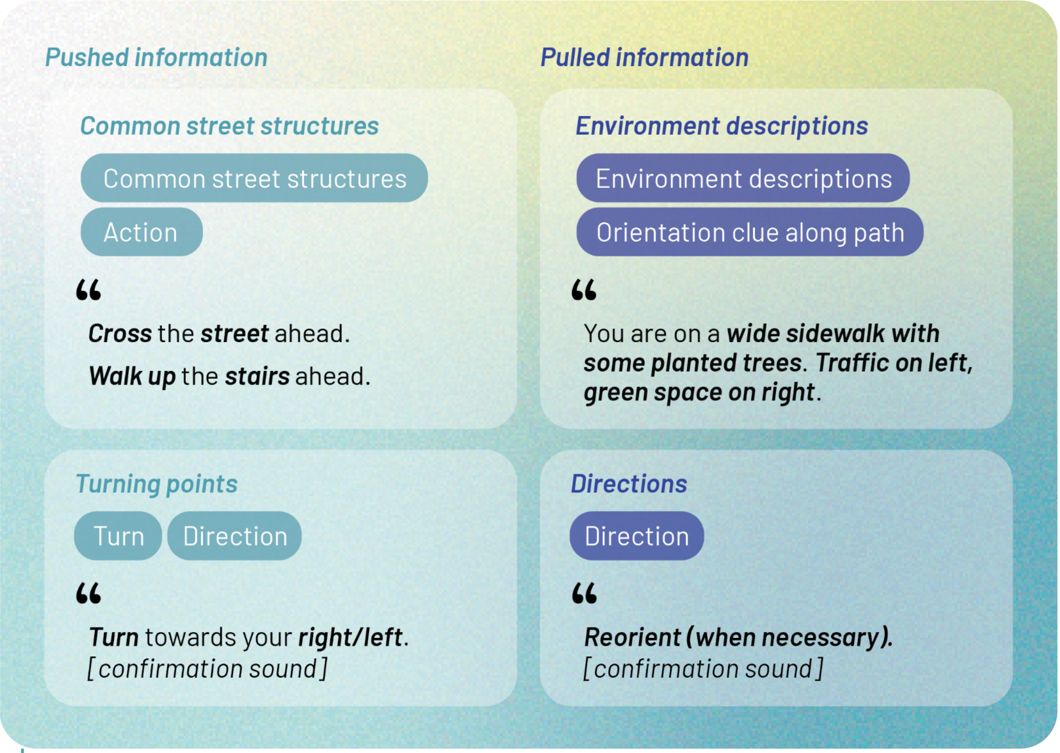
```
2022-06-23 14:23:05.920524  |        Client (iPad)   172.20.10.1 8000
RECEIVE |     /u/buttonUp ->
(True,)                              Server (iPhone) 172.20.10.7 2370
```

Pushed information

‘turning points’
‘turn towards left’ button
‘turn towards right’ button

‘common street structures’
text field
send button
list of prepared descriptions

Figure 4.7 The UI of the controller.



Pushed information

Common street structures

Common street structures

Action

“

Cross the ***street*** ahead.

Walk up the ***stairs*** ahead.

Turning points

Turn Direction

“

Turn towards your ***right/left***.
[confirmation sound]

Pulled information

Environment descriptions

Environment descriptions

Orientation clue along path

“

You are on a ***wide sidewalk with some planted trees***. ***Traffic on left, green space on right***.

Directions

Direction

“

Reorient (when necessary).
[confirmation sound]

Figure 4.8 Structure of the announced instructions.

Figure 4.9 All the prepared information on the route. Adapted from Mapbox.

- Pushed information should be kept to a minimum to avoid miscommunications.
- Differentiate the use of notification sounds and voiced sentences according to the information density.
- Instructions should consist of information identified in section 4.2.2 except 'hazard' information since this data is challenging to obtain.

According to these principles, the following design decisions were made.

Define segments based on 'common street structures' on the route

As mentioned before this was the most requested information from the first user study, and it effectively bridges the gap between information for far-space and near-space mobility.

Discard street and distance information that tends to be unintuitive

Although participants mentioned that street names are useful, it is only needed when one is completely lost. It would be useful for creating a mental map of the area, but this is not needed since it is an unfamiliar route that PVIs do not intend to remember.

Discard previews to avoid unintended mistakes

Previews lengthen instructions and they also cause participants to make mistakes.

Based on these design decisions, two types of pulled information and two types of pushed information were finalized. Figure 4.8 shows what kind of information each type of instruction consists of.

The pushed information consists of 'turning points' and 'common street structures'. 'Common street structures', as explained in section 4.2.2, are information about common obstacles such as street crossings, stairs, tunnels, slopes, bridges, etc. that users encounter on a chosen route. The information is paired with an action to indicate if they should, for example, cross the street or not. The 'common street structures' that were prepared for the route in this study are listed in Figure 4.9.

'Turning points' are the most essential information when following a route. They are announced at three points on the route, where there are clear streets to turn on. After the navigation system announces, 'Turn towards the left/right', a confirmation sound notifies the user that they are oriented correctly. 'Turning points' are intentionally not set in open areas since setting a turning point that cannot be sensed even with vision, confused participants in the first user study.

The pulled information consist of the 'environmental descriptions' and 'directions'. This information includes a general description of what is on the left and right side of the participant, along with some descriptions of objects that users may encounter. The 'environmental descriptions' that were prepared for the route in this study are listed in Figure 4.9.

Finally, when the 'direction' instruction is pulled, the navigation system gives audio cues that help users face the correct direction. If the participant is already oriented in the correct direction, a confirmation sound plays. On the contrary, if they are not, the navigation agent says 'reorient', which triggers the participant to turn in various directions. When they are oriented in the correct direction, a confirmation sound notifies they are on track. .

Data selection

Table 4.7 shows a list of behavioral data that were collected in this user study. The heart rate data was discarded from the previous user study since it did not have high correlations with the 'reorienting' and 'following' behaviors. The environmental data were kept the same. The final selection of devices was the same as the previous user study and consisted of an iPhone, an Apple Watch, and GoPro.

Table 4.7 'Behavioral' data selected for this study and additional 'context' data necessary for analysis.

Device	Behavior type	Sensor
iPhone	Travel speed	Accelerometer
	Body orientation	Magnometer
	Body movement	Accelerometer
Apple Watch	Cane movement	Accelerometer
		Gyroscope
Device	**Context type**	**Sensor**
iPhone	Location	GPS
GoPro	Environment features	Camera
	Environment sounds	Microphone

4.2.2

Methods

Participants

Three participants were recruited for this study. One participant was recruited from an emailing list of VIPs in the Netherlands accessed through Bartiméus, and two participants were recruited through snowball sampling. Table 4.8 shows an overview of the participant demographics, vision impairment details, and travel habits that were collected in an initial questionnaire through a phone call or online via Microsoft forms.

There were two main criteria for selecting participants. First, participants who had undergone O&M training were selected to ensure they have the basic skills to stay safe outdoors. Second, participants who preferred to use a guide dog for the navigation task were not selected, since collecting cane movement data was important for the study. Of course, it was also important that the participant was willing to navigate an unfamiliar route in an urban area on their own.

However, P7 had a companion, who was asked specifically not to guide the participant, put their hand on their shoulder for mental support. The vision impairment type or degree was not included as a criterion because this does not determine the participant's willingness to navigate an unfamiliar route and to avoid limiting the number of participants that may be interested.

The study was conducted in English for P2, since the participants were comfortable speaking in English. For P1 and P3, the study was conducted in Dutch with the help of a Dutch-speaking interpreter. The navigation system announced instructions in Dutch for all three participants.

Ethical considerations

This study was reviewed and approved by the HREC committee at Delft University of Technology (submission ID: 2323). Participants read through a detailed study description and gave informed consent beforehand (see Appendix F). Furthermore, the study description and explicit consent points were reviewed on the day of the navigation task to ensure that participants are well informed. During the navigation task, an extra, sighted researcher walked in the proximity of the participants to ensure their safety.

Procedure

As shown in Figure 4.10, the study consists of the navigation task and post-navigation interview. The navigation task and post-navigation interview were conducted according to a user manual shown in Appendix F.

After a short introduction to the study, the researcher explained how the navigation system works. Participants were asked to wear bone conduction earphones (Shokz Open Run) and hold the iPhone the navigation system runs on. The researcher then explained what information the two pushed and pulled information consisted of, without mentioning when they should pull information. Then, the participant practiced operating the two buttons on the iPhone on a demonstration route around Rotterdam Blaak station.

Next, the devices for data collection were placed on the participants. The video camera (GoPro Max) was mounted on the strap of a backpack, a separate iPhone was placed in the right pocket of the same backpack, and the Apple Watch was worn on the wrist of the arm the participants use to hold the cane.

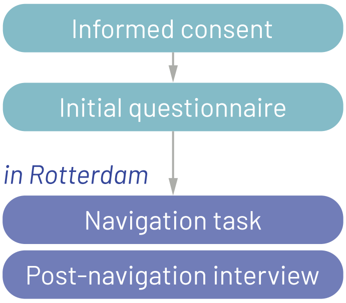


Figure 4.10 Overview of procedures.

Table 4.8 Overview of participant demographics, vision impairment details, and travel habits.

#	Demographics		Vision impairment				Travel in unfamiliar areas	
	Age	Gender	Type	Timing	Residual vision	Mobility aid	Frequency	Comfort level
P4	20-24	Female	Blind	16 years	Tunnel vision <5 degree, not able to see well with too much or too little light	White cane	Monthly	Neutral
P5	30-34	Female	Blind	Birth	None	White cane	Monthly	Neutral
P6	45-49	Female	Blind	4 years	Light perception	White cane	Monthly	Somewhat comfortable

For the data collection, the GoPro was set to '360 mode' to capture a 180-degree view of the environment in front of the participant. On the iPhone used for the data collection and Apple Watch, an app called SensorLog (Bernd Thomas, 2022), which was downloaded beforehand, was opened and started to log data from the sensors inside of the respective devices with a sampling frequency of 30 Hz.

The participant was asked to navigate from Rotterdam Blaak station to a café 'Joy Espresso and More' with the navigation system prototype, which was controlled by the researcher. During the navigation task, the navigation system announced 'Stop' only if there was a dangerous situation (e.g. walking on to a street or tram line, encountering an object that participants could not detect with their cane, etc.).

The follow-up interview took place at 'Joy Espresso or More'. The interview consisted of two parts. In the first part, each instruction that was pushed and pulled was reviewed with the participants to understand what triggered them to pull information and the usefulness of the instructions. The usefulness of each instruction was rated on a scale of -3 to 3, -3 being 'not useful at all' and 3 being 'very useful'. In some cases where the 'direction' button was pressed too many times, they were grouped according to specific situations, and the questions were asked for each situation.

In the second part, the participants were asked whether they would prefer having control over when the instruction is announced (pull) or prefer to have the instruction announced automatically (push) for each of the four types of instructions.

Both parts of the interview were recorded. The researcher also recorded answers and took notes on the participants' remarks through a Microsoft form.

Data analysis method

To answer the first research question regarding the specific information in 'following' and 'reorienting' states, the collected data were analyzed in two different ways.

First, the location where information was pulled was mapped out and compared to the observed 'following' and 'reorienting' states on the route. To compare the pulled data with the two behavioral states, the video footage and behavioral data were reviewed and annotated using the DCL tool, which was also used in the first user study. The location of the pulled data, the type of information that was pulled ('directions' or 'environmental descriptions'), and the location where participants were found to be 'reorienting' was mapped out using Mapbox and plotly on python.

Second, a thematic analysis was conducted by coding the qualitative data collected from the first part of the interview to further analyze why the information was pressed and how useful the information was. This was done in Microsoft Excel by coding the qualitative data and identifying recurring themes.

To answer the second research question regarding the preference for control over certain types of information, the second part of the interview was analyzed. Since there were not many reoccurring themes, the results are introduced directly in the next section.

4.2.3

Results & findings

All participants were able to complete the navigation task with the navigation agent prototype.

Information needs when 'following' route and 'reorienting' on route

Figure 4.11 shows moments of 'reorienting' (density map) and the location where 'direction' information (blue dots) and 'environmental description' information (orange dots) were pulled by each of the participants. The route the participant walked is also displayed, but the GPS was not able to track the participant in the tunnel. Therefore, the route near the tunnel is skewed. The largest image in Figure 4.12 shows this information for all the participants.

The initial hypothesis was that PVIs prefer information for near-space mobility when they are 'following' a route and prefer information that helps get them back on track with far-space mobility when 'reorienting' on a route. If this is true, the 'direction' information (blue dots) should coincide with the moments of 'reorienting' (density map), and 'environmental description' information (orange dots) should not coincide with moments of 'reorienting' (density map).

P4 and P5 had similar ways of using the prototype and mainly pulled 'direction' information (blue dots) in moments of 'reorienting' (density map). This is in line with the hypothesis. However, it is apparent from Figure 4.11 that P6 used the 'direction' information (blue dots) more continuously throughout the entire route.

The 'environmental description' information (orange dots) was pulled more scarcely compared to the 'direction' information (blue dots) in moments when participants were

Figure 4.12 Moments of 'reorienting' (density map) and the location where 'direction' information (blue dots) and 'environmental description' information (orange dots) were pulled for all participants.

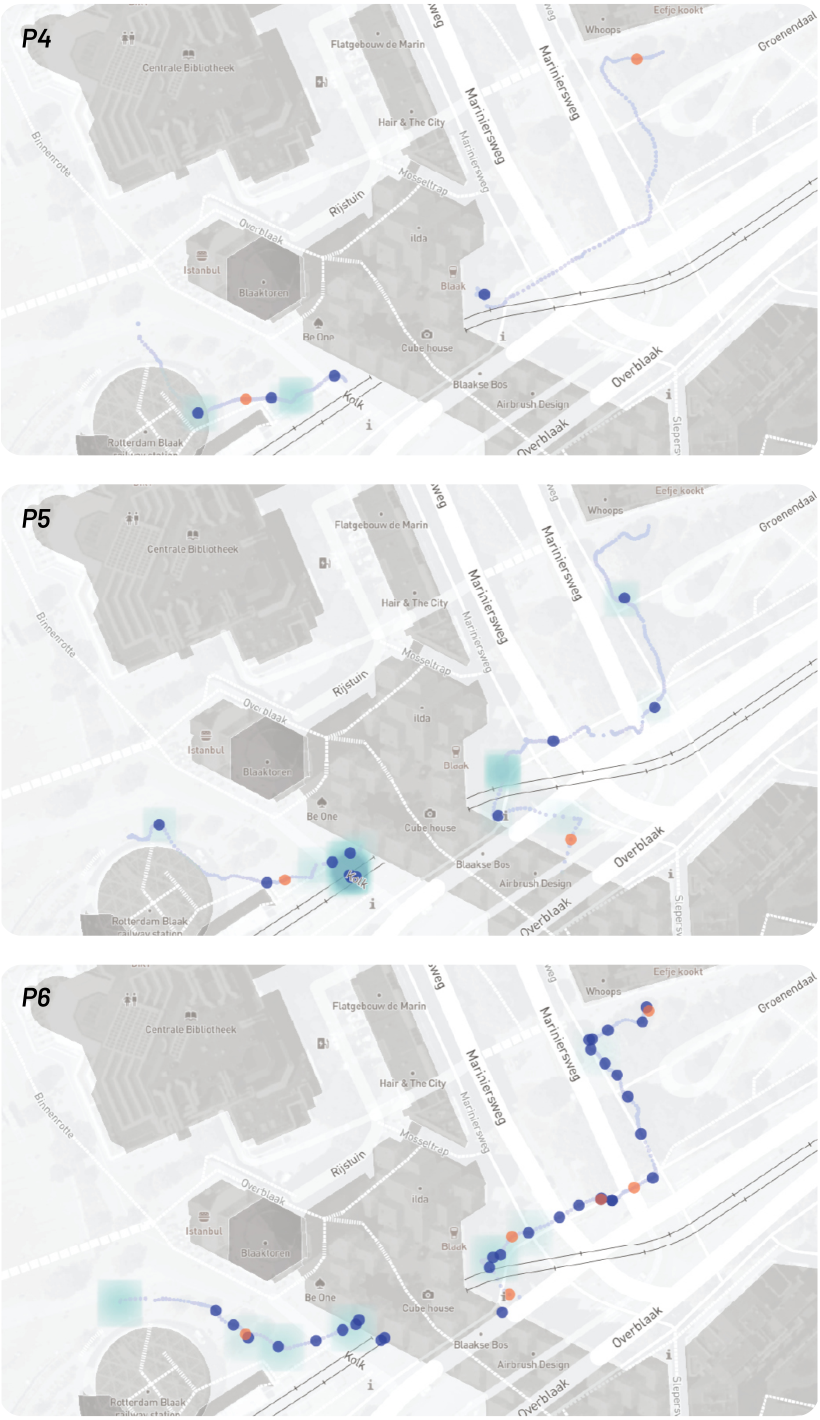


Figure 4.11 Moments of 'reorienting' (density map) and the location where 'direction' information (blue dots) and 'environmental description' information (orange dots) were pulled for each of the participants.

'following' the route. Again, P6 pulled this instruction more frequently than P4 and P5.

From these results, it is apparent although the hypothesis was correct in some cases, the information needs turned out not to be as clear-cut as expected. The reason for this is further analyzed through the thematic analysis of why participants pulled information.

Triggers to pull information

The 'direction' information (blue dots) was pulled in two main cases: physical reorientation and mental confirmation. Physical reorientation occurred when participants encountered an obstacle and became disoriented, when participants were navigating in the open space, and when participants were trying to find the entrance of the tunnel. These were the cases in which the pulled 'direction' information (blue dots) coincided with 'reorienting' behavior.

On the other hand, the 'direction' information (blue dots) was also used for mental confirmation. These were moments when the participant simply wanted to stay on track, confirm the direction after being distracted (e.g. sound of cars, uneven ground, etc.), confirm the direction after intentional veering, and confirm if the tactile pavement could be used. In these moments, the pulled 'direction' information (blue dots) coincided with when participants were 'following' the route.

The 'environmental description' information (orange dots) was pulled when the participant sensed a change in the environment. They were either insecure since they did not know what environment they are in, or curious to know additional information about the surroundings. The first case was more in line with the initial hypothesis, and the 'environmental descriptions' were 'needed', whereas in the second case, the 'environmental descriptions' were 'desired'.

The information provided in the 'environmental descriptions' fulfilled a 'need' mainly in the case of P6. They described the instructions, 'You are on a wide sidewalk with some planted trees. Traffic on left, green space on right.' helped them seek the safer side of the path. For P4 and P5, the information was pulled out of curiosity, they expected information regarding POIs (e.g. details about shops, public transport), aesthetic details about buildings (e.g. yellow buildings), and details about the destination (e.g. terrace café, type of seating, location of door). P4 also mentioned that this information is more useful for learning a route and not as necessary in this scenario.

In either case, it is important to note that the 'environmental description' was pulled when participants were walking, or 'following' the route and had more mental capacity to listen.

Usefulness of information

The usefulness of the 'environmental descriptions' was rated an average of 2 on a scale of -3 to 3. Both P4 and P6 mentioned that the information was useful, and the length of the instructions was ideal. However, P4 and P5 also mentioned that when mentioning objects (e.g. trees), it would be better to add information about where the objects are located.

The usefulness of the 'directions' was rated an average of 1.8 and the 'turning points' were rated an average of 2.3 on a scale of -3 to 3. Participants liked that the audio cues because it was easy to understand how much you needed to turn. There was one main problem that occurred with P5. A lag caused by the connection between the puppet (iPhone) and controller (iPad) delayed the confirmation noise and caused the participant to be slightly disoriented. These were the instances when the 'direction' and 'turning point' information was rated slightly lower.

The usefulness of the 'common street structures' were rated an average of 0.9 on a scale of -3 to 3. The timing proved to be a very important factor with this information. For the information to be useful, it should be announced right before they can detect the 'common street structure' using their residual senses. In one case, the information to cross the street was rated -1 because the participant already sensed the tactile pavement that indicated a crossing. However, the information cannot be announced well in advance as well. For example, when participants heard that there was a tunnel on the route, they became confused because they could not immediately sense that there is a tunnel nearby.

Nevertheless, this information helped anticipate that there is a small opening with walls on both sides (P6) and helped confirm they were on the right track after they found the tunnel (P4, P5). In addition, all participants preferred having more details about the 'common street structures'. For example, whether a street crossing has traffic lights, and if there are railings on the stairs.

Preference for pushed and pulled information

All participants agreed that 'common street structures' and 'turning points' should be pushed since they are necessary to complete the route safely.

For the 'environmental descriptions' and 'directions', preferences vary. P4 and P6 liked having control over 'environmental descriptions' since automated descriptions can easily become distractions and it allows the traveler to focus on the route when necessary. P5 mentioned she would rather receive all the information she could get because she could easily decide not to listen to instructions if it was too much.

For the 'direction' information, P4 preferred to have control since it would be annoying to hear that you are on the wrong path when intentionally veering off the path to avoid objects, while P5 preferred to have it automated since then there is immediate feedback when veering off route. P6 preferred to have a mix of both (e.g. manual operation in areas such as street crossings where there are potential safety risks, and automation in generic paths). This seems to be highly dependent on personal preferences and the amount of confirmation one prefers to have.

4.2.4

Main takeaways

How do information needs change when they are 'following' the route vs 'reorienting' on the route?

- As hypothesized, 'direction' information was necessary for situations where PVIs were 'reorienting' on the route. However, it was also pulled when users were seeking mental confirmation.
- 'Environment description' information was pulled when participants noticed a change in environment and were either curious or insecure about their surroundings. This was also slightly contrary to the hypothesis that PVIs would pull information mainly to fulfill 'needs'.
- Despite that results were not as clear-cut, there was a tendency for 'direction' information to be pulled when PVIs were in an uncertain state, while 'environmental description' information was pulled when PVIs were in a state of ease.

Is there information that users prefer to have control over? What information do the users want to be automated?

- All participants agreed that 'common street structures' and 'turning points' should be automated because they are essential for navigation and safety.
- The preference for automation of 'direction' and 'environment description' information varied for each participant. It mainly depended on how the amount of information participants found tolerable.

Chapter 5

Discussion

> **In Chapter 5, the implications of the user-aware navigation agent tested in the previous section are discussed. In addition to possible future iterations, a reflection on human-agent partnerships and the data-centric design methods used in the thesis are discussed.**

5.1

Future directions

> **The activities conducted in this thesis and all the findings throughout the process open opportunities for further development. In this section, the recommendations and implications when a user-aware navigation agent is used by more people are discussed.**

5.1.1

Recommendations

The initial idea was to design a navigation agent that can push relevant information based on what it senses from the user. However, the interactive setup that involved both pushed and pulled information allowed users to generate quantitative behavioral data that is directly linked to their needs while using the agent for navigation.

The 'direction' button was pressed more often in situations where PVIs were uncertain if they were on track. Meanwhile, the 'environmental description' button was pressed in situations where PVIs knew they were on track and had the mental capacity for other matters. Although this was not anticipated, the 'environmental description' information was pulled not only when participants 'needed' the confirmation but also when POI information was 'desired'.

By making slight changes to the current setup, it is possible to create a navigation agent that generates behavioral data that reflects two distinct user states: an uncertain state where users must reorient on the route, and a state of ease where users want to know more about surroundings.

More specifically, the following should be changed from the current setup to make sure the resulting data better reflects user states.

> **Adding an option to automate 'direction' information, while keeping the option to pull 'direction' information at any time.**

This will help decrease the cases travelers pull 'direction' information for mental confirmation and emphasize cases when travelers pull this information for physical reorientation.

> **Changing the button for 'environmental description' to a button for 'POI' information and keeping 'environmental descriptions' as an option for pushed information.**

Clarifying the role that each information and categorizing information that is 'needed' or 'desired' would be an important step. Since the 'environmental descriptions', which included 'orientation clues along the path', is information that is 'needed' for many people, it should be kept as an option for pushed information. Switching the pulled information to 'POI information' better reflects moments where additional information is 'desired'.

In addition, using an iPhone as the basis of the prototype also resulted in the following constraints. Although some should be kept the same, there is a lot of room to experiment as well.

> **Explore control options other than buttons to pull information**

Methods to pull information in a hands-free manner is ideal since one hand is occupied with the cane and the other hand should is needed in cases where for example, there is a hand railing. It could also provide options for guide dog users, who usually use one hand to carry a cane, and the other to hold the harness of the guide dog. Gesture control or voice commands could be options.

> **Exploring the use of vibration cues**

This depends on the traveler's preference and access to devices. For example, if they have a smartwatch, the confirmation sounds could be replaced with a vibration cue.

> **Only a maximum of two pieces of information should be pulled**

Although the main reason the number of pulled information was limited to two was that the iPhone only had two buttons (volume up and down buttons), it kept the interaction simple and easy to learn. All participants had no trouble learning how to use the navigation app after a simple demonstration.

5.1.2

Implications of big data

In a future scenario where more people use this navigation agent, there will be a larger database on the location of where 'direction' and 'POI' information was pulled. This rich data that quantify user needs and desires can be used in a variety of ways to further improve the outdoor travel experience for PVIs.

In cases where there are a lot of requests for 'POI' information, more details about the POI could be added. The areas where this information is requested often also could indicate what type of areas cause less mental load than others.

Areas with a lot of requests for 'direction' information could also be useful for rating the difficulty of a route. For municipalities, this information can also be helpful to detect areas that are hard to pass, for example, areas where bikes are parked on pathways. Many people do not realize that this makes traveling a lot harder for PVIs and a simple sign could already help raise awareness.

For the ML system, more data will be needed to increase the accuracy of the algorithm. The pulled 'direction' information could be used to label moments of 'reorientation' and increase accuracy. In the end, this model can be used as a trigger to automate information or trigger requests generated by the agent.

5.2

Reflections

The research in this thesis focused on one of the fundamental aspects of an agent: the user-sensing capabilities of the agent. In this section, other aspects of human-agent partnerships, such as task delegations, character, and collaborations are discussed.

In addition, since data-centric design methods are not established, there was a lot of experimenting involved when planning the user studies. Here, the strengths and limitations of the data-centric design methods, as well as the tools needed to make methods more accessible to designers are discussed.

5.1.1

Human-agent partnerships

Task delegation

The expertise of the PVI traveler is their O&M skills that allow them to understand immediate surroundings at a specific moment. On the other hand, an agent's expertise is the information available on the internet (e.g. maps, route information, and POI information). The agent's responsibility is to guide the traveler from a bird's eye view in the navigation task. However, as the first user study showed, the information regarding far-space mobility must be communicated through the information that is useful to PVI travelers. Instead of 'continue for 20m on Blaak', agents should announce 'go through the tunnel ahead' and provide spatial audio cues.

Character

However, even in the second user study, some misunderstandings between the agent and user caused problems. In one event, a user expected an agent to help navigate around parked vehicles. However, this would not be possible for an agent that only has a bird's eye view of the situation. This is where the character of the agent could help.

Current navigation system instructions are highly assertive. The instructions are rather commands that tell you to turn or proceed. Although this keeps instructions clear and short, it could also cause PVIs to feel the need to follow what the agent says. Instead, the agent should be supportive but uncertain at times and should be able to tell the user when it cannot help. For example, in the previous situation, the agent could say 'You're oriented in the correct direction, but if you can't proceed, maybe try navigating around it.' Also, in cases of structures that might be hard to find, instead of saying 'Go through the tunnel ahead', the agent could say 'There seems to be a tunnel on the route. Can you find it?'.

Collaborations

Another expertise that PVIs have is the detailed information about landmarks and clues they memorize on familiar routes. This is valuable information that is hard to create through satellite images but has the potential to be useful for other PVIs as well. If an agent has an intention to create a very detailed map of the world, PVIs can help agents add information in familiar areas and receive information on precise landmarks through the agent in unfamiliar areas. For example, if a PVI that regularly travels in Rotterdam Blaak teaches their agent that the street crossing has traffic lights, this information can easily be added to the 'common street structure' information for those crossing that street for the first time.

Another scenario the agent and PVI could collaborate is when PVIs want to learn a route. The agent could act as a memo tool while a sighted family member or O&M instructor points out landmarks and clues on the route. Later, the agent could help memorize the route by gradually reducing the amount of information in each iteration. The agent's ability to sense when users are 'reorienting' could be set as the trigger to announce information as well.

Co-development

When a PVI starts a partnership with an agent, they will know nothing about each other. However, over time, as the PVI travels with the agent, the agent will start recognizing familiar areas (i.e. routes that are completed several times with no moments of 'reorientation') and areas that are not. When this is established, there will essentially be a digital twin of the user's mental map, and the agent will know exactly how to collaborate in familiar and unfamiliar routes, as well as routes that users are learning. The agent should be curious to know more about environments that users are familiar with while being excited to guide and take PVIs to new places.

5.1.2

Data-centric design

This thesis followed a data-centric design process, especially in the two user studies. Overall, the data-centric design process suited my project because the behavioral data was not only used as a design tool to gain empathy but also to look at the problem from the perspective of the agent.

Participatory Data Storytelling

In the first user study, I explored one of the emerging methods being explored at the Data-Centric Design Lab: participatory data storytelling. In participatory data storytelling, collected behavioral data is analyzed with users and used as material to tell a detailed story of what user's experience (Bourgeois, 2021). Since the target user in this study had vision impairments, it was not possible to directly show the data to the user. Therefore, the researcher searched through the data, identified notable situations, and discussed these moments with the users in the follow-up interview.

The purpose of the user study was to explore the problem and dive deep into the context. No specific hypotheses could be made at this stage. Therefore, all relevant behavioral data were collected. In the case of my thesis, this involved a lot of time-series data from sensors embedded in devices on the market.

Behavioral data is powerful because it often reflects one's mental state that is hard to detect through observations. For example, P1's travel speed decreased in the tunnel because the environment suddenly became dark. The change in travel speed was not noticeable through observations, but it showed up on the sensor data. Of course, it is not possible to prove scientifically why the data suddenly changed. However, one of the major merits of participatory data storytelling is that the slight changes in the behavioral data trigger conversation. It lets designers know that this could be an interesting moment to bring up.

The main limitation of this method is that it is time-consuming. Additional devices with sensors, that are not needed for observational research, need to be made or prepared. I minimized this time by using devices that were already on the market and by leveraging apps such as SensorLog (Bernd Thomas, 2022), that allowed access to the device's sensors. In addition, since it is a challenge to limit the number of data types in the exploration phase of the design process, the data analysis phase takes a considerable amount of time.

To make this method more accessible to designers, a specialized data exploration tool is necessary. There are already tools and software for data exploration that is used for Business Intelligence, such as Tableau. I also used a tool developed by SensiML called the Data Capture Lab. However, I was not able to find a tool that can synchronize location data, time-series data, and video footage automatically using the timestamp. Other functions such as an interactive UI that allows easy exploration and annotation are also desired. These functions already exist and can be created using Javascript libraries such as (dygraph and plotly). However, an integrated solution is yet to be created.

Participatory Data Creation

The second user study was like the first one in many ways. Behavioral data was captured and then reviewed with the users to gain further insight into user experience and needs. However, the major difference was the data I collected. The behavioral data I collected in this section was the location of where information was pulled.

Personally, this was one of the most fascinating aspects of the data-centric design process. The users were simply using the prototype to guide them on a route. However, this stream of data that the users were naturally creating reflected the needs and desires on the route. As a designer, while designing the functions of the prototype based on prior research, I was also designing the behavioral data that would be produced from the prototype. This collaborative process to create meaningful data that reflects user experience is why I called the second user session participatory data creation.

The behavioral data collected in this iteration was also a lot thinner than the sensor data collected in the first user study. Therefore, the analysis was a lot easier and complex data analysis tools are not needed. A visualization (e.g. density map) was all that was necessary. Thin data also opens opportunities for big data, as explained in the previous section.

Of course, the insights from the first user study were important, driving factors in the second user study. The thick data capture rich insights however, it is only feasible for short sessions (maximum 1 hour) and small samples. However, this transition from thick data to thin data is what made the thin, big data as meaningful as the thick data.

	Participatory data storytelling	Participatory data creation
Summary	- ***Stage in the design process***: Discover - ***Purpose***: Diving into the context to explore user needs - ***Behavioral data***: Timeseries data (e.g. movement), thick data - ***Collection method***: Sensors embedded in the iPhone and Apple Watch	- ***Stage in the design process***: Define - ***Purpose***: Quantifying user needs - ***Behavioral data***: Location of where information was pulled through button presses, thin data - ***Collection method***: Python code that detects when iPhone volume buttons were pressed and GPS data
Strengths	- Behavioral data capture minor changes in behavior that make it easier for designers' to identify potential moments of interest that should be discussed in detail.	- Direct results are obtained by designing behavioral data that quantifies user needs - Thin data is easier to analyze, and no complex data analysis or visualization tools are necessary. - It is possible to increase the number of participants. - Behavioral changes over a long period could be captured.
Limitations	- Additional devices with sensors should be made or prepared. - Going through several data types is a time-consuming process. - Due to the time-consuming nature, it cannot be conducted with large sample sizes. - Behavioral changes over a long period cannot be captured when using thick data. - Data analysis and visualization tools are necessary to effectively explore the data.	- Additional devices with sensors should be made or prepared. - It would be challenging to use this method at the start of the design process.

Figure 5.1 Comparison of data-centric design methods explored in the thesis.

References

Balata, J. (2018). *Verbal Route Descriptions in Navigation of People with Visual Impairments*.

Balata, J., Mikovec, Z., & Maly, I. (2015). Navigation Problems in Blind-to-Blind Pedestrians Tele-assistance Navigation. In J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, & M. Winckler (Eds.), *Human-Computer Interaction – INTERACT 2015* (pp. 89–109). Springer International Publishing. https://doi.org/10.1007/978-3-319-22701-6_8

Banovic, N., Franz, R. L., Truong, K. N., Mankoff, J., & Dey, A. K. (2013). Uncovering information needs for independent spatial learning for users who are visually impaired. *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, 1–8. https://doi.org/10.1145/2513383.2513445

Bayer. (2021, November). *Light*. Visual Acuity Tool. https://visualacuitytool.bayer.co.uk/light

Bennett, C. R., Bex, P. J., Bauer, C. M., & Merabet, L. B. (2019). The Assessment of Visual Function and Functional Vision. *Seminars in Pediatric Neurology*, *31*, 30–40. https://doi.org/10.1016/j.spen.2019.05.006

Bernd Thomas. (2022). *SensorLog* (5.2) [Computer software]. https://apps.apple.com/us/app/sensorlog/id388014573

Bourgeois, J. (2021, November 22). *Vision*. Jacky Bourgeois. https://jackybourgeois.com/vision/

Cantamessa, M., Montagna, F., Altavilla, S., & Casagrande-Seretti, A. (2020). Data-driven design: The new challenges of digitalization on product design and development. *Design Science*, *6*. https://doi.org/10.1017/dsj.2020.25

Cila, N. (2022). Designing Human-Agent Collaborations: Commitment, responsiveness, and support. *CHI Conference on Human Factors in Computing Systems*, 1–18. https://doi.org/10.1145/3491102.3517500

Cuturi, L. F., Aggius-Vella, E., Campus, C., Parmiggiani, A., & Gori, M. (2016). From science to technology: Orientation and mobility in blind children and adults. *Neuroscience & Biobehavioral Reviews*, *71*, 240–251. https://doi.org/10.1016/j.neubiorev.2016.08.019

Douglas, G., Corcoran, C., & Pavey, S. (2006). *Network 1000: Opinions and circumstances of visually impaired people in Great Britain*. Visual Impairment Centre for Teaching and Research, University of Birmingham. https://www.rnib.org.uk/knowledge-and-research-hub/research-reports/general-research/network-1000-survey-1

Dreamwaves. (2022). *waveOut*. https://apps.apple.com/us/app/waveout/id1496541182

Espinoza, R. (2022). *Lazarillo—Accessible GPS*. https://apps.apple.com/us/app/lazarillo-accessible-gps/id1139331874

FeelSpace. (2022). FeelSpace GmbH. https://feelspace.de/en/

Goldschmidt, M. (2018). Orientation and Mobility Training to People with Visual Impairments. In E. Pissaloux & R. Velazquez (Eds.), *Mobility of Visually Impaired People: Fundamentals and ICT Assistive Technologies* (pp. 237–261). Springer International Publishing. https://doi.org/10.1007/978-3-319-54446-5_8

Google Maps Help. (n.d.). *Explore new street-level details*. Retrieved July 19, 2022, from https://support.google.com/maps/answer/10311344?hl=en-GB

Gupta, M., Abdolrahmani, A., Edwards, E., Cortez, M., Tumang, A., Majali, Y., Lazaga, M., Tarra, S., Patil, P., Kuber, R., & Branham, S. M. (2020). Towards More Universal Wayfinding Technologies: Navigation Preferences Across Disabilities. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). Association for Computing Machinery. http://doi.org/10.1145/3313831.3376581

Hersh, M. (2020). Route Learning by Blind and Partially Sighted People Abstract. *Journal of Blindness Innovation and Research*, *10*(2). https://nfb.org//images/nfb/publications/jbir/jbir20/jbir100207abs.html

Hersh, M. A., & Johnson, M. A. (2008). Mobility: An Overview. In M. A. Hersh & M. A. Johnson (Eds.), *Assistive Technology for Visually Impaired and Blind People* (pp. 167–208). Springer. https://doi.org/10.1007/978-1-84628-867-8_5

Home | I-Cane. (2018, September 17). I-Cane. https://i-cane.nl/nl/home/

IBM. (2021, August 27). *Business Intelligence*. What Is Business Intelligence? https://www.ibm.com/business-intelligence

Indoor navigation app. (2022). Bartimeus. https://www.bartimeus.nl/innovatie/navigatie-app

Katz, B. F. G., Kammoun, S., Parseihian, G., Gutierrez, O., Brilhault, A., Auvray, M., Truillet, P., Denis, M., Thorpe, S., & Jouffrais, C. (2012). NAVIG: Augmented reality guidance system for the visually impaired. *Virtual Reality*, *16*(4), 253–269. https://doi.org/10.1007/s10055-012-0213-6

Khoury, B., Kogan, C., & Daouk, S. (2017). International Classification of Diseases 11th Edition (ICD-11). In V. Zeigler-Hill & T. K. Shackelford (Eds.), *Encyclopedia of Personality and Individual Differences* (pp. 1–6). Springer International Publishing. https://doi.org/10.1007/978-3-319-28099-8_904-1

Khoury, R. E. (2021, January 16). *Google Maps is rolling out incredibly accurate street-level details in these 4 cities*. Android Police. https://www.androidpolice.com/2021/01/16/google-maps-is-rolling-out-incredibly-accurate-street-level-details-in-these-4-cities/

References

Limburg, H., & Keunen, J. E. E. (2009). Blindness and low vision in The Netherlands from 2000 to 2020—Modeling as a tool for focused intervention. *Ophthalmic Epidemiology*, *16*(6), 362–369. https://doi.org/10.3109/09286580903312251

Manduchi, R., & Kurniawan, S. (2011). Mobility-Related Accidents Experienced by People with Visual Impairment. *AER Journal: Research and Practice in Visual Impairment and Blindness*, *4*(2), 44–54.

Marrone, M. (2020, August 14). *What Are The Different Types of White Canes?* CABVI - Central Association for the Blind and Visually Impaired. https://www.cabvi.org/articles/what-are-the-different-types-of-white-canes/

Michael Gleeson, P. D. (2018). The Art and Science of Teaching Orientation and Mobility to Persons with Visual Impairment. *Vision Rehabilitation International*, *6*(1). https://doi.org/10.21307/ijom-2013-010

Microsoft. (2022). *Soundscape*. https://apps.apple.com/us/app/microsoft-soundscape/id1240320677

MIPsoft. (2022). *BlindSquare*. https://apps.apple.com/us/app/blindsquare/id500557255

Nabriya, P. (2021, July 12). *Feature Engineering on Time-Series data*. Medium. https://towardsdatascience.com/feature-engineering-on-time-series-data-transforming-signal-data-of-a-smartphone-accelerometer-for-72cbe34b8a60

omz:software. (2022). *Pythonista for iOS* (3.3) [Computer software]. http://www.omz-software.com/pythonista/

Optelec International. (n.d.). *Eye diseases affecting your vision*. Optelec International. Retrieved June 12, 2022, from https://in.optelec.com/eyeconditions

Orientation and Mobility Skills. (n.d.). VisionAware. Retrieved July 6, 2022, from https://visionaware.org/everyday-living/essential-skills/an-introduction-to-orientation-and-mobility-skills/

Pasqualotto, A., Spiller, M. J., Jansari, A. S., & Proulx, M. J. (2013). Visual experience facilitates allocentric spatial representation. *Behavioural Brain Research*, *236*, 175–179. https://doi.org/10.1016/j.bbr.2012.08.042

Portch, R. (2018). *Rowena Portch's answer to "What are the pros and cons of using a white cane/ guide dog?"* Quora. https://www.quora.com/What-are-the-pros-and-cons-of-using-a-white-cane-guide-dog

Quinones, P.-A., Greene, T., Yang, R., & Newman, M. (2011). Supporting visually impaired navigation: A needs-finding study. *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, 1645–1650. https://doi.org/10.1145/1979742.1979822

Real, S., & Araujo, A. (2019). Navigation Systems for the Blind and Visually Impaired: Past Work, Challenges, and Open Problems. *Sensors*, *19*(15), 3404. https://doi.org/10.3390/s19153404

Richard, K. (2015, July 7). Data Visualization: Processing Images at 1250MB/s. Wiredcraft. https://wiredcraft.com/blog/data-visualizations-images/

Rotterdam Neighborhood Map. (n.d.). Hoodmaps. Retrieved July 19, 2022, from http://hoodmaps.com/rotterdam-neighborhood-map

Rozendaal, M. C., van Beek, E., Haselager, P., Abbink, D., & Jonker, C. M. (2020). Shift and Blend: Understanding the hybrid character of computing artefacts on a tool-agent spectrum. *Proceedings of the 8th International Conference on Human-Agent Interaction*, 171–178. https://doi.org/10.1145/3406499.3415066

Saitis, C., & Kalimeri, K. (2016). Identifying Urban Mobility Challenges for the Visually Impaired with Mobile Monitoring of Multimodal Biosignals. In M. Antona & C. Stephanidis (Eds.), *Universal Access in Human-Computer Interaction. Users and Context Diversity* (pp. 616–627). Springer International Publishing. https://doi.org/10.1007/978-3-319-40238-3_59

SensiML. (2022). *Data Capture Lab* (2022.2.0.0) [Computer software]. https://sensiml.com/products/data-capture-lab/

Slade, P., Tambe, A., & Kochenderfer, M. J. (2021). Multimodal sensing and intuitive steering assistance improve navigation and mobility for people with impaired vision. *Science Robotics*, *6*(59), eabg6594. https://doi.org/10.1126/scirobotics.abg6594

Swobodzinski, M., & Raubal, M. (2009). An Indoor Routing Algorithm for the Blind: Development and Comparison to a Routing Algorithm for the Sighted. *International Journal of Geographical Information Science*, *23*(10), 1315–1343. https://doi.org/10.1080/13658810802421115

Taskar Center for Accessible Technology (TCAT). (n.d.). *OpenSidewalks*. OpenSidewalks. Retrieved July 19, 2022, from https://www.opensidewalks.com/

Timmermans, P. (2021). *Patricia Timmermans's answer to "What are the pros and cons of using a white cane/ guide dog?"* Quora. https://www.quora.com/What-are-the-pros-and-cons-of-using-a-white-cane-guide-dog

Wan, C. Y., Wood, A. G., Reutens, D. C., & Wilson, S. J. (2010). Early but not late-blindness leads to enhanced auditory perception. *Neuropsychologia*, *48*(1), 344–348. https://doi.org/10.1016/j.neuropsychologia.2009.08.016

Wayband. (2022). WearWorks. https://www.wear.works

WeWALK. (2020). WeWALK Smart Cane. https://wewalk.io/en/

What Type of Cane Should I Use? (n.d.). VisionAware. Retrieved July 6, 2022, from https://visionaware.org/everyday-living/essential-skills/an-introduction-to-orientation-and-mobility-skills/what-type-of-cane-should-i-use/

References

Wiggett-Barnard, C., & Steel, H. (2008). The experience of owning a guide dog. *Disability and Rehabilitation*, *30*(14), 1014–1026. https://doi.org/10.1080/09638280701466517

Williams, M. A., Galbraith, C., Kane, S. K., & Hurst, A. (2014). "just let the cane hit it": How the blind and sighted see navigation differently. *Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility*, 217–224. https://doi.org/10.1145/2661334.2661380

Williams, M. A., Hurst, A., & Kane, S. K. (2013). "Pray before you step out": Describing personal and situational blind navigation behaviors. *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, 1–8. https://doi.org/10.1145/2513383.2513449

Wooldridge, M., & Jennings, N. R. (1995). Intelligent agents: Theory and practice. *The Knowledge Engineering Review*, *10*(2), 115–152. https://doi.org/10.1017/S0269888900008122

Zeng, L. (2015). A Survey: Outdoor Mobility Experiences by the Visually Impaired. In *A Survey: Outdoor Mobility Experiences by the Visually Impaired* (pp. 391–398). De Gruyter. https://doi.org/10.1515/9783110443905-056