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Masterarbeit

User-Centric Approach of Visual Cues to Enhance VR Orientation for People with Visual Impairments

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Abstract

For successful navigation through the world, a good orientation is needed. Our orientation is directly influenced by how well we can build and use a cognitive map of the environment around us. Cognitive maps are mental representations of spatial information of an environment. A lack of visual information can impede the successful acquisition of a cognitive map. As such, people with impaired vision can struggle with tasks requiring spatial orientation. With a goal to facilitate orientation, we created a set of visual cues designed to compensate for the lack of information needed for cognitive mapping. To meet the needs of different visual impairment, we followed a user-centric approach for the visual cue design. For this, we first conducted a formative interview with visually impaired people, investigating what information should be highlighted and how. With these insights, we created six different visual cue categories providing information about *Obstacles, Points of Interest (POI), Entrances,* and *Shape Information*. The visual cues in each category come in different forms, tailored to different needs. In a subsequent user study, we let participants with impaired vision explore a city scene in Virtual Reality using our visual cues. To evaluate the cues' efficacy for orientation, our study investigated the participants' cognitive mapping process. Our study results indicate that four out of five participants were able to successfully build and use a cognitive map of the virtual city. Given a remaining vision of 10%-15% combined with a Field of View of less than 5°, the visual cues could not provide sufficient aid. Nonetheless, all visual cue categories were reported as helpful, with the *Shape Information* cues being deemed as most important for exploration.

Kurzfassung

Für eine erfolgreiche Navigation durch die Welt ist eine gute Orientierung erforderlich. Unsere Orientierung wird direkt davon beeinflusst, wie gut wir eine kognitive Karte der Umgebung um uns herum aufbauen und nutzen können. Kognitive Karten sind mentale Repräsentationen von räumlichen Informationen einer Umgebung. Ein Mangel an visuellen Informationen kann die erfolgreiche Bildung einer kognitiven Karte erschweren. Dies hat zur Folge, dass Menschen mit eingeschränktem Sehvermögen Schwierigkeiten bei Aufgaben haben können, welche eine räumliche Orientierung erfordern. Mit dem Ziel, die Orientierung zu erleichtern, haben wir eine Reihe von visuellen Hinweisen entwickelt, die den Mangel an Informationen, welche für die kognitive Karte wichtig sind, ausgleichen sollen. Um den unterschiedlichen Bedürfnissen von Menschen mit Sehbeeinträchtigungen nachzukommen, verfolgten wir bei der Entwicklung der visuellen Hinweise einen nutzerzentrierten Ansatz. Dazu führten wir zunächst Interviews mit sehbeeinträchtigten Personen durch, um herauszufinden, welche Informationen auf welche Weise hervorgehoben werden sollten. Auf der Grundlage dieser Erkenntnisse haben wir sechs verschiedene Kategorien von visuellen Hinweisen erstellt, welche Informationen über *Hindernisse, Points of Interest (POI), Eingänge* und *Form* bieten. Die visuellen Hinweise in jeder Kategorie gibt es in verschiedenen Formen, zugeschnitten auf unterschiedliche Bedürfnisse. In einer anschließenden Nutzerstudie ließen wir Teilnehmer mit eingeschränktem Sehvermögen eine Stadtszene, mit unseren visuellen Hinweisen, in virtueller Realität erkunden. Um die Wirksamkeit der Hinweise für die Orientierung zu bewerten, haben wir die kognitiven Karten-Prozesse der Teilnehmer untersucht. Unsere Studienergebnisse zeigen, dass vier von fünf Teilnehmern in der Lage waren, erfolgreich eine kognitive Karte der virtuellen Stadt zu erstellen und zu verwenden. Bei einem verbleibenden Sehvolumen von 10%-15%, in Kombination mit einem Blickwinkel von weniger als 5°, konnten die visuellen Hinweise keine ausreichende Hilfe bieten. Nichtsdestotrotz wurden alle Kategorien der visuellen Hinweise als hilfreich eingestuft, wobei sich die Forminformationen als die wichtigsten für die Erkundung herausgestellt haben.

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1 Introduction

While navigating the world, people with impaired vision face different challenges, affecting everyday tasks, such as finding stores or locating a post office [SZA16]. A key factor influencing navigation through the world is the process of orientation [PV18]. Orientation defines how well we understand, remember, and recall spatial information of objects around us [HG00]. This process is referred to as cognitive mapping [Gol99]. Cognitive maps are mental representations of the spatial information of an environment. They serve as a memory aid for our navigation, helping us find and follow routes to our destination [ON78]. Spatial information stored in a cognitive map can be perceived through two different views: in relation to our own position, i.e. through an *egocentric view*, or independent of our own position and only in relation to other objects, i.e. an *allocentric view*. While an *egocentric view* is important for following pre-defined routes to a destination, finding new routes or detours requires *allocentric* spatial information [Giu10]. Hence, an *allocentric view* view is crucial for a successful cognitive map process [Kit94].

Golledge et al. [GKL96] regard visual information as the most efficient and reliable for constructing cognitive maps. This is because the human visual system can simultaneously perceive objects in relation to our current position and also in relation to each other [DBJ18]. As such, with just one glance we can receive both the *egocentric* and *allocentric* coordinates of objects.

For people with impaired vision, perceiving objects through an *allocentric* view can be difficult [HG00]. Due to a lack of visual information, visually impaired people often need to rely on non-visual senses. However, this affects the way they build and use their cognitive maps [NZP06]. As a result of this, individuals with impaired vision tend to form cognitive maps primarily with *egocentric* spatial information [DHC82]. Different studies have shown that this leads to challenges in performing spatial tasks requiring allocentric views. [RGH86; RLP80; TG97]. For instance, a study by Rieser et al. [RGH86] showed that while following previously traveled routes was not a problem, participants had difficulties finding new routes to the same target.

In order to successfully obtain an *allocentric* cognitive map, research has shown that it is crucial to actively explore a place [DBJ18; DS96; RGH86; TH82]. However, most assistive aids designed for visually impaired people do not provide exploration assistance [BFT+13; JTC+23]. Instead, most focus on obstacle detection and turn-by-turn navigation. Hence there is a lack of assistive aids that directly help visually impaired people improve their spatial orientation. To help individuals with impaired vision acquire an *allocentric* cognitive map, assistive aids need to provide exploration assistance [Giu18].

Furthermore, most assistive tools provide solely non-visual feedback. However many visually impaired individuals still possess some remaining visual capabilities, and various studies report that most prefer using their remaining vision whenever possible [LSM22; TBB20; ZKC+19; ZKTA18]. Due to the significance of visual information for cognitive mapping, it is thus important to shift the focus of assistive aids from non-visual to visual feedback.

With the recent advances in Virtual (VR) and Augmented Reality (AR), new possibilities have emerged to assist visually impaired people through visual cues. Using virtual visual cues, we can enhance an environment with information not present in the real world. This information can help visually impaired people detect and identify objects better. Additionally, Virtual Reality provides a safe and controlled space for exploration training[SSAW23]. In recent years, there has been different work done on visual cue design for visually impaired people [FAW+23; NZS+24; ZKC+19; ZSKA16]. However, most of it either does not directly facilitate exploration [FAW+23; ZKC+19; ZSKA16] or it focuses on exploration in VR games instead of a realistic environment [NZS+24].

Since a good orientation is crucial for successful and independent travel, it is important to extend the current research and facilitate exploration visually. As such, the goal of this thesis is to create visual cues that help visually impaired people gain a mental image of an unfamiliar environment during exploration. To allow safe exploration, we built a virtual city scene in VR, which we augmented with our visual cues. In order to address the specific visual needs, we focused on designing visual cues in a user-centered approach. For this, we first conducted a formative interview with visually impaired people. Our interview was guided by two research questions: (1) *what* information in the environment should be provided, and (2) *how* this information should be provided through the visual cues. From the gathered insights we collected a set of four main visual cue categories, each providing different information for the user. Based on the information these cue categories provide, we defined these categories as: *Obstacle-, Points of Interest (POI)-, Entrance-* and *Shape Information* - cues. For each visual cue category, we defined a set of two to three different visual cue designs, suitable for different needs. Finally, after designing and implementing our visual cues, we conducted a user study to evaluate the efficacy of our cues for orientation. The user study investigated the following research questions: (1) How well are participants able to build and use a cognitive map of an unfamiliar city given our visual cues? (2) How helpful are the visual cues for this process? More concretely, for (2), we investigated the following two aspects of our presented cues: a) How helpful is the information highlighted by the cues (i.e. the chosen cue categories)? b) How well do the visual cues convey the needed information?

Structure of Thesis

The structure of our thesis is guided by our visual cue design, implementation, and evaluation process. First, we take a look at the underlying theoretical background and related work in Chapter 2. In Chapter 3, we discuss the insights gathered from our formative interview with three visually impaired individuals. Following this, Chapter 4 presents our implemented VR prototype, consisting of the design and creation of our visual cues and virtual city. Next, in Chapter 5, we go over our user study design. Subsequently, we present the corresponding user study results in Chapter 6. Finally, in Chapter 7, we provide our conclusion where we also discuss the limitations of our study, potential design modifications for the cues, as well as an outlook for the future.

2 Theoretical Background and Related Work

In this chapter, we present the necessary theoretical concepts and related work to understand the motivation for our work. The first section, Section 2.1, focuses on gaining an understanding of spatial orientation and cognitive maps. Following this, in Section 2.2, we delve into how visual impairment affects orientation and cognitive mapping. Next, in Section 2.3 we discuss the importance of exploration assistance for visually impaired people. Lastly, in Section 2.4, we examine how we can provide visual feedback to visually impaired people.

2.1 Spatial Orientation and Navigation

Navigating the world safely and efficiently requires us to process different types of information around us. A lack of visual information directly influences how we can process this information. In order to successfully reach a destination, two key abilities are needed: *mobility* and *orientation* [Giu18].

Mobility describes the ability to safely move from one place to another without hitting obstacles, tripping, or falling [Her18]. For safe mobility, humans need to correctly perceive imminent objects, obstacles, and dangers both moving and stationary [PV18]. A lack of visual information can make the perception of these obstacles more challenging. As such, impaired vision has a direct effect on mobility [SdG92]. To support safe mobility for visually impaired people, different travel aids were developed for obstacle detection [DLLF05; Ltd; PM16; Res11; SBK98; UB01].

On the other hand, the process of orientation is a more complex cognitive task. Orientation refers to an understanding of the spatial relations between objects in our surroundings and their spatial relation to us [HG00]. A good sense of orientation implies the human brain must process and store spatial information in a mental representation, and use it for travel [MML+18]. In cognitive science, this mental representation of an environment is defined as a cognitive map [Gol99]. In their work on locomotion challenges for blind people, Brambring [Bra85] explains that the process of orientation is directly impacted by problems in the perception of objects. Hence *how* we perceive objects in our surroundings directly shapes our orientation. To further understand how visual impairment influences orientation, we must first understand the process of cognitive mapping.

2.1.1 Cognitive Maps

First introduced by Tolman [Tol48], the term cognitive map, also called *mental map*, describes the way spatial information is stored as a mental representation. These cognitive maps are the knowledge of spatial relations between different elements in an environment [CKK95]. Cognitive maps serve as a memory aid while traveling, helping us find and follow routes to targets [Gol99].

Although the name may imply otherwise, the spatial representation in cognitive maps does not need to be "map-like" in nature. Instead, they are usually abstract representations of a space [ON78].

The spatial information stored in a cognitive map can be perceived either through an *egocentric* frame of reference, or an *allocentric* one [Giu10]. These different types of frames of reference result in different types of spatial knowledge. Siegel and White [SW75] define these as either *route knowledge* or *survey knowledge*. With an egocentric frame of reference, spatial information is perceived and remembered from the perspective of one's current location. This means the direction and orientation of objects in the environment are seen relative to oneself. Spatial information stored with an egocentric frame of reference results in *route knowledge*. This knowledge contains the sequence of landmarks that are expected to be encountered on a route, and knowing the corresponding actions required to follow that route. It is acquired through step-by-step navigation [TG97]. In contrast, with an allocentric frame of reference, we perceive the locations of objects in the environment independent of self-position. It implies a global view of the environment and is needed in order to obtain *survey knowledge*. This knowledge encompasses information about object locations and inter-object distances in terms of an allocentric frame of reference. Survey knowledge is crucial for planning and executing efficient and flexible routes [DKF18].

While both survey and route knowledge are important for building a cognitive map, survey knowledge is considered more flexible and provides a higher spatial ability than just remembering a sequence of landmarks for a route [Giu10]. This is because simply pre-planning a route is often not enough to successfully reach a destination. When a specific route becomes unavailable, survey knowledge is necessary for finding an alternative route. Successful navigation of an environment involves continuous adjusting and re-planning with the use of survey knowledge [SKL+17]. As such, an allocentric cognitive map built from survey knowledge is crucial for good orientational skills.

2.2 Cognitive Mapping with Visual Impairment

So far we discussed the theoretical concepts of cognitive mapping in general. Now we want to further look at how visual impairment influences the cognitive mapping process.

Over the years, various researchers have considered visual cues as the most efficient and reliable sources of information for accomplishing spatial tasks [DBJ18; GKL96; Lyn60; RGH86]. When observing our surroundings, we can see a number of different spatial relations between various objects in the environment with just one glance [WWB10]. Furthermore, when we move through the world with vision, we can directly see the changing spatial relations of objects in relation to our movement. This provides us with both the egocentric and allocentric coordinates of the objects simultaneously [GKL96].

For individuals living with a form of visual impairment, none or only a small portion of visual information is available. As a result, the lack of visually perceived information must either be supported or completely replaced by other senses, such as touch, smell, or hearing. However, perceiving information through non-visual senses has an impact on the way spatial data gets processed [Bli86]. It is harder to gain both egocentric and allocentric spatial information by touch.

Most haptic stimuli are limited to only objects in close proximity to oneself (within arm's reach, or cane reach). Meanwhile, many important objects in our surroundings are too large, too far away, or too dangerous to touch. Additionally, only a small number of objects can be perceived simultaneously through touch. This means most information has to be explored sequentially when relying on non-visual senses [DBJ18]. As a result, most objects are primarily perceived in relation to oneself. Whereas the spatial relations between objects independent from oneself are harder to perceive. Meaning, that most spatial information of objects is formed predominantly through an egocentric view, resulting in a lack of allocentric spatial information of an environment. This lack of allocentric spatial information leads to insufficient survey knowledge. As such, the cognitive maps of visually impaired people tend to be formed only from route knowledge [DHC82]. This lack of survey knowledge affects orientation and hinders individuals from successfully performing spatial tasks such as determining shortcuts, finding alternative routes, or reorienting if lost [Kit94].

2.2.1 Acquisition of Survey Knowledge

In an attempt to help visually impaired people acquire survey knowledge, tactile and interactive maps were created [AE13; ICG+04; Jac92; Jam75]. They are a form of pre-planning aids, meaning they provide the user with information about the environment prior to their physical arrival in a space. Hence they can facilitate information acquisition without any safety risks.

However, when investigating how to acquire an allocentric cognitive map, research has shown that spatial information gained through a map alone is not sufficient to form good survey knowledge [CW13; DS96; Gol93; TH82]. Instead, a place has to be directly explored in situ. This was shown in the experiments on spatial orientation conducted by Thorndyke and Hayes-Roth [TH82]. For their experiments, they investigated the orientational skills of two groups of participants. Group 1 was given a map of a space but did not navigate through it directly. Whereas Group 2 got to navigate through the space but did not receive a map prior to navigation. The results showed that over time, the more Group 2 navigated directly through the environment, the more accurate their spatial knowledge became compared to Group 1. Darken and Sibert [DS96] argued that while *survey knowledge* is map-like in nature and can be acquired directly from map use, it tends to be orientation-specific. In contrast, navigating in an environment directly is more likely to result in *survey knowledge* which is orientation-independent. Herman and Siegel [HS77] describe the acquisition of such *survey knowledge* as a combination of *route knowledge* of different routes. When exploring an environment, landmarks on the traversed path are remembered as *route knowledge*. The *route knowledge* of various routes is then combined based on their shared landmarks, forming *survey knowledge*. Hence, in order to acquire a rich allocentric cognitive map, the environment has to be explored directly.

2.3 Exploration Assistance

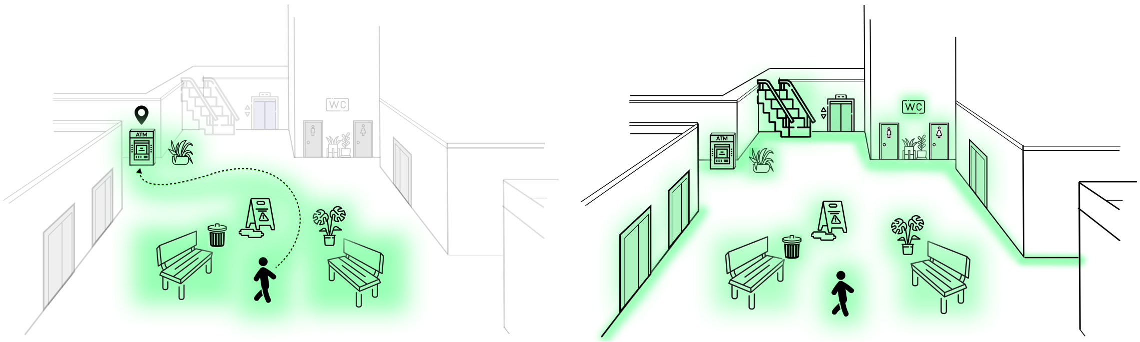
Exploring an environment, especially outdoor environments, comes with a number of potential hazards for people with impaired vision [MK11]. At the beginning of this Chapter, we briefly mentioned travel aids supporting safe mobility for visually impaired people. Over the years, there have been different approaches made to further facilitate independent and safe navigation through in-situ aids. In the following, we look at the current state of in-situ travel aids and their suitability as exploration assistance.

2.3.1 Current Travel Aids

In-situ aids are designed to assist users in real time as they traverse their environment. They provide information about the immediate surroundings, and often, offer turn-by-turn navigation. As of today, traditional in-situ aids such as white canes and guide dogs have remained the most commonly used travel aids [PVHU17]. While guide dogs are trained to lead a person to familiar locations and navigate around obstacles, they do not provide further information about their surroundings. In contrast, white canes offer more detailed information about the immediate surroundings, such as the presence of ground-level obstacles and surface textures. However, their detection range is limited, typically only up to a distance of one meter. Additionally, they primarily detect ground-level obstacles, thus missing hanging objects [PCLB].

To help visually impaired people detect obstacles missed by a standard cane, Electronic Travel Aids (ETAs) were developed [DLLF05; Ltd; PM16; Res11; SBK98; UB01]. They increase the detection range of traditional travel aids and provide additional information about the objects. Through auditive or haptic feedback, they inform users about relevant information about obstacles, such as their distance to the user or their size [DBJ18]. The so far discussed aids mainly focus on providing safe mobility. However, they typically do not provide any additional identification information of the surrounding objects. As such, users are typically only alerted about the presence of obstacles, but not about what type of objects are actually around them. To further facilitate independent travel, the development of ETAs was extended from obstacle detection to navigation and wayfinding assistance [BCG93; Cor06; SOG+19; Woo11; YPM+11]. The goal of these aids is to navigate the user to a target destination while providing important information of objects on route[CPBR17].

However, most of these travel aids are not directly focused on facilitating free exploration. Instead, they focus solely on helping their user reach a determined destination. Such navigation assistance is often referred to as turn-by-turn navigation [JTC+23]. Turn-by-turn assistive aids provide users only with information relevant to a route, disregarding other information in the environment. An example of this can be seen in Figure 2.1a, where a turn-by-turn assistive aid guides a user to a destination. Here, information about potential obstacles encountered on the route is provided so that the user can safely reach their target. Information that is not directly relevant to the route is thus not provided. Hence, users do not receive information about the shape of the room, locations of entrances, stairs, and other important points in the environment. While these assistive aids help users form route knowledge, they fail to directly support the acquisition of survey knowledge. As such, there is a lack of assistive aids supporting users in building an allocentric cognitive map. In order to bridge this gap, assistive tools need to facilitate active exploration instead of providing turn-by-turn navigation [BFT+13; JTC+23; MK11]. In Figure 2.1b, we present how exploration assistance should support the user compared to the previously shown turn-by-turn assistance of Figure 2.1a. To explore the environment, assistive aids need to provide relevant information about the entire environment, not only a specific route. In the following, we go into more detail on what information such exploration assistance tools should provide.



(a) Turn-by-turn navigation assistance **(b)** Exploration assistance

Figure 2.1: Difference between travel aids providing (a)turn-by-turn navigation and (b) exploration assistance [37].

2.3.2 Information Needs for Exploration

One of the first theories on what information visually impaired individuals rely on when exploring an unfamiliar environment were defined by Hill and Ponder [HP76]. They defined two strategies, *Perimeter* and *Reference Point*. With a *Perimeter* strategy, individuals track the *shape* of a place by following its border. Whereas with a *Reference Point* strategy users move inside the borders of the environment, from one reference point to the next, in order to understand their relation to one another in the space. These exploration strategies were shown to be applied by many visually impaired people in different studies over the years [JTC+23; Tel92; TG97]. Tellevik [Tel92] and Thinus-Blanc and Gaunet [TG97] performed user studies with visually impaired people, observing their exploration of new spaces. Both results indicated that at first, participants tended to track the *Shape* of the space similar to the *Perimeter* strategy. With additional exploration, participants started to adopt a *Reference Point* strategy, going from object to object to memorize their locations. More recently, Jain et al. [JTC+23] conducted an interview with visually impaired people investigating information requirements for exploration. During their interview, participants reported first needing *Shape information* for a high-level overview, which is then expanded by *Layout information*. They described *Shape Information* as a skeletal wire-frame or boundary shape of a place, resembling the *Perimeter* strategy defined by Hill and Ponder [HP76]. For indoor spaces, participants mentioned wanting to know the shape of walls or corners. For instance, the shape of offices are typically square, while hallways tend to be elongated rectangles. *Shape Information* of outdoor places was described as the shape and width of the walkable area, i.e. sidewalks, streets, pavements, or crosswalks. The subsequent *Layout Information* participants defined as information about the location of objects within the space. This *Layout Information* parallels the information acquired with a *Reference Point* strategy.

Obstacles, Points of Interest, and Landmarks

In the following, we look at the mentioned *Layout Information* in more detail. As stated above, this information refers to specific objects located inside the space. For these objects, Brambring [Bra85] makes a distinction between *obstacles* and *landmarks*. Other work further extends *landmarks* to *points of interest (POI)* [Giu10; HG00] .

POIs and landmarks in an environment serve as orientational points or *Reference Points* when navigating a space [Giu10]. As such, they are crucial for creating and using a cognitive map in an environment. POIs commonly refer to specific objects, locations, or facilities, whereas landmarks usually describe unique features of an environment [Giu10]. Unique landmarks can also help to identify POIs. Since landmarks are typically unique, they are mostly location-specific. On the other hand, POIs often consist of commonly used objects or facilities that can be found in most places. Hence, when designing assistive aids that should provide information for exploration, there is a set of POIs that can be pre-determined. In their work, Motta et al. [MML+18] defined such a set of POIs that should be provided by assistive tools for visually impaired people. Their mentioned POIs consisted of daily used services such as a post box, public transport, or pharmacies. The information that the assistive aids should provide should help the user identify POIs in their environment as independently as possible. The ability to correctly perceive and identify an object is directly influenced by the knowledge of its existence and location [WWB10]. If a person knows what to look for and where to look for it, then the object can be much more easily perceived. Hence the described assistive aids should not directly tell the user that they are standing next to a pharmacy. Instead, the assistive tools should rather point to the information, or specific landmarks, in the environment that can help users identify the pharmacy themselves. This way the user can actively look out for clues, or landmarks, that can help them recognize and identify the POI themselves. Once a user knows what to look for, they can detect and recognize it better next time. For instance, without an assistive aid, a person with low vision walking by a pharmacy might not notice or recognize a green cross logo. An assistive aid can guide their attention to the logo and provide them with the needed help to identify it as a pharmacy cross. This person then expects this logo when they pass the pharmacy and can actively look outfor its colors and shape.

While some objects in an environment are important for daily use, not all objects need identification information for successful navigation. For instance, it is typically less important to distinguish between poles, traffic lights for cars, or street lights. However, it can be crucial to know about their presence, as they can be direct obstacles in our travel paths. Since detecting obstacles is often a challenge, many visually impaired people must memorize static obstacles in order to avoid them. As a result, the cognitive maps of visually impaired people contain more information about obstacles in an environment compared to sighted people [Her20; PVHU17]. Hence besides identification information for POIs, it is also important to provide information about obstacle location.

In summary, the presented work indicates that in order to facilitate active exploration of an unfamiliar place, with the goal of acquiring a cognitive map, we need to provide the following information:

1. **Shape Information:** First, the user should be provided with information about the *Perimeter* or boundary of the space in terms of how the streets, paths, or walls are laid out in the environment. This serves as a skeletal wire-frame of the space in which users can walk through and where they can expect objects to be located.
2. **Layout Information:** This is then extended with the information of how the specific objects are laid out inside the boundaries of this space. Here we further divide these objects into Obstacles and POIs, resulting in the following two subcategories:

- **Obstacle Detection**: In order to safely navigate the space the user needs to detect obstacles on their path and maneuver around them. Since moving obstacles are not relevant for a cognitive map, the focus here lies on static obstacles that do not change their location.
- **POI Identification**: While POIs are typically frequently used for daily tasks, they also serve as important orientation points during navigation to other locations. As such, the user should be provided with information that helps them recognize and identify important POIs. These POIs then serve as *Reference Points* during orientation.

2.3.3 Exploration in VR

With the growing advances in Virtual Reality (VR), a new form of assistive aid has emerged. Through VR, exploration of unfamiliar spaces can be performed in a safe and controlled environment [TBB20]. In addition to providing a safe training ground, VR can also provide additional information to support the process of creating a mental map [LGB+17].

Cognitive mapping in Virtual Reality has already been a topic during the early ages of VR development. Similar to cognitive mapping in the real world, during the exploration in VR, the user collects spatial information through interaction with objects and POIs. With this information, the user constructs a cognitive map of the virtual environment. Research on sighted people showed participants were able to acquire spatial knowledge of a virtual environment and successfully transfer it to the real environment [DB98; NCK+07; RPJ97].

In more recent years, research on VR was extended to the inclusion of visually impaired people [CCSM14; CMA17; Lah22; LGB+17; LM08; LSS15]. In order to allow visually impaired users to explore a VR scene, there have been different approaches made. Nair et al. created NavStick [NKS+21], an audio-based tool that enables users to "look around " a virtual environment by using the thumbstick of a controller, receiving information about objects that are pointed to. Similarly, in their study, Lahav et al. [LGB+17] used a Wii controller for looking around when exploring a space. Since many visually impaired people rely on a white cane, to detect obstacles, another option is to provide feedback through cane usage [KG19; LMM+03; SSK+20; ZBB+18]. Various studies investigated the exploration of unfamiliar VR environments [CCSM14; CMA17; Lah22; LGB+17; LM08; LSS15]. Their results showed participants with impaired vision were able to construct cognitive maps through the exploration of unfamiliar VR spaces [LGB+17; LM08; LSS15]. Furthermore, visually impaired participants could then transfer these cognitive maps acquired in VR to the real space [CCSM14; CMA17; Lah22].

However, most work in VR exploration so far focuses solely on the exploration of a virtual environment through non-visual senses. Yet many visually impaired individuals still possess some remaining visual capabilities. In a study by Thevin et al. [TBB20], participants with low vision even showed to pay more attention to details in a virtual scene than sighted people. In their study, they investigated VR exploration with visually impaired students. Besides mainly providing auditive feedback they also showed the virtual scene visually so that the environment could also be seen by the study conductors. Since the intent of the visual presentation of the scene was mainly for the study conductors, the scene was not created very realistically. Surprisingly, the participants with remaining vision showed to be very sensitive to visual information, often noticing inconsistencies and errors in the virtual representation that the study conductors did not pay attention to themselves. For example, they noted how cars in the simulations did not have any drivers. In real life they pay attention to the driver's behavior when crossing the street, for instance, they look at drivers to establish whether it is safe to cross. Hence, when navigating the virtual environment, they immediately noticed missing drivers. Another example was one-way streets lacking direction signs prohibiting cars from driving in from the other way. This shows that visual information can be highly beneficial for visually impaired people. As we have already discussed, visual information allows the easiest acquisition of allocentric cognitive maps during exploration. Hence when designing VR systems for visually impaired people, it is important to provide visual feedback for different visual capabilities.

2.4 Providing Visual Information for Visually Impaired People

In the following, we take a look at how we can use visual cues to facilitate exploration for visually impaired individuals. For this, we first discuss what visual attention is and how it plays a role in our visual cue design. At last, we present the current work done on visual cue design for visually impaired people in Virtual and Augmented Reality.

2.4.1 Visual Attention

The human visual system is presented with a large amount of visual information during navigation. In order to efficiently process this information, we must prioritize relevant stimuli within our surroundings while filtering out less important details [DBD07]. This process of information selection is referred to as attention. The human attention system processes information in a combination of a top-down and bottom-up way [CEY04]. Bottom-up visual attention involves the automatic, involuntary response to salient or significant stimuli in the environment, such as sudden movements or bright colors. This is critical for detecting and processing unexpected or potentially important stimuli in the surroundings and as such helps us safely navigate the world. Top-down visual attention is driven by individual goals, beliefs, and expectations. It involves the use of prior knowledge and context to selectively focus on particular visual stimuli. For example, while walking to a destination we rely on specific features that guide us to our destination. Top-down attention guides the focus to these relevant target features while searching in a cluttered environment. Thus, while a bottom-up process pays attention to salient items in our environment, top-down attention regulates the bottom-up signals while looking for something specific. The integration of both top-down and bottom-up visual attention mechanisms enables individuals to safely and efficiently navigate the world.

Lack of visual information causes the top-down and bottom-up visual attention to be affected [DBP10]. Not being able to perceive visual stimuli results in our attention not being guided to potential obstacles. As such, obstacle detection becomes difficult. Similarly, actively guiding attention to important information also becomes a challenge. Using salient visual cues we can guide attention to important information in the environment. As such, the focus of our work is to create visual cues that can help visually impaired people receive the needed information to acquire a cognitive map.

2.4.2 Visual Cues for Visually Impaired People

Using Virtual (VR) and Augmented Reality (AR), we can augment the world with helpful visual cues. To make product searching in a supermarket easier, Zhao et al. [ZSKA16] created and examined visual cues that guide the user's attention to the target product. However, most work using AR visual cues for visually impaired people focuses on facilitating safe mobility. One mobility challenge for visually impaired people is stair navigation. For this, Zhao et al. [ZKC+19] designed two different AR visualizations, using projection-based AR and smartglasses. The projection-based approach projects visual cues directly onto stairs, signaling the user where each step ends and where the whole stairs end. With the smartglasses, the user is shown a visualization indicating their own position on the stairs. In a subsequent user study, the projection-based visual cues showed an increased walking speed of participants and a higher self-reported security. Another mobility challenge is avoiding obstacles. For this, Fox et al. [FAW+23] developed visual cues highlighting obstacles in two different types, world-locked cues and heads-up cues. While world-locked cues "stick" to the obstacles and are thus only visible when the object is in the field of view, the heads-up cues point in the direction of obstacles outside the user's field of view. Kinateder et al. [KGD+18] chose another approach for facilitating obstacle avoidance. They developed an AR application that shows the distance to objects through colors. The objects in the captured view are colored with different colors based on their distance from the observer. Using visual cues in the form of braille blocks, Hommaru and Tanaka [HT20] created an AR system that projects a virtual braille blocks on the walking surface. When an obstacle is in view, a warning braille block is projected in front, with additional directional braille blocks showcasing a path around it. It also provides haptic and voice feedback and registers the usage of a white cane. To facilitate obstacle detection,

While there has been a number of work done on AR visual cues, there is little done for VR. Zhao et al. [ZCH+19] presented a set of adjustable vision tools for existing VR applications that can help make visual information in VR applications more accessible to people with low vision. Tools such as a magnification lens, edge enhancement, or highlighting can be used for any existing VR applications. However, they are not directly designed to facilitate exploration in a VR environment. In their most recent work Nair et al. designed Surveyor [NZS+24], an assistance tool providing visual cues that facilitate active exploration and discovery in VR games. Surveyor tracks where the player looks and provides visual cues that highlight unexplored areas for them. Currently, this seems to be the only work done using visual cues to facilitate VR exploration for visually impaired people. However, their work focuses more on exploration in VR video games and not realistic environments such as an urban city.

3 Requirements Analysis: Interviews with Visually Impaired People

When designing prototypes for people with visual impairment, it is crucial to gather as much input from the target users as possible. The first step of our work consists of conducting a formative interview with visually impaired people to investigate exploration strategies and needs. For our interviews, we focused on the exploration of two different example environments, an urban city, and a supermarket. Although we later narrowed down our work of visual cue design to the urban city scenario, we present the findings for the supermarket scene as well.

In Section 3.1, we first present the research questions guiding our interviews. Following this, we present the participants in Section 3.2. Next, in Section 3.3, we go over our procedure, followed by a presentation of the asked questions in Section 3.4. In Section 3.5 we then go over how we analyzed our data before presenting the results in Section 3.6. Lastly, from the presented results we define design guidelines for our VR application design, shown in Section 3.7.

3.1 Research Questions

In order to design visual cues which facilitate exploration in VR there are two central questions to be investigated: *What* should be highlighted by a visual cue, and *how* the visual cue should look like. As such, the conducted interviews serve to answer the following two research questions:

RQ1: What type of visual stimuli can be perceived best and which pose a challenge or are irritating?

RQ2: What environmental features or parts are paid attention to the most while familiarizing with an environment?

For our second research question, we specifically focused on two example environments, an unfamiliar supermarket and an unfamiliar urban city.

Participant	Gender	Age	Travel Aids	Diagnosis	Remaining Vision	O&M skills
P1	female	35	primarily guide dog; sometimes long cane	Nystagmus; Cone rod dystrophy; (mild) Color blindness	2-5%	●●●●●
P2	female	33	long cane	Retinal detachment	2% (right eye)	●●●●○
P3	female	16	long cane	Nystagmus; Cataract; Aniridia	2%	●●●●●

Table 3.1: List of interview participants and their *gender; age; daily travel aids; diagnosis; remaining vision;* and their self-reported *orientation & mobility skills* on a scale of 1-5, with 5 being the best.

3.2 Participants

For the interviews, we recruited 3 visually impaired participants. A list of the participants along with their diagnoses can be seen in Table 3.1. All participants identify as female and their ages range between 16-35. Their self-reported remaining vision ranges between 2 %- 5% and all have a form of light sensitivity accompanied by varying degrees of blurred vision due to their diagnoses. Additionally, due to Nystagmus, P1 and P3 also have eye twitching or oscillating movement of the eyes. On a score of 1-5, with 5 being the best, all participants estimate their Orientation and Mobility (O&M) skills as very good, ranging between a 4-5 out of 5. Two participants named the long cane as their primary travel aid while P1 relies primarily on their guide dog and uses their long cane only occasionally, such as in new environments or public transport.

3.3 Procedure

We conducted a semi-structured qualitative interview guided by the two previously stated research questions R1 and R2. The interviews were conducted in person for participant P1 and via video call for the others. Due to P3 being underage, a legal guardian was present throughout the interview, who offered further input. The average length of the interviews was around 1.5 hours and the participants were compensated with 12€ per hour. A consent form and data privacy form were given to each participant before the interviews. Each participant was informed that they could choose not to answer a question or end the interview at any moment, however, this did not occur for any of the three sessions. The interviews were recorded with the consent of all participants and the resulting audio was then transcribed and analyzed.

3.4 Questions

After gathering the general demographic information (age, gender, diagnosis, remaining vision, used mobility aids, O&M skills), shown in table 3.1, the interviews consisted of two parts.

Visual Perception: The first part of the interview consisted of open questions about the individual perception of different visual stimuli. Here, the participants were asked how they perceive these visual stimuli, what can be perceived best, and which ones pose challenges or can be irritating given different scenarios. This part was guided by our first research question R1.

Exploration: The second part of the interview focused on the exploration and orientation in two given scenarios, a *supermarket* and *city* scenario. Starting with a *supermarket* scenario, participants were asked open questions about their strategies when they explore, navigate, and familiarize themselves with a supermarket, which features or visual stimuli are most helpful, and what challenges they face. Afterward, the same was asked for the scenario of exploring an urban *city*. For both scenarios, we also discussed possible design solutions with participants which could help with the mentioned challenges. The goal was to gain insights for our second research question R2.

3.5 Data Analysis

To analyze the data, we followed a thematic analysis approach [BC06]. At first, we employed open coding on the interview transcripts. The codes were then clustered into higher-level categories. Following this, the categories were iteratively overviewed on similar patterns and grouped into more general themes.

3.6 Results and Findings

In the following, we look at the different findings we gathered from the interviews, as well as the resulting implications for our visual cue design. The findings are separated by the two different interview blocks **Visual Perception** and **Exploration**, mentioned in Section 3.4. Furthermore, we separate our findings from the second block based on the two scenarios *Supermarket Exploration* and *City Exploration*. This separation makes it easier to draw conclusions for visual cue design since the different scenarios require different visual cues. Although we ended up only using the *City* scenario for our further cue design process, we also present the results for the *Supermarket* scenario as it provides valuable insights for future work.

3.6.1 Visual Perception

Four different visual stimuli play a role in the design of visual cues. These consist of *Contrast and Color, Shapes, Illumination and Light*, and *Motion*. In the following, we look at the corresponding findings.

High Contrast and Unique Colors: The most important visual feature reported by all participants was high contrast. If the contrast is not high enough, perceiving shapes and colors or reading signage becomes extremely difficult. P1 described that the single colors themselves do not play a huge role, but rather the contrast and difference between them. As such, the used colors have to be different enough in order to distinguish them. For example, P1 explained that dark blue and dark purple are the same to them. Similarly, P3 mentioned that they cannot distinguish between light green and yellow. Furthermore, all participants reported that color can help them recognize objects, even if they cannot fully perceive the objects themselves. For instance, P2 mentioned: *"Mailboxes, for example, are relatively easy to find thanks to their wonderful yellow color."* -P2. Similarly, P1 also gave an example of Oreo cookies being distinguishable based on their blue background with black and white details. P3 also reported using mainly color to recognize and find objects from a distance when they are not yet able to recognize the shape: *"..when you approach from a distance, you may not see the shape, but you automatically look for color"* -P3. As such, all participants expressed the desire for more use of color for important objects, in order to recognize them better. Especially obstacles such as poles or street lights were mentioned as needing more distinguishable colors. However, P1 mentioned that too many contrast-rich colors are also not ideal, hence the number of different colors should be limited: *"[...] it also depends on the contrast. So if everything is colorful, then it doesn't really contrast with each other, does it?"* -P1.

Simple and big shapes: While all participants reported being able to recognize most shapes when they are close enough, they also reported preferring simpler shapes so they are easy to perceive from a distance as well. P1 and P2 mentioned using the shape of known objects to help them recognize those objects better. As P1 put it: *" [...] shapes are also [important for finding things], you have learned them and then you know what you are looking for."* -P1. Participants P1 and P2 further added that their brain automatically interprets objects based on their shape even though they cannot fully see them. For example, P1 mentioned that - while they cannot read the logo of the bakery "Kamps", - they can recognize the shape and hence know at which bakery they are: *"[...] by now, of course, I already know brands. Then you read 'ah Kamps' [...] although I can't actually read it. But I look at it and from the shape my brain then knows, 'OK, that's Kamps'."* -P1. Similarly, P2 described: *"I also believe that [...] sometimes even if I don't see it properly through my eyes, my brain just knows, 'OK, there's a tree up ahead'. [...] although I may not perceive the tree from a purely visual point of view, I still see it because my brain simply knows 'OK, that thing is a tree' because it looks like a tree in terms of its shape."* -P2.

Illumination and light sensitivity: Since all participants reported having light sensitivity, they preferred a darkened environment. Furthermore, P2 mentioned the additional challenge of shadows created by illumination as too many different shadows cause disorientation. While too much illumination and brightness are perceived as blinding by all, P1 sees the usage of lightning and blinking as beneficial for signaling and highlighting important objects. For example, they mentioned finding entrances would be easier if there was a blinking effect around or on them. On the other hand, P2 and P3 find this rather irritating and prefer the usage of color for highlighting objects. Indirect lighting, however, was perceived as very useful by P2, as they mentioned it as a big factor in orientation.

Limited motion: While all participants find too much movement or motion distracting and irritating, P1 sees the benefits of motion in search tasks: *"For example, if I'm looking for a colleague, walking through the office, of course, if he moves, then that's super helpful."* -P1. However, P2 and P3 dislike the use of motion in general and perceive it as irritating.

3.6.2 Supermarket Scenario

Although we did not end up designing visual cues for a supermarket scenario, the findings are still of value for future work. Our findings are divided into two parts, **exploration strategies** and the **faced challenges during exploration**.

Exploration and Navigation Strategies

From our interviews, we gathered five different strategy themes: using *Unique Colors and Shapes*, *Layout Similarity*, *Signage and Labels*, *Phone Camera for Enhancement*, and *Non-Visual Senses*. These are discussed in detail in the following.

Unique Colors and Shapes: When looking for specific products, all participants reported first looking for the color palette associated with the product category. For instance, P3 reported recognizing baked goods based on their brownish tones: *"But you can usually recognize [baked goods] because most of [their packages] are transparent and contain gold, brown rolls."* -P3. Similarly, P1 reported also using the shape of products to first recognize the category and then use color when looking for a specific product. They mentioned that they memorize the colors of their favorite sweets to find them more easily: *"Color plays a big role with sweets because you see all these brand logos and names. [...] over time, you get a feeling that your favorite Haribo is blue on top and I look for it. So at first [I] maybe [look for] the shape, but then, [when] I see here is the shape of Haribo packages, then I look for the one with the blue on top for Tropifrutti."* -P1. However, they further added that this is only possible for products with distinguishable colors. Similarly, P2 mentoined how Milka chocolates usually have a purple color, making them distinguishable from other brands: *"Milka is very prominent in terms of the color scheme, this bright purple, which is immediately noticeable [...]"* -P2. Furthermore, P1 also mentioned using the unique shape of products in order to find the right category in supermarkets, such as wine bottles. Overall, unique color and shape were reported as being the most helpful features when looking for a specific product.

Layout Similarity: When talking about how they would navigate an unfamiliar supermarket, all participants mentioned relying on familiarity with the layout of most supermarkets. For example, P2 reported: *"The good thing is that most supermarkets are more or less all laid out in the same way. So when you come in, you are in the fruit and vegetable section, behind that you'll usually find cereals, bread, and meat and sausages."* -P2. Similarly, P1 also reported the same sentiment: *"Experience totally helps. Usually, you already know that fruit and vegetables come* *first, followed by all sorts of other things, and finally at the end the registers."* -P1. This makes it easier to narrow down the general area of a product they search for. P3 also mentioned the layout of the shelves being fairly similar in most stores, typically following a more horizontal arrangement. All participants then reported that they take the time to walk through every aisle and investigate what product categories are placed there and try to memorize them for future visits: *"When I go to a supermarket for the first time, I actually consciously take more time to see what this supermarket has to offer and where I can find exactly what [products] so that I at least have a rough orientation. [For example] 'here I can find the pasta, fruit and vegetables'. [...] 'at the back in front of the registers I might find the sweets'. So that you basically have a rough orientation, [or] a rough idea."*

Signage and Labels: Although most labels and signs were reported by all to be difficult to read, P1 mentioned using signage above shelves to read the product categories if they can recognize them. However, they added that not all supermarkets have readable product signage as many are either too high or too small. While P2 and P3 both noted that they do not use product category signage, P2 reported using labels on price tags of individual products to check whether they are at the right food category. However, they have to get extremely close in order to be able to read the labels. As such, they typically rely on other senses for identification instead and only use labels to check. Additionally, P3 mentioned that often price tags are not placed directly under or over the corresponding product, making it difficult to pick the exact right product. Lastly, P2 reported using the number signs over registers. While they reported they cannot read the individual number on them, they can recognize what color they are glowing in: *"Many cash registers now have numbered plates [hanging], and depending on whether the cash register is occupied or not, it is either green or red."* -P2. Hence they use this to check whether they are at the registers and if the register is open.

Phone Camera for Enhancement: As reported earlier, reading signage and labels is rather difficult in many stores. This makes it a challenge to know which of the presented products is the one they are looking for. As such, when looking for specific products, P1 and P2 mentioned using their phones for visibility enhancement in order to check whether they have the correct product in their hand.

Non-Visual Senses: In addition to the visual features used for guidance in a supermarket, all participants reported using non-visual senses as well. For example, they can recognize baked goods or meat counters by smell, whereas cash registers can be recognized by their beeping sounds: *"Fruit and vegetables usually have a smell, [...] and packaged cereals, bread, and meat don't. [...] In most cases, I can actually recognize the checkout area relatively well through the beeping from the checkout."* -P2. Similarly, P1 also mentioned only recognizing cash registers through sound: *" I don't think I've ever found a checkout visually, only by where it beeps"* -P1. Furthermore, when they cannot see the shape of a product, participant P1 reported using their hands to feel it.

Challenges and Possible Design Solutions

In the following, we discuss the challenges faced during supermarket exploration. During the interviews, we also discussed possible design solutions for these challenges. Therefore, for each mentioned challenge we also discuss how it could be addressed through a design solution.

Distinguishing Products: The first challenge mentioned by all participants is perceiving and distinguishing different products on shelves due to too similar packaging. P2 described that often different products are either placed too close next to each other without any barrier, or they are even completely mixed together. Thus, P2 expressed a desire for a barrier between different products: *"For example, in the refrigerated section, [...] in one shelf, [...] there are always different products that [are] not necessarily clearly separated from each other. [...] I think a complete separation of the entire compartment is missing here."* -P2.

Design Solution S1: A clear separation of different products.

Signage and Label Visibility: Most signage about the product category was regarded as too small to read by all participants. P1 further added that the signage often hangs too high making it difficult to read. *"If the shelves are too high [...] I can't see what's up there. And those price tags that hang down from the top are nonexistent for me."* -P1. Additionally, the contrast between the text and background is often not big enough, as noted by P2. As such, P1 expressed a desire to place the signage on the floor instead of above shelves for better readability. P3 also liked this idea: *"On the ground, I think you pay more attention to that [signage] than when [having to] walk with your head up."* -P3. However, P2 prefers the location above shelves, just making the text bigger and with more contrast. Furthermore, P2 and P3 mentioned that the number signs above the registers are not readable because they are too far away and too small as well: *" I think they [register number plates] should be a bit bigger than they are at the moment [...] and actually right back where I'm supposed to line up."* -P2.

Design Solution S2: Make signage bigger with high-contrast text.
Also, provide the option to place signage on the floor.

Locating Start of Checkout: Although participants reported that once they are close enough they can recognize the checkout based on green and red number signs above registers, they cannot see it from a distance. Thus they have to get really close in order to recognize that they are at the checkout registers. As a result, P2 explained they need longer to locate the checkout area. Hence, they expressed that arrows pointing to the checkout would be helpful, similar to the concept in most Ikea stores, where arrow floor markings point the way through the store. Furthermore, P2 and P3 mentioned the register signs only help them identify the register area, but not the start of it, i.e. where they need to queue. P2 reported that they wish the signs would hang at the start of the checkout instead of directly above the registers, as this would help them locate the start of the checkout line: *"This number plate is usually always at the front of the checkout, i.e. when you are at the front of the conveyor belt with the cashier. In order for me to be able to recognize it faster and better, it should be where I want to queue, so I'm able to see it immediately."* -P2.

Design Solution S3: Use arrow floor markings pointing to the checkout throughout the supermarket. Additionally, provide floor markings that highlight the start of the checkout line.

Distinguishing Entrances & Exits: Although locating exists was not regarded as a challenge once inside, P3 expressed having problems distinguishing exits from entrances when outside. While they are separated inside the store, from the outside they are typically placed right next to each other as two glass doors: *"Yes, sometimes you walk into the wrong door and think: why won't it open now?"* -P3. Hence P3 expressed that a clearer separation from the outside would be helpful as well.

Design Solution S4: Highlight entrances.

Illumination and Brightness: Too much illumination was already described as a big hurdle in the prior *Visual Perception* block. This was mentioned to be especially the case in most supermarkets, as all participants reported them to be too bright. This makes the above-mentioned challenges even harder.

Design Solution S5: Adjustable illumination and contrast.

Rearrangement and Changes: As discussed in the *Exploration Strategies* results, all participants reported relying on memorizing the layout of product categories and the location of specific products they typically use. However, often supermarkets rearrange their products or even their whole layout. All participants expressed their frustration with this. As P3 described, they have to restart the whole familiarization process again: *"The problem is, if they rearrange [the supermarket], then it's just like starting all over again."* -P3. This can be extremely time-consuming over time.

Design Solution S6: Highlight products that have changed locations. (However, this can also become too overwhelming if too many products are rearranged and impossible for layout changes.)

Other People: The last challenge mentioned by all participants was described to be other people, as they obscure the already limited view: *"The biggest obstacle is not the path, stairs, or anything else, but the people."* -P1. Additionally, they make it difficult to focus on exploring the supermarket and finding products, as the attention is shifted to trying to maneuver around other customers. Although this poses a major challenge, moving obstacles are not a factor in the cognitive mapping process and are thus not included in our later VR design. Hence we do not provide any additional design solution for moving obstacles.

3.6.3 Urban City Scenario

The second scenario we investigated was an urban city setting which we ended up using for our visual cue design. We present the findings analogously to the supermarket scenario, divided into the investigated **exploration strategies** and the **faced challenges during exploration**.

Exploration and Navigation Strategies

For exploration strategies, we identified four main groups, consisting of *Pre-Planning and Memorization*, *Landmarks and Points of Interest*, *City Layout*, and *Public Transport*. In the following, we discuss the findings for each.

Pre-Planning and Memorization: Before arriving in an unfamiliar city, all participants reported doing pre-planning first. This includes gathering knowledge about useful routes and points of interest by either asking people or using Google Maps: *"Before I actually arrive, I've already 'been' to the city, because I looked at a map of where everything is roughly."* -P1. Upon arrival, participants then reported navigating with navigation apps to these points of interest in order to familiarize themselves with the routes. Points of interest were considered any buildings or services that are needed in daily life, such as post boxes, ATMs, pharmacies, cafes or supermarkets. For instance, P2 reported using navigation apps when they first visit a new cafe: *"When I go there for the first time, I [use navigation apps] to navigate my way there, but if I go there a 2nd or 3rd time and it becomes my favorite café, then I actually orient myself based on the surroundings."* -P2. During their navigation, participants mentioned memorizing details on routes that otherwise can be hard to perceive, to facilitate their future travel: *" I actually memorize the route itself on the way there. How exactly do I have to walk, how many streets do I have to cross? Is there a street with traffic lights or no traffic lights? [I] also [memorize] relatively significant points so that I know I can find the route in the dark without any problems."* -P2. Similarly, P1 mentioned using memory and counting to navigate, such as memorizing the number of entrances before the target entrance or the number of stairs in a stairway. P1 further mentioned remembering obstacles that are not easily visible in order to avoid them: *"Poles are the ones I always know by heart where they are because I can't see them. By now I can tell you every single pole on my routes because I've already run into them at least once and so I have experience of how to avoid them."* -P1. They further added that they then use these obstacles as a form of orientation for future travel: *"In this respect, of course, they [poles] also help with orientation if I now know that something was before or after the pole. [...] In principle, everything I've ever run into or fallen off is of course also a point of reference."* -P1.

Landmarks and Points of Interest: In order to orient themselves, all participants reported using specific points of interest in the city, such as restaurants or cafes. Especially large POIs such as parks, rivers, and big buildings were considered helpful: *"Rivers and parks and things like that, or big buildings, are really helpful to orientate yourself by, because that's something you can research beforehand, and then I know, OK, I'm wrong if there isn't this river."* -P1. Also, any POIs with unique or easily perceivable features, such as vibrant colors or a high contrast to their surroundings. Often these features do not have to be unique by themselves but can stand out given the context they are in. As such, participants explained that in order to find and recognize certain buildings, they might memorize any particular object that is in front of it, such as stairs, trees, or a parking lot: *"If there are objects around it or if there is perhaps a parking lot directly in front of it or if there is a tree or other such prominent things where you know that that is the right house."* -P3. Hence when looking for that building participants specifically look out for these things: *"[...] when there's something that stands out the most. For example, I want to go to the town hall and there's a tree right in front of it. Of course, then I always look for the big tree."* -P1. It is crucial however that the chosen landmarks are permanent. P1 mentioned that once they remembered a cafe based on the tables and chairs in front of it. However, during winter these were removed, hence when they were looking for the same cafe again, they could not find it as they focused on searching a landmark that was no longer there. Furthermore, to support their perception of the POIs, all participants also reported additionally using non-visual senses, such as the smell of bakeries or loud train noises of a train station.

City Layout: Most urban cities exhibit certain similarities in their layout, typically consisting of clear and large shapes with parallel or orthogonal streets. This was regarded as very helpful by P1. They further mentioned following big streets during their travel: *"For orientation, it's simply better to walk along a big road [...] because big roads are usually straight. Or when they take a turn, it's very abrupt. So they're just such clear structures that you can follow."* -P1. If they cannot see something, P1 reported trying to logically deduce it. For instance, when crossing a street, while they may not see the curb of the sidewalk on the other side, they expect it to come and hence can prepare for it in advance: *"Many things are built according to the same principle [..] and there is logic. I try to figure out what I don't see in some other way. To memorize it somehow or to approach it with logic. [For example, when crossing a street] there's another curb of some kind on the other side, even if it's just a very flat edge, but there's something there [so] I look for it because I know it has to be there. If I know that something has to come, then I can see it better because I'm looking for it."* -P1.

Public Transportation: As driving with a car is impossible, all participants underlined the importance of public transportation. Knowing where each bus or train stop is located, which bus lines frequent that stop, and what places are reachable from there, was reported to be among the most vital information needed for travel. P1 and P3 regarded the routes of the public transport lines as a guide through the city. P1 described that with each route, slowly a mental picture of the city develops: *"I find public transport really helpful for orientation so that I already know where I have to go, and then a picture slowly starts to emerge."* -P1. Furthermore, they reported that the main station serves as a starting point for any destination: *"In my head, my starting point is always arriving at the station. And then the first question is, how do I get to the next point where I really need to go? Then I actually start by looking at how to get there."* -P1.

Challenges and Possible Design Solutions

Analogously to the supermarket scenario, we present the challenges during city exploration with additional design solutions addressing each challenge. These design solutions are used to guide the visual cue design in the next Section.

Unexpected Objects and Changes: All participants regarded unexpected objects on their path as the biggest challenge during their travel. Especially since most obstacles are grey and thus there is little contrast to the grey streets. It was expressed by all participants that they wished obstacles such as poles, street lights, trash cans or benches were highlighted with a vibrant color. For instance, P1 mentioned how a bright red could make benches much easier to perceive: *"When I'm hiking, I always notice that there are sometimes these benches that are painted such a beautiful red. And then I always think 'Yes, that's how a bench should be'. I can see the contrast immediately. [...] Benches simply painted in contrasting colors, just colorful [and] bright would be great."* -P1. While P1 preferred the whole obstacle being colored by a vibrant color, P2 mentioned not wanting the whole object to be colored. Instead, they should just contain a little marking indicating their presence: *"It would actually be enough if there were just three or four yellow or orange stripes along the entire length [of the object] so that you know that there is a pole. It just has to be ensured that these poles, regardless of whether they are traffic lights, lanterns, or bollards, that there is somehow a high-contrast element around them."* -P2.

Design Solution C1: Highlight obstacles with vibrant color. Additionally, provide a less obtrusive obstacle highlight.

Sidewalks, Curbs, and Steps: Since most streets and sidewalks in urban cities are made out of asphalt, there is little contrast between them, as P3 put it: *"The curbs are usually just as gray as the road."* -P3. This makes it extremely difficult to recognize where a sidewalk ends and a drop-off occurs. Some sidewalks contain white tactile pavings which can also be perceived visually if they are bright enough. However, as P3 reported, they are only used in some places. Similarly, some stairs also contain white or yellow markings at the end of each step, however, not all stairs and some of the markings are too run down. Furthermore, P2 and P3 also mentioned little contrast between bike lanes and pedestrian lanes, or not enough markings signaling a shared lane: *"If the cycle path and pedestrian path are on the same level, i.e. if they share the same road, I've experienced that quite often, they're not easy to distinguish from each other, so there's no real separation between them. It should be better separated, also by color."* -P2.

Design Solution C2: Highlight curbs, edges of steps, or whole sidewalks in a color that contrasts car and bike lanes.

Inconsistencies in the Environment: As mentioned previously, helpful navigation features and markings are not always used throughout the whole city. Furthermore, these features are not always the same. For instance, P3 mentioned that tactile pavings differ from city to city or that bike lanes can be marked with different colors, depending on the city. This is additionally dangerous when one city uses e.g. red for bike lanes and another one red for pedestrian paths. As such, P1 also mentioned that the colors of any visual cue type should always be consistent and never change.

Design Solution C3: Provide consistent visual cues.
Also, let the user choose the colors.

Finding Entrances: Finding entrances was another challenge mentioned by all participants, especially for adjacent stores it can be difficult to identify the correct entrance. P2 wished for a better color-separation in this case: *"[...] for example, if there are 2 stores and they are next to each other and both share a platform or a step at the front and one entrance to the store is on the left and the other on the right and I want the left-hand store. There should be maybe a better color separation."* -P2. Similarly, P1 also reported wanting a strong contrast-rich color highlight for entrances: *"the entrance [should be] in a bright color, because that's what's relevant. "* P1. Furthermore, P1 provided the additional idea of having entrances highlighted with a glowing or blinking effect: *"[...] like when a string of lights comes on briefly around the door frame."* -P1. On the other hand, P3 preferred less usage of light but still mentioned the need to have entrances made more visible. P1 and P3 further reported challenges finding glass door entrances next to windows, making it difficult to distinguish between doors and windows. As a result, P3 mentioned that they often walk into glass doors because they are not visible enough: *"Glass or anything like that shouldn't be used with us visually impaired and blind people, because we bump into it very quickly."* -P3. They expressed a desire for some form of glass markers and to have the door outlined so they can recognize that it is a door and not an open space.

Design Solution C4: Highlight entrance borders or the whole door.
Additionally, provide an optional blinking effect.

Reading Signage: As was the case for the supermarket scenario, reading signage and labels in cities is also a challenge as they are either not big enough or because of a lack of contrast. This results in missing important information about the environment. As such, it can be difficult to recognize the correct building. Hence all participants expressed a need for bigger and more readable signage throughout cities. When asked what they wished was provided so they could better recognize for instance, a bakery, Participant P1 responded: *"Special lighting or glowing of all kind. Or illuminated pretzels, hanging over [a bakery]."* -P1.

Design Solution C5: Make bright and large logos and signs (potentially with added glow).

Illumination and Brightness: Another challenge discussed was the brightness and illumination. Just as for the supermarket scenario, all participants mentioned being extremely sensitive to overly bright visuals. P1 also mentioned the constant changes between dark and bright visuals being an added challenge as they have to constantly adjust their eyes.

Design Solution C6: Adjustable illumination and contrast.

Moving Objects and People: Similarly to the supermarket scenario, other people are a challenge when exploring cities as well. Additionally, cities have the added danger of cars and bicycles. This was expressed as one of the biggest challenges by all participants. However, as already mentioned for the supermarket case, we do not include moving obstacles in our VR design.

3.6.4 Summary

The biggest challenges in the day-to-day lives of visually impaired people come from not being able to perceive things correctly. After conducting our interviews we have gathered the following criteria that make perception difficult. The first major influence on the inability to correctly perceive things comes in the form of unexpectedness. This is due to either inconsistencies in the environment, such as unexpected obstacles or layout changes, or movement of people and vehicles. Everything that is not expected is harder to perceive and thus poses a challenge when trying to either avoid obstacles or find specific things.

Another difficulty with perception comes from things being too small, too bright, or having too little contrast. As such, tasks like reading text and finding specific products or entrances, are directly influenced by how small the text is, how much contrast is between the text/entrance and its background, or how much illumination is present.

In order to deal with the mentioned challenges, the participants of our interview reported various workaround strategies. These strategies come down to using a combination of unique features, familiarity, logic, and memorization. For instance, unique colors or shapes can help with the identification of specific objects, such as store logos or products. Being familiar with similar street or supermarket layouts can help logically deduce the layout of other streets and supermarkets. Or memorizing specific actions needed to reach a target, such as remembering the number of entrances or stairs, can be helpful when the target itself is hard to recognize. Other strategies involve orientation based on specific landmarks or points of interest, such as bus stations, and using non-visual senses.

3.7 Design Implications

Based on our findings and the information gathered by the research in Chapter 2, we define a set of guidelines for the design of visual cues in an urban city scenario.

Design Guidelines for Visual Cues:

For the design of the visual cues, we define the following three general guidelines:

1. **Consistency:**
   Visual cues should be used consistently throughout the city. We need to divide the landmarks or objects in the environment into categories based on the information that the visual cue needs to provide about them. The objects or landmarks within the same category should then be highlighted by the same type of visual cue throughout the city. For instance, all obstacles should be highlighted by the same cue.
2. **Provide Relevant Information:**
   Simultaneously to consistency within a category, the cues for different categories should be different enough in order to provide information to the user about which category the object belongs to. For instance, obstacles should have a different cue than entrances as they serve different purposes in the scene. Furthermore, the cue should be designed in a way that it provides the relevant information about an object. For instance, cues for points of interest should contain information about what type of point of interest it is. Meanwhile, for obstacle objects, it is typically not as important to know what specific object it is, i.e. whether it is a pole or a street light. The main purpose of the visual cue of obstacles is to draw attention to their location so they can be avoided.
3. **Adjustability to Different Needs:**
   The color, transparency, and brightness of the cues should be adjustable according to the different needs of the user. Furthermore, the visual cues should come in forms suitable for different visual capabilities. For instance, for people with central vision loss, the cue should be placed outside of the object, so that the cue can be better perceived when the user looks at the object. On the other hand, for people with peripheral vision, the cue needs to be placed directly on the object so that it can be perceived when the object is looked at. Hence, each category of cues should come in a few different variants from which the user can choose.

Design Guidelines for City Environment:

For the design of the city environment, we define the following three general guidelines:

1. **Realistic:**
   The scene should be realistic, containing small details, such as crosswalks, street markings, and various other street props that can be found in a real city. Additionally, as mentioned in the interviews, well-known logos of e.g. bakeries help with the identification even though they might not be directly readable. Thus well-known logos can contribute to realism and help with the identification of POIs.

2. **Contain Unique Landmarks:**
   Another feature that contributes to the realism of an environment is the inclusion of unique landmarks. Each part of a city is unique and should thus include props that can make this part identifiable e.g. by placing benches and trees in one area. Also, the buildings in the scene should be different from one another, e.g. have different walls, windows, or entrances.

3. **Only Static Objects:**
   The main point of a VR exploration is to use it as a pre-planning and training tool, i.e. it enables a safe exploration of a space. Thus gaining a cognitive map of a place can be done virtually before arriving at a real place. While moving obstacles, such as people and cars are mentioned as a big challenge by most visually impaired people, they do not contribute to the creation of a cognitive map of a place. Only static objects in the environment that can be remembered are relevant for cognitive mapping. Typically moving objects make the process even harder, as the attention shifts to avoiding them instead of focusing on the surroundings. Thus moving vehicles and people should not be included.

4. **Simple and Familiar City Layout:**
   The city layout should be simple, consisting of orthogonal and parallel streets, similar to most larger urban cities. Furthermore, the city should be structured in a logical manner, for instance placing clothing stores together, as can be seen in real cities.

4 Implementation

In this Chapter, we look at the design and implementation of the visual cues and the virtual city. First, we briefly go over the used technologies in Section 4.1. Afterwards, in Section 4.2, we present the design and creation of our visual cues. We follow this with the creation of the virtual city environments in Section 4.3. Lastly, we discuss the implemented user interaction in Section 4.4.

4.1 Technologies

Our implementation of the virtual city environment and the visual cues is done in the Unity[1] game engine with C#. We use Unity Version 2020.3.23f1 and to support the use of virtual reality content on VR headsets we use the Steam VR platform, which provides a variety of tracking and input systems. To enhance the visual design, we also use the Post Processing Package from Unity, which comes with different design elements such as color correction, different effects, or lens and camera settings. This package also provided the feature to control contrast and brightness, which we let participants adjust to their needs. For the VR hardware, we chose to implement and conduct the user studies with the HTC Vive VR Headset and its provided controllers.

4.2 Visual Cues

In the following, we present the design steps of our visual cues. Our design was guided by the *Design Solutions S1-S6* and *C1-C6* we investigated during the interviews in Chapter 3, and the resulting three *Visual Cue Design Guidelines* we defined thereafter.

4.2.1 Visual Cue Categories

In order to follow the first *Cue Design Guideline* for visual cues we need to define categories of visual cues based on what objects or landmarks they should highlight. As defined by the work of Jain et al. [JTC+23], we first divide the objects and landmarks in an environment into *Layout* and *Shape Information*. Based on the categorization of Brambring [Bra85], we further make a distinction for the *Layout Information* between *Obstacles* which need to be avoided, and *Points of Interest (POI)* used for orientation. *POIs* consist of either free-standing objects, for instance, a post box, or indoor/outdoor facilities, such as cafes. These two types need different visual cues. As reported by participants of the interviews in Chapter 3, finding entrances to different facilities can

[1] https://unity.com/

be a challenge. For this reason, we add an additional category of *Entrances* to POIs. This leaves us with four different categories for cues: *Obstacles*, *Points of Interest (POI)* (objects), *Entrances* (to POI), and *Shape Information*.

4.2.2 Provided Information of Visual Cues

Following the second *Design Guideline* for visual cues, we now define what information the visual cues should convey for each category. We present the needed information for each category in Table 4.1. Additionally, the table contains example objects for each category gathered from the conducted interviews and research of Chapter 2.

The category *Obstacles*, includes every static obstacle in the scene. Moving obstacles such as people or driving cars are not included since they do not contribute to the creation of a cognitive map. As defined by the framework of Brambring [Bra85], the main goal for obstacles is their detection. As such visual cues for this category should make obstacles detectable so that users can see their exact location and avoid them. Following the framework by Brambring [Bra85] further, for the *Points of Interest (POI)* category only detecting a POI is not enough. It is important to additionally know what type of POI it is. This means the user needs to know whether they are looking at a post box or an ATM. Therefore, this cue category needs to provide identification information in addition to detection. Furthermore, we also need to let users know where they can find potential *Entrances*. Thus for these types of POIs, detection information is needed. Lastly, for *Shape Information* the visual cue needs to provide identification information about areas that are meant for pedestrians and can safely be traversed. We call these areas *walkable areas*, and every other area a *non-walkable area*. Optionally, the cue should also provide additional identification information for distinguishing non-walkable areas that can and cannot be crossed. *Crossable areas* would thus encompass every area that can be crossed but is not meant for walking pedestrians, such as car lanes or bike lanes. *Non-crossable areas* would include any barriers in the path, such as walls, fences, or railings. Although fences and railings could technically be seen as *Obstacles* as well, we make their distinction by defining *Obstacles* as objects on the path that can be easily walked around. On the other hand, *Non-crossable areas* refer to a direct border or end of the path. Note, that the shape information category would also include information about stairs, however, we do not make stairs accessible for exploration in our VR prototype and focus only on ground-level exploration. Hence, any occurring stairs in our prototype are seen as a non-crossable area, as they cannot be walked through.

4.2.3 Visual Cue Design

Following our third *Cue Design Guideline*, for each category we provide at least two different options of visual cues with different salience. Since participants of the interviews reported color and high contrast as the most important visual features, our visual cues are mainly designed to convey information through color. However, some information could not be provided only through color alone. Following *Design Solution C3* and *C6*, we let the users choose the color and brightness of all cues according to their preferences and needs. In the following, we present all cues and their design process.

Category	Necessary Information	Examples
Obstacles (static)	Detection	*Benches, Trash Cans, Trees, Poles, Street Lights*
POI	Identification	*Post Box, ATM, Phone Booth*
Entrances	Detection + Logo Identification	*Shop, Cafe, Restaurant, Pharmacy, WC, Bus Stop, Park*
Shape Information	Walkable Area Identification Non-Walkable Area Identification (Non-Crossable Area Identification)	*Pedestrian Path* *Car Lane, Bike Lane, Bus Lane* *(Building Walls, Fences, Railings)*

Table 4.1: Visual Cues Categories and the necessary information they should provide. Additionally, examples for each category are given.

Obstacles

For the Obstacle category, we offer two types of visual cues, Highlight and Shadow. For the latter, we further provide two types, *outline* and *filled*. The three cases can be seen in Figure 4.1

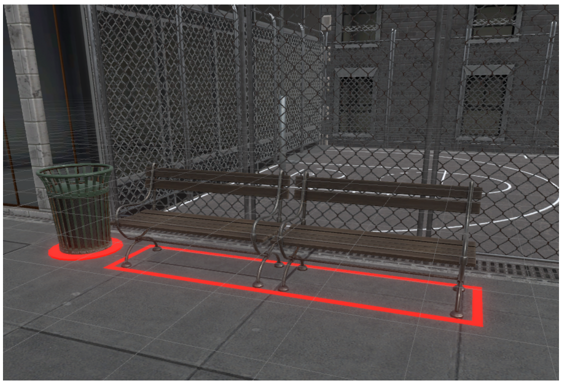
Highlight
The first type of visual cue for *Obstacles* is a simple coloring of the whole object, inspired by *Design Solution C1*. An example can be seen in Figure 4.1c. Since this cue is suited for object *detection*, due to the coloring of the object, the details inside can get lost, making it less suited for object *identification*. As the cue is only limited to the shape of the object, it may also be more suitable for peripheral vision loss and less for central vision loss.

Shadow
Following the *Design Solution C1* further, we provide a less obtrusive way to highlight an obstacle. Inspired by the idea of floor markings of *Design Solution S3*, the second type of cue marks the area of the object on the ground. As the object itself is not modified, only the location, width, and length of the object are provided. Thus it does not facilitate identification. Unlike the Highlight cue, the Shadow cue is less suitable for peripheral vision loss. However, it might be more detectable with central vision loss. The shadow cue comes in two forms, a *filled* shadow seen in Figure 4.1a, and a less salient version, *outline* shadow, seen in Figure 4.1b. The difference between these two options is only visible for objects with a shape that is larger above ground than on the ground area, such as benches with four legs For objects such as trashcans, both Shadow cue types are the same.

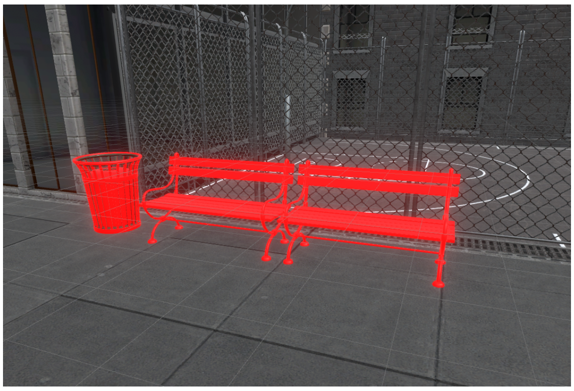
Points of Interest (POI)

Freestanding *POI* objects, such as an ATM, are also *Obstacles* that have to be avoided, hence we can reuse the same cue for *detection*. However, unlike *Obstacle* objects, *POI* objects need to be *identifiable*, thus a Highlight cue is not suited, as it makes object identification more difficult. Therefore, we only reuse the Shadow cue. To facilitate *identification*, we provide a new cue, Symbols. An example of an ATM POI object with both cues can be seen in Figure 4.2

(a) Filled Shadow Cue



(b) Outline Shadow Cue



(c) Highlight Cue

Figure 4.1: Visual Cues for Obstacles.

Shadow
We use the same type of shadow cue for *POI detection* as for *Obstacles*. We also provide the same option of either *filled* or *outline* Shadow, however, for most chosen POI objects there is no difference.

Symbols
To provide identification information for freestanding objects that do not have a clearly identifiable logo, we provide the option to add a Symbol cue showing the type of POI. These Symbol cues can be used in addition to the Shadow cues. Inspired by the needs of *Design Solution S2* we provide the option to place the Symbol cue either above the POI object, on the ground in front of it, or both. Furthermore, we also provide an optional blinking effect.

Entrances

As defined by the *Design Solution C4*, we provide two different forms of cues for *Entrances*, Filled and Outline. Since these cues are placed directly on the entrance they are less suited for central vision loss. For this reason, we provide an additional Symbol cue that is not directly placed on the

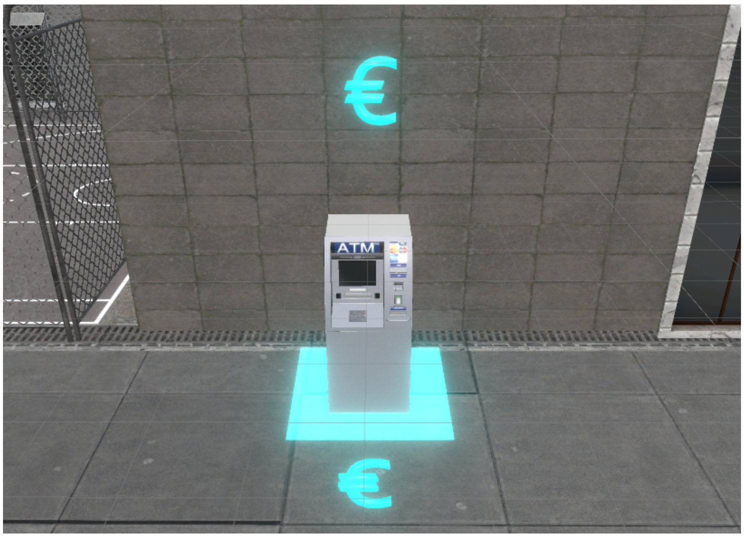


Figure 4.2: Visual Cues for Points of Interest Objects: Shadow and Symbol (top and bottom).

door, but instead above or in front of the entrance. The *Entrance* cues can be seen in Figure 4.3

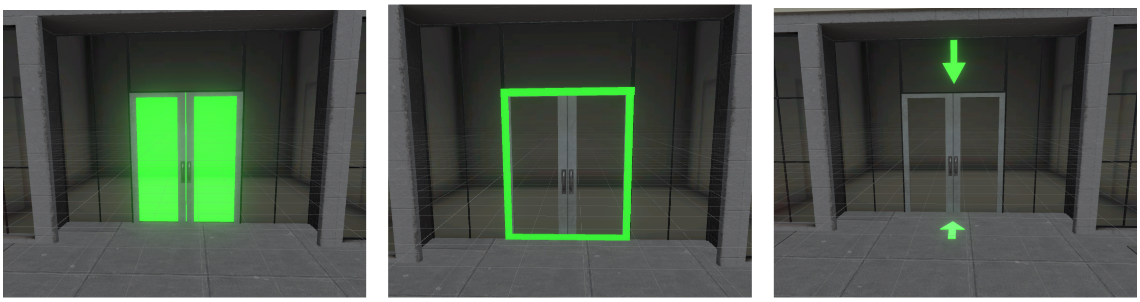
Filled
The first variant of the *Entrance* cue as defined by *Design Solution C4*, colors the whole door, similar to the Highlight cue for *Obstacles*. An example can be seen in Figure 4.3a

Outline
The second type of *Entrance* cue comes in the form of marking the outlines of the door, seen in Figure 4.3b. Similar to the two forms of the Shadow cue, the Outline cue provides a less obtrusive variant of the Filled cue.

Symbol (Arrow)
In addition to the other two cues, we provide an optional arrow Symbol cue. As with the other Symbol cues, we also allow the users to choose the place of the arrow to be either above the entrance, on the floor directly in front of it, or both. Since the Filled and Outline cues are less suited for central vision loss, the arrow Symbol cues can be used to provide information about the entrances. Following the *Design Solution C4* further, we also provide the option to have the arrow Symbol blink. An example of a top and bottom arrow Symbol cue can be seen in Figure 4.3c.

Shape Information

In order to provide information about walkable areas, non-walkable areas, and walls we provide two different cues which can be used either separately or in combination. Their design follows *Design Solution C2* and examples can be seen in Figure 4.4. Additionally, for both cues, we also added a white highlight to the crosswalks for better visibility.



(a) Filled Cue **(b)** Outline Cue **(c)** Arrow Symbols Cue

Figure 4.3: Visual Cues for Entrances.

Filled
Similar to the Filled cue for *Entrances*, this cue colors the whole walkable area, thus separating it from non-walkable areas. We present an example of this cue in Figure 4.4a. However, this cue alone does not provide information for differentiating between streets and walls (crossable and non-crossable areas).

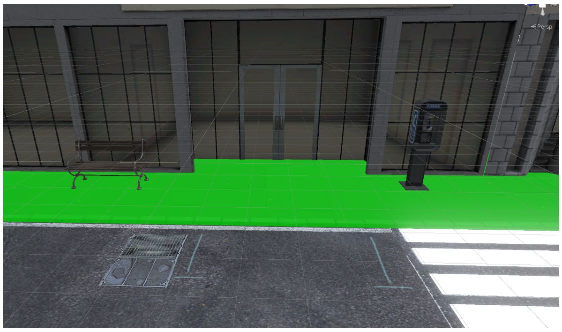
Outline
Further inspired by *Design Solution C2*, this cue highlights the curbs of sidewalks and walls bordering on the walkable area, and marking the non-walkable areas. The Outlines are colored in separate colors, depending on whether they are a street or a wall. This allows the user to additionally differentiate between crossable and non-crossable areas. Furthermore, in the case of crosswalks bordering on the walkable area, we use a dashed Outline to indicate their presence. We can see an example of this in Figure 4.4b. To make the walkable area more salient, this cue can be used in addition to the Filled cue, which can be seen in Figure 4.4c.

4.2.4 Visual Cue Implementation

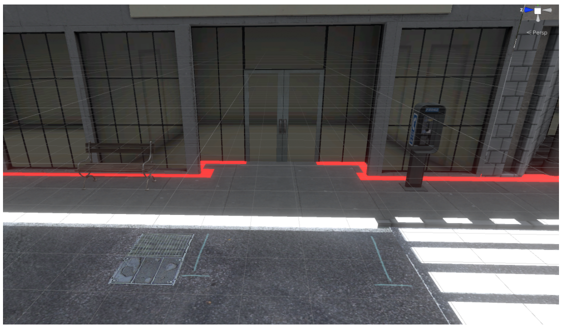
After presenting our visual cue designs, we briefly discuss their creation in Unity.

For the Symbol cues of the *POI* objects and the *Entrances*, we downloaded different shapes as prefabs from various websites[2][3][4][5] for free. The rest of the cues were created by using the available GameObjects by Unity. To allow a blinking effect for the Symbol cues we used the Bloom effect of the Postprocessing Package to give them a glow. The participants had the choice to either turn the blinking effect up or down to their liking. Furthermore, to follow *Design Solution C5*, we also made the shop logos and signs for the other POI brighter with the Bloom effect to make them more readable. Lastly, we also added glow to the white stripes of the crossings as well as the park gates, as these were pointed out to be less visible during the pilot study .

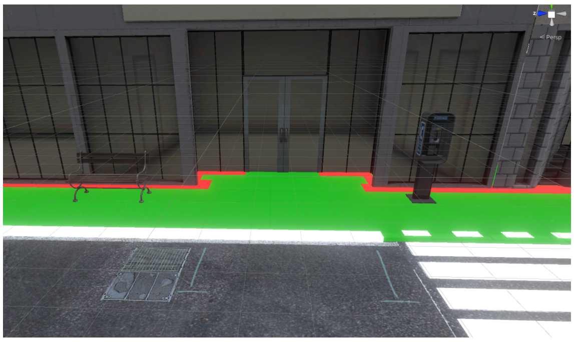
[2] https://sketchfab.com/feed
[3] https://www.turbosquid.com/
[4] https://www.cgtrader.com/
[5] https://free3d.com/



(a) Filled Cue



(b) Outline Cue



(c) Outline and Filled combined

Figure 4.4: Visual Cues for Shape Information.

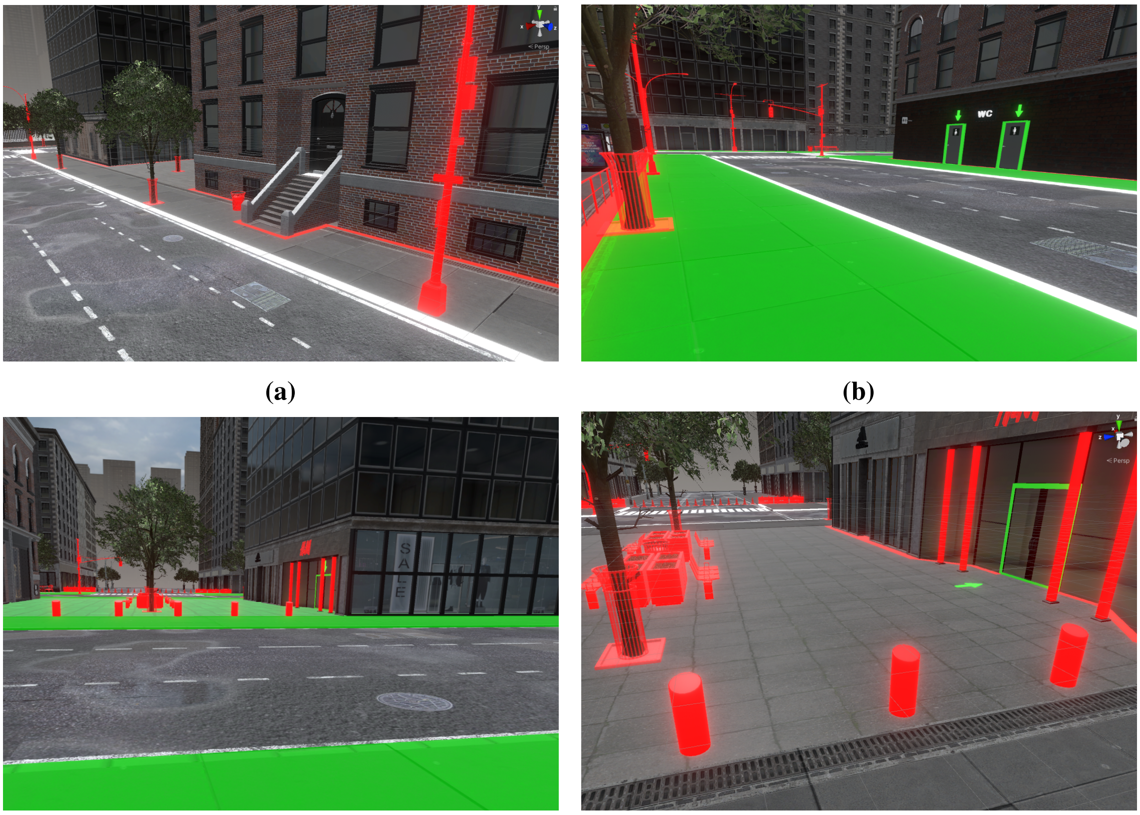
In Figure 4.5, we show a number of further examples of what the combination of each cue category can look like.

4.3 Virtual Cities

In the following, we present the creation of the virtual city environment we used for our user study in Chapter 5. For our user study, we needed the following scenes:

1. City 1 for training without visual cues
2. City 2 for exploration with visual cues
3. City 2 for searching POIs with visual cues

The goal was to create two similar cities of the same size, similar layout, and containing the same POIs, only rearranged.



(a) (b) (c) (d)

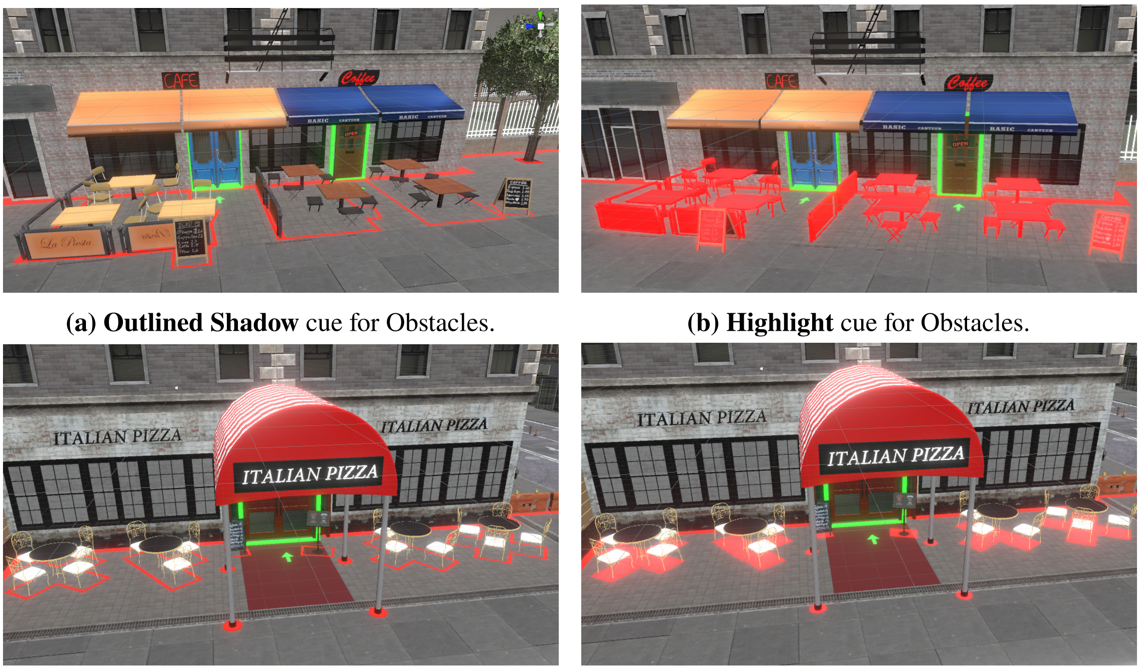
Figure 4.5: Examples of different visual cue combinations. **Highlight** cue for Obstacles: **(a) - (d)**. **Outline** cue for Shape Information: **(a), (b), (d)**. **Filled** cue for Shape Information: **(b), (c)**. **Outline** cue for Entrances: **(b), (c), (d)**. **Top Symbol** cue for Entrances: **(b). (c)**. **Bottom Symbol** cue for Entrances: **(d)**

4.3.1 Chosen POI

The first step of the creation process was to choose a set of POIs from our previously defined Table 4.1. Since we use the same POIs for both environments, we need to define this set only once for both environments.

The first key POI to be included in our city was a main station, as participants stressed the importance of public transport in our conducted interviews in Chapter 3. Since they mentioned using the main station as a starting point when exploring a city, we decided to also use a **Main Station** as a starting point for both cities for the training, exploration, and search tasks. The built **Main Station** is seen in Figure 4.7b. Then as a free-standing POI object, we included an **ATM**, seen in Figure 4.2. Furthermore, we added a **WC**, (Figure 4.5b), an **H&M**, (Figure 4.5d), a **Pizzeria**, (Figure 4.6), and two adjacent **Cafes**, (both seen in Figure 4.6). Lastly, to add more variety to the city, we added a large **Park** with a gate as an entrance and a tall fence surrounding it, (Figure 4.7a).

Initially, we built a larger City 1 and 2 containing more POIs. However, after conducting



(a) Outlined Shadow cue for Obstacles.

(b) Highlight cue for Obstacles.

(c) Outlined Shadow cue for Obstacles.

(d) Filled Shadow cue for Obstacles.

Figure 4.6: Outline & Bottom Symbol cues for Entrances and different Obstacle cue variants.

our pilot study, we downsized City 2 and the number of POIs for the user study. Nonetheless, we kept City 1 as it was, since we ended up using it mostly for training instead of a direct exploration comparison.

Large Prototype

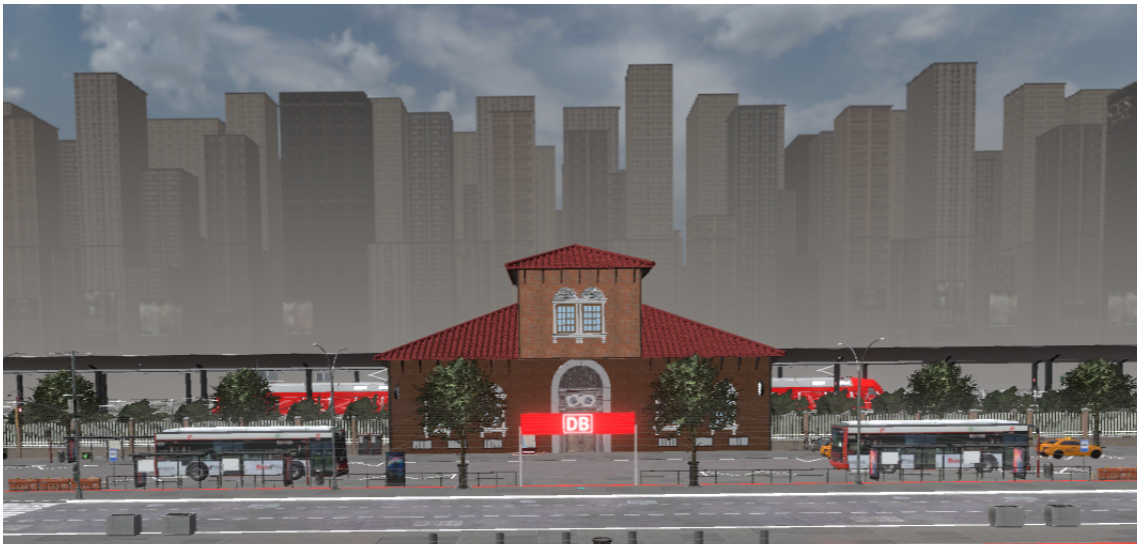
In the following, we go over the additional POIs we added in City 1 and the larger City 2 prototype. Apart from the **Main Station**, we also included a separate **Bus Stop** as another free-standing POI. Then as additional free-standing POI objects, we included a **Post Box** and a **Phone Booth** and placed them in front of a **Post Office** and a **Vodafone** store for better recognizability and realism. Additionally, we added a **Bank** behind the **ATM**. Next to the **H&M** store, we also included additional **Adidas, Puma, Nike, Dior, Apple**, and **Samsung** stores. Lastly, we also provided a **Pharmacy** and a **Hotel**. In Figure 4.8 we show a number of these POIs that were created for the larger prototype.

4.3.2 Creation of POIs

After choosing which POIs to include in our city, the next step was to create them in Unity. As the main building block for the city creation, we used the "NewGen:Urban"[6] Asset. This asset contains a set of different building blocks for streets, path walks, and buildings. It also contains a number of

[6] https://assetstore.unity.com/packages/3d/environments/urban/newgen-urban-229501

(a) Park POI.



(b) Train Station.

Figure 4.7: Train station and park POI in City 2.

(a) Bus stop POI. (b) Dior store POI.

(c) Post office and post box POIs. (d) Vodafone and phonebooth POIs.

(e) Pharmacy POI. (f) Hotel POI.

Figure 4.8: POIs in the large prototype that were excluded in the smaller prototype.

different city props, such as traffic lights, trees, benches, trash cans, and others. For more variety, we used a number of different websites[7][8][9][10] to download free prefabs.

To follow the first *City Design Guideline*, we downloaded well-known logos of the clothing store POIs, and a Pharmacy sign, to provide realism. Other signage, such as the Hotel, Pizzeria, and WC signs also came from these websites. The German Post Office logo, as well as the shopping windows, were created by downloading free stock images and using them as textures. Similarly, the ATM, Post Box, and Phone Booth objects were also downloaded for free from these websites. As a

[7] https://sketchfab.com/feed
[8] https://www.turbosquid.com/
[9] https://www.cgtrader.com/
[10] https://free3d.com/

participant mentioned recognizing restaurants based on outdoor tables and chairs, we downloaded separate 3D models of chairs and tables to place them in front of the Pizzeria and Cafes. While the "NewGen:Urban" Asset contained train tracks, it did not provide any additional parts for the Main Station. Therefore we used the same aforementioned websites to download different parts from which we built our Main Station. As such, the separate bus stations, buses, bicycles, the station building, the parking lot, the parking garage, and the kiosk were all built from separately downloaded objects. After the pilot study, we also added a "DB"-banner to make the Main Station more recognizable. This could be seen as an additional *POI* Symbol cue, as we did not provide any Main Station visual cue prior to the pilot study. To add more variety to the scene and follow the second *City Design Guideline*, two separate buildings were also downloaded which differed from the buildings provided by the "NewGen:Urban" Asset. Additionally, we also downloaded different doors for the Pizzeria, Cafes, and the Dior store to add further variety to the limited doors provided by the "NewGen:Urban" Asset. We then added crosswalks, trees, benches, and other street props from the "NewGen:Urban" Asset to make the scene as realistic as possible. Various obstacles that were mentioned in the interviews were also placed in the scene. These consisted only of static ones, as defined by our third *City Design Guideline*. The "NewGen:Urban" Asset also provided a Park with a fence, for which we additionally downloaded a gate. After the pilot study, we added white highlights to the fence as the pilot participant suggested.

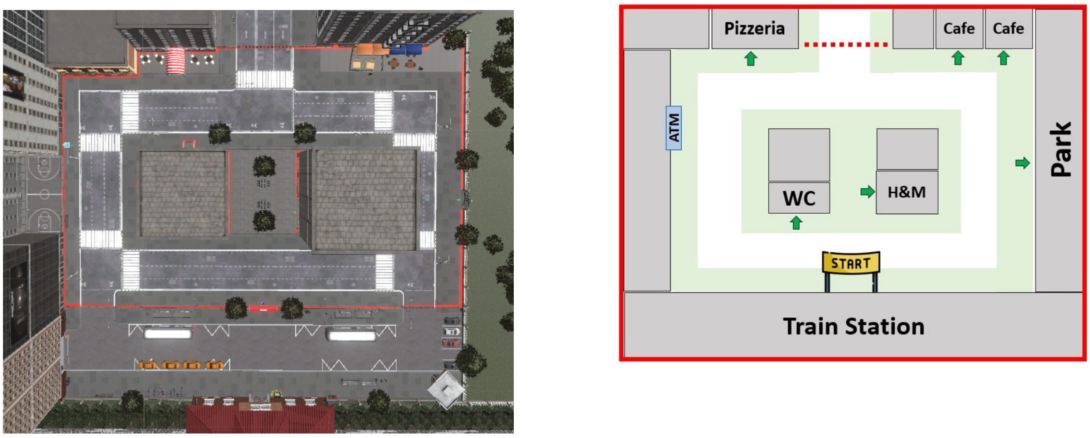
4.3.3 City Layout

Following our fourth *City Design Guideline*, we designed a simple city layout, consisting of a quadratic form, with orthogonal and parallel streets. To follow a logical structure we placed similar POIs close together such as the clothing stores in the center, and the Pizzeria and Cafes on the same street. To further limit the city size, the Main Station was not made accessible and only served as a starting point and background.

In Figure 4.9, we see the layout of the small City 2, used in the user study for the exploration and search task. On the left in Figure 4.9a we show the scene view, and on the right, in Figure 4.9b, we show a drawing of the layout containing all POIs. The entrances to the POIs are marked with green arrows. As mentioned, we initially built a larger City 2, which was subsequently used for the pilot study. The layout of this larger prototype can be seen in Figure 4.10, with the same two layout views. For City 1, we rearranged the layout of the larger City 2, while maintaining its simple quadratic form and logical structure.

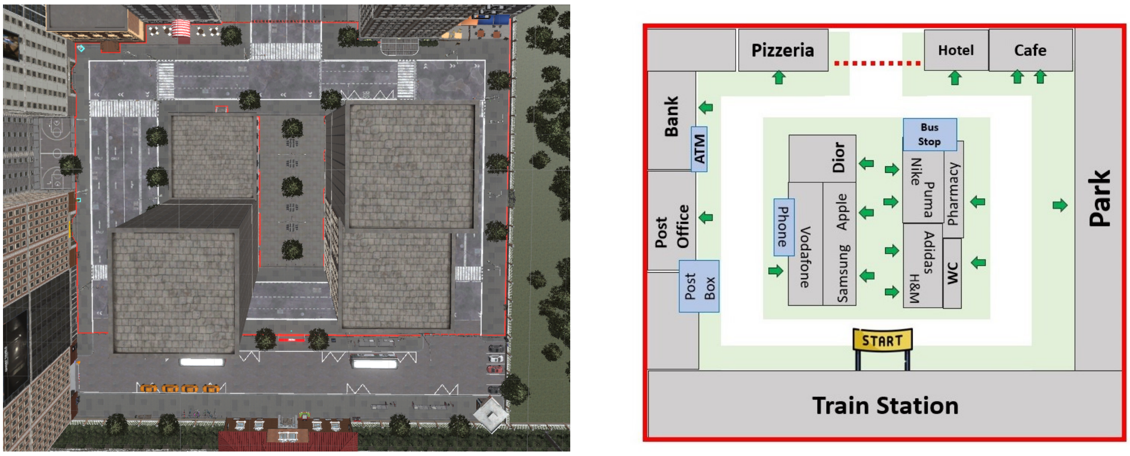
4.4 User Interaction

Since our users are people with visual impairment, their interaction with the system was held to a minimum. This means starting the task, clicking on visual cues during selection, or adjusting brightness was done by the study conductor. As such there was not a need for any user interface. The user interaction was limited and consisted only of teleportation locomotion using the controllers. In Figure 4.11 the left HTC Vive controller and the action of each button is shown. The right controller has the same functionality as the left controller.



(a) (b)

Figure 4.9: Layout of City 2 used in the user study.



(a) (b)

Figure 4.10: Initial layout of City 2 prior to downsizing.

4.4.1 Locomotion

The headset tracks the user's position and displays it accordingly in the VR environment, thus theoretically the user could walk in the virtual environment by walking in real life. However, due to safety and lack of available space, this was not possible for the user study, hence we had to implement a form of locomotion where the user would not have to move in the real space. Initially, we tried to implement a continuous locomotion using the trackpad of the controller to determine the direction. However, this quickly led to dizziness and motion sickness, hence why we could not keep continuous locomotion for our user study.

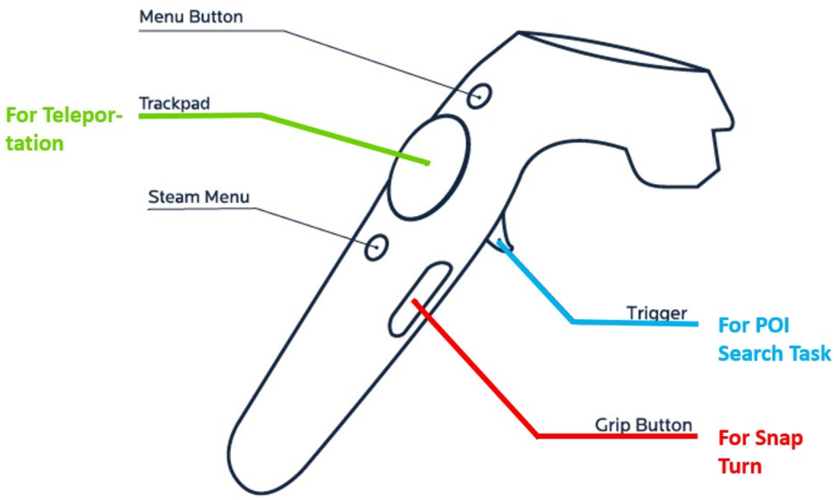


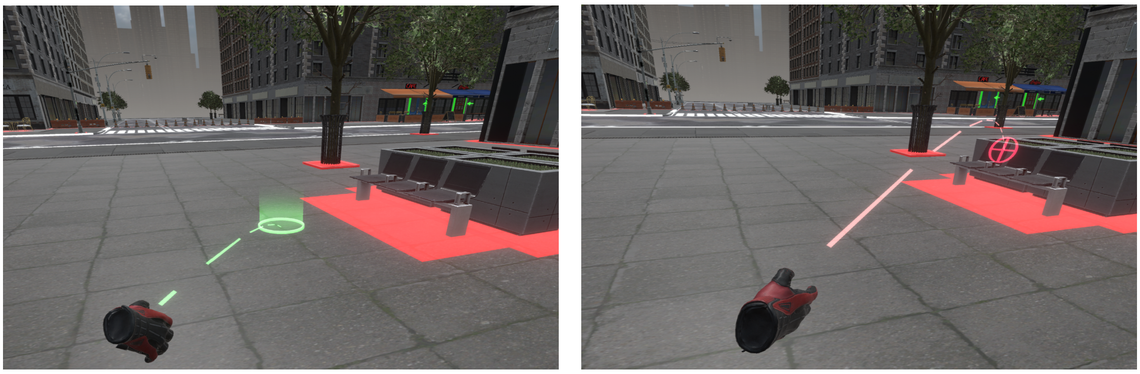
Figure 4.11: Button usage of controllers.

4.4.2 Teleportation

To counter-act motion sickness, we chose to implement a teleportation locomotion instead. Although this is not ideal, as teleportation can lead to disorientation, we had to prioritize the health and well-being of the participants. A user teleportation was already provided by Steam VR. We chose to use the trackpad button for teleportation as it is the largest one on the controller. The teleportation works the same for both the right and left controllers. While pressing the trackpad button down, a virtual ray shoots out of the controller and ends on the ground. The end of the ray is marked by a circle on the ground, showing where the user will get teleported if the pressed button is released. The teleportation ray is either green if teleportation is possible, or red if not, e.g. when trying to teleport on an object. In Figure 4.12a, we see the teleportation ray of a valid teleportation point, and in Figure 4.12b one for an invalid point, placed on a bench obstacle.

4.4.3 Snap-Turn

Since the teleportation only moved the user to a different location, they still had to move their head to change their direction in the VR environment. Due to the headset being connected to a cable, this led to some difficulties when a larger turn was necessary, i.e. when users wanted to turn around 180°. As a result, we added a snap-turn option to the grip button on each controller, with the right controller allowing a clockwise turn and the left controller a turn in the opposite direction. The initial turn degree was set to 30°, this could however be adjusted if the participant wanted. The participants were encouraged to only use it for cases where they have to make bigger turns, in order



(a) Valid teleportation point.

(b) Invalid teleportation point.

Figure 4.12: Teleportation Rays.

to avoid additional disorientation.

4.4.4 Search Task

Lastly, for the search task, we implemented a feature where the user had to press the trigger button on either one of the two controllers when they arrived at the searched POI. If the POI was correct, a large green checkmark would appear in front of them accompanied with a register cash sound to convey success. In the larger prototype, we also implemented the case of a cross and buzzer sound appearing in case the user was at the wrong POI. However, this case was left out in the smaller prototype. In case participants took too long for the exploration and subsequently did not encounter every POI in the city, we would need to change the pre-determined POI search to contain only the encountered POI. For this reason, we left out the cross signal entirely and manually wrote down cases when participants navigated to the wrong POI and informed them about it ourselves. The checkmark signal is shown in Figure 4.13.

Figure 4.13: Checkmark signal when correct POI was found.

5 User Study

To evaluate our visual cues, presented in Chapter 4, we conducted a user study with people with varying degrees of visual impairment. In this chapter, we present the user study design, starting with the research questions guiding our study, discussed in Section 5.1. We follow this with a detailed description of the procedure in Section 5.2. Here, we additionally discuss what data was gathered during the study and how it was analyzed in order to gain insight into the previously defined research questions. Following this, Section 5.3 briefly presents the apparatus of our study. In Section 5.4, we discuss our pilot study and lastly, in Section 5.5, we present the participants. The corresponding results of this study are discussed in Chapter 6.

5.1 Research Questions

The goal of this study is to evaluate the efficacy of the presented visual cues for orientation. Since the spatial orientation of an individual is guided by their mental representation of a place, i.e. the cognitive map, we investigate the cognitive mapping process of an unfamiliar virtual city scene augmented with our visual cues. In this context, we formulate the following research questions:

- **RQ1:** How well are participants able to build and use an allocentric cognitive map of an unfamiliar city given our visual cues?

  More concretely we investigate the following:
  (a) How well do the participants understand the spatial layout of the city?
  (b) How well do participants understand the locations of the POIs?
  (c) How well do participants know the routes to each POI from different locations?

- **RQ2:** How helpful are the visual cues for building and using this cognitive map?

  More concretely, we investigate the following two aspects of our presented cues:
  (a) How helpful is the information highlighted by the cues (i.e. the chosen cue categories)?
  (b) How well do the visual cues convey the needed information?

5.2 Procedure

In the following, we go over the procedure of the user study, first presenting general information about our setup, then a description of the study tasks, and lastly we discuss the taken measurements.

5.2.1 General Information

The user study was conducted in person in the VR Lab of the VISUS building. It consisted of tasks performed in VR, as well as an interview portion containing questions about the participant's experiences. The average length of the study was around 1.5 hours and the participants were compensated with 12€ per hour and provided with beverages. A consent form and data privacy form were given to each participant beforehand. After the participants signed the consent form, we explained the process of the study and encouraged them to ask questions at any time if something was unclear. During the VR tasks, each participant was free to take a break at any time. We also asked participants to inform the study conductor about any potential discomfort during the VR Headset usage. Besides one report of the VR headset getting a little heavy over time we did not get any reports about other factors of discomfort and none of the participants needed a break during the VR task segments. Additionally, participants were also informed that for the asked questions during the study, they could choose not to answer any question at any moment, however, this did not occur for any of the five sessions. The sessions were recorded with the consent of all participants.

5.2.2 Study Tasks

After initial demographic questions, the study started with a VR training task in City 1 and the selection of the presented visual cues. Following this, we let participants perform two VR tasks in City 2, each followed by a separate round of questions. In both City 1 and 2, the starting point of the participants was in front of the Main Station POI, with their backs facing it. In the following, we discuss each part of the study in detail.

1. **Explaining Teleportation & Controller Usage:** Before we put participants into the VR scene we briefly explained how they could move through the scene and what buttons were needed on the controllers. Participants P3, P4, and P5 were also given the snap-turn option for the controllers but we encouraged them to only use it sparsely, such as in cases when they needed to turn around 180°. For participants P1 and P2 we did not yet provide the snap-turn feature and had to additionally move the cable around them to prevent it from getting tangled.

2. **Training in City 1 without Cues:** To let the participants get accustomed to the teleportation locomotion we let them explore City 1 without any visual cues, starting at the main station. Upon starting the scene, the participants were given a description about where they were located and then asked what they could see. This served to gain an understanding of the individual vision level of the participant and to determine how much help they might need during the tasks. We also asked if they wished to adjust the brightness and contrast of the scene. The duration of this step was left to the participant, but in general, this did usually not exceed 10 minutes. After the participants were sufficiently familiarized with the controller usage, we turned off the scene and suggested either a break or to continue with the next step.

3. **Choosing Visual Cues:** The next step consisted of showing the participants the available visual cues and letting them choose and customize them to their liking. For this, participants were presented with an example for each visual cue category. We first described what was present in front of them going over every single category, i.e. the *Obstacles, POIs, Entrances*

and *Shape Information*. During this, we presented each visual cue option of this category and encouraged them to choose a different color and adjust the brightness of the cue. Additionally, for Symbol cues, the participants were given the option of a blinking effect. After choosing the visual cues the participants were asked if they wanted to either take a break or to continue with the next step.

4. **Exploration Task:** After the preferred cues were chosen, the participants were put into City 2, containing the chosen visual cues. This city is presented in Figure 4.9 of Chapter 4. Starting once again at the Main Station, the task was for the participants to explore the city and familiarize themselves with the available POIs and layout, i.e. acquire a cognitive map. Similarly to the prior steps, the participants were given the option to have the brightness and contrast adjusted to their liking. Additionally, the color and brightness of the cues could be adjusted at any time as well in case necessary. After starting the application, the participants were once again explained where they were located. During the exploration, the participants were encouraged to report what they could see and recognize and ask questions if they had any problems. As the perception levels of the participants varied, we tried to adjust our given support individually to each participant. The duration of the exploration was generally left to the participant, however, we made sure that each participant walked through each part of the city and encountered each POI before ending the exploration. Nonetheless, none of them asked to end the exploration before they were confident that they saw everything in the city. The only exception was P1, who showed more difficulty exploring the city. Due to time constraints, we ended P1's exploration task after about 30 minutes despite them not having visited every POI. The asked questions and the following search task was then adjusted to this exception.

5. **Questions I:** After the exploration task, participants were asked a mix of different open and closed questions and to rank the presented cues on their efficacy. The asked questions are discussed in more detail in the next subsection.

6. **Search Task:** The last VR task consisted of searching for the previously encountered POIs. For this, participants were once again starting in front of the main Station in the same city as in the exploration task, City 2, with the same visual cues. We then asked them to find the first POI. Once they found it, participants had to press the trigger button, upon which a green checkmark signaled to them that they were successful. Once they received the checkmark, the participants were then told the next POI they should find. The searched POI were ordered so that the overall search path was held relatively short and easy and their order varied slightly between participants. All sequences started with the WC followed by the H&M entrance. Afterwards, the sequences continued with either one of the following: the Pizzeria, then the ATM, and lastly one of the two adjacent Cafe entrances; or first one of the two Cafes, then the Pizzeria, and lastly the ATM. For both options, the optimal search path over all POIs has the same length. The exception was made for P1, who we only asked to find the only POI they encountered during their exploration, i.e. the H&M entrance, and left out the rest. During the search task, the participants were notified in case they navigated to the wrong POI and told to keep looking.

7. **Questions II:** Similarly to the first question round, we asked the participants a mix of different open and closed questions, and to rank the presented cues on their efficacy regarding the search task. Here, we additionally let participants answer a NASA-TLX questionnaire.

5.2.3 Measurements

To get answers to our previously defined research questions, we combine qualitative feedback with different task performance measurements of the participants. While all gathered data is used for both research questions, for RQ1 we mainly analyze task performance measurements of the participants, and for RQ2 we focus primarily on qualitative feedback.

Completion Time

The first aspect of task performance we look at are the completion times. Here, we measure the following:

1. **Exploration Time:** How long did participants need to explore the whole city?
2. **Search Time:** How long did participants need to find the target POIs?

Since the participants have different levels of remaining vision, their performance times may vary drastically. With the measured exploration time we can gain insight into which participants might have had the most difficulty during exploration due to their vision. Comparing the exploration time to their search time, we can then analyze how fast participants could accomplish the search task given their prior difficulties during exploration.

Path Tracking

In addition to the completion times, we investigate the path the participants took when searching for each POI. Here, we look at the following:

1. **POI Search Sequence:** Did participants navigate to the correct POI?
2. **Shortest Route:** Did participants take the shortest route to each target POI (i.e. no unnecessary roundabout ways)?

With a good cognitive map, we can navigate to a target destination without having to walk through the whole city searching for the target, meaning we know direct routes to the target from different locations. As such, we can evaluate whether the location of the correctly found POI was found due to an active search or whether participants took direct routes to them. Furthermore, a good allocentric cognitive map is needed for finding the shortest route to the target from any location. The VR city layout is built in a way where there are at least two different paths leading to each POI, with one optimal path existing for each POI. Thus, by tracking if participants took the shortest route to a target location, we can further investigate if they were able to build an allocentric cognitive map.

Questions on Cognitive Mapping

In addition to analyzing the measured task performance on the cognitive mapping success, we also ask the participants about their own subjective experience during the process. After each of the two tasks, the participants were given three different statements, which they were asked to rate with a Likert-Scale of 1 to 5 (with 1 representing „I strongly disagree“and 5 „I strongly agree“). These statements consisted of the following:

Questions I: Exploration Task

- **Mental Image:** I was able to create a mental image of the city scene.
- **Layout:** I understood the layout of the city scene.
- **Detours:** I am able to find detours to given spots (if the spot can be reached with more than one path).

Questions II: Search Task

- **Remembering POIs:** I knew the location of the target POI already through the prior exploration.
- **Searching POIs:** I did not need to actively search for the target POI.
- **Success Searching:** I was able to successfully navigate to the target POI.

NASA-TLX Questions:

To gain insight into the workload of the search task, we also asked the participants a set of six NASA-TLX[1] Questions, consisting of *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort*, and *Frustration*.

Visual Cue Ranking:

After each of the two tasks, we asked the participants to rank each visual cue category on how helpful they were for the given task. For this, we also use a Likert-Score of 1 to 5 (with 1 = not helpful at all, and 5 = extremely helpful). Additionally, we also asked participants to state which visual cues they found the most helpful during the *Exploration* and *Search* tasks separately. To get more detailed feedback we put the Symbol cues from the *POI objects* and *Entrance* categories into an additional separate category, resulting in the following visual cue categories: *Obstacles, POIs (objects), Entrances (to POIs), Symbols* and *Shape Information*.

[1] https://humansystems.arc.nasa.gov/groups/tlx/

Qualitative Feedback

We also ask a set of open questions after each task, consisting of the following:

- Which information or parts of the city did you use for orientation/ navigation to the target?
- Which information highlighted by the cues was the most helpful?
- What were the biggest challenges?
- What information or part of the city would be beneficial to have additionally highlighted with cues, or was not efficiently highlighted with the cues?

5.3 Apparatus

- *VR Equipment:* We used the HTC Vive Headset and its accompanied controllers for the study. The controller usage is explained in Section 4.4 of the Implementation Chapter 4.

- *Software:* We presented participants with our Unity prototype of VR environments that mimic urban settings with various visual cues designed for orientation. The brightness and contrast of the presented VR scenes were adjusted to the participants needs. We present our VR prototype in more detail in the Implementation Chapter 4.

- *Data Collection Tools:* The completion times and path tracking data were recorded by our VR application. We read the questions mentioned in the previous section to the participants and used audio recording devices and observation notes to collect their feedback. The recorded audio was then transcribed and analyzed.

5.4 Pilot Study

Since we only had the interview feedback but no additional input from visually impaired people during the design phase, we needed to test whether our study design was overall feasible before we could conduct our real study. For this, we recruited a pilot participant with a cone-rod dystrophy and a self-reported remaining vision of 10% - 20 %, to test our prototype. Similar to the real study, the participant was compensated with 12€ per hour and given a consent and data privacy form to sign. We did not take any direct measurements for this pilot study, instead, we focused on gathering qualitative feedback about the design of the city and the visual cues.

First, we showed the participant the first city without visual cues and let them try out the teleportation. While we first intended on having them explore the whole city without the cues, this was not possible as they could perceive very little and subsequently, we had to end the exploration time due to time constraints. Following this, we showed them the available visual cues. After selecting their preferred options for cues, the pilot participant was then shown the second city with visual cues which they then explored. During this, we gathered feedback on what they could perceive, what was helpful, or what was challenging.

Here, we gathered that the city layout was too large as we did not have time to let the participant explore the whole layout. As a result, we scaled down the size of the city and the number of POIs for the real study. Additionally, following further feedback we made logos and signage in the city brighter and added a white glow to the street crossings, as well as the park railings to make them more detectable.

Originally, we planned for participants to first perform the same exploration and search task in the city without visual cues in order to get a direct comparison of the performances with and without cue help. However, the pilot participant could not recognize anything in the city without visual cues. Hence, we could not make a direct comparison. Instead, we kept the focus on acquiring insight into the efficacy of the visual cues through direct user feedback paired with their performance of the search task.

Note: While in the later real study, most participants were able to recognize the city without visual cues, this was not the case for all participants. Hence in order to keep the study setup consistent, we kept the change nonetheless and used City 1 without cues only as a training ground.

5.5 Participants

For our study, we recruited five individuals with varying degrees of visual impairment. The background information of participants about their age, gender, diagnoses, remaining vision, and self-reported O&M skills is presented in Table 5.1. Among the participants, three identified as female, P2, P3, and P4, and two identified as male, P1, and P5. The age of participants ranged between 25 - 59, with P4 being the youngest and P2 the oldest. Their self-reported remaining vision varied between 3% - 15%, with P3 having the lowest of 3%, P2 the highest of 10% - 15%, and the rest varying between 8% - 10%. Additionally, two participants, P1 and P2, reported a limited Field of View (FOV) with P2 stating their FOV being between 5°- 7° and P1 less than 5°. The rest of the participants, P3-P5, did not report any FOV limitations. Both participants P1 and P2 also reported the same diagnosis of retinitis pigmentosa, with P1 additionally stating a color blindness. While participants P2-P5 mentioned slight difficulties differentiating colors if they were too similar, they were able to differentiate the colors they chose for the visual cues. In contrast, P1 reported not being able to distinguish the colors of individual visual cues, however, they could recognize the presented cues. The diagnoses of the rest of the participants consisted of an Idiopathic intracranial hypertension of P4, a Cone rod dystrophy of P5, and an Autosomal dominant optic atrophy (Kjer's type) of P3. The most commonly used travel aid was the long cane, as reported by P1-P4. Other used aids included a smartphone for zooming or screenreading, used by P4 and P5, and edge filter glasses worn by P2 and P3. Additionally, P3 also reported carrying a magnifying glass. Their self-reported O&M skills ranged between 2.5 - 4.5 on a scale of 1 to 5, with 5 being the best. The highest ranked O&M skills of 4.5 were given by P5, followed by a 4 given by P4. The lowest scores of 2.5 and 3 were given by P2 and P1 respectively, and participant P4's score laid in the middle with a 3.5.

Participant	Gender	Age	Travel Aids	Diagnosis	Remaining Vision	O&M skills (5 = best)
P1	male	58	long cane	Retinitis pigmentosa	10% - 15% left eye (less than 5° FOV)	●●●○○
P2	female	59	long cane, edge filter glasses	Retinitis pigmentosa	10% right eye (5°- 7° FOV)	●●◐○○
P3	female	48	long cane, edge filter glasses, magnifying glass	Autosomal dominant optic atrophy (ADOA) Kjer's type	8%	●●●◐○
P4	female	25	long cane, smartphone, screenreader	Idiopathic intracranial hypertension (IIH)	3% left eye	●●●●○
P5	male	36	smartphone for zooming	Cone rod dystrophy	8%-10%	●●●●◐

Table 5.1: List of user study participants and their *gender; age; daily travel aids; diagnosis; remaining vision;* and their self-reported *orientation mobility skills* on a scale of 1-5, with 5 being the best.

6 Results and Discussion

In this chapter, we present the results of our conducted user study. In the following, we present the results of each measurement separately, followed by a summary of what insights we can gather for our previously defined research questions. First, we present which visual cues participants chose for each cue category in Section 6.1. Following this, we start with the first gathered results, the completion times in Section 6.2, followed by the path tracking results in Section 6.3. Next, in Section 6.4 we focus on how participants perceived their task performance regarding cognitive mapping and the resulting workload. Afterwards, in Section 6.5 we look at the visual cue rankings of participants. Lastly, we present the qualitative feedback in Section 6.6.

6.1 Selected Visual Cues

Before we look at the results of the user study, we briefly present the visual cues each participant chose during the user study. In Table 6.1 we show the type of cue selected for each category, *Obstacles, Entrances, Shape Information* and *Symbols*. We also show whether participants chose to use the blinking option for the *Symbol* cues. Each of the visual cues can be seen in Chapter 4. Note that the visual cues shown there are captured in their default state, i.e. before their adjustments based on participants' preferences. Thus, the visual cues picked by participants typically varied in color and brightness between participants.

From each visual cue category, every type of cue was picked at least once, with the exception of the *filled* Shadow cue for *Obstacles*. Overall, the Highlight cue for *Obstacles* and the Outline cue for *Shape Information* seem to be the most preferred ones, as they were picked by four out of

Participant	Obstacles	Entrances	Shape Inform.	Symbols	Symbol-blinking
P1	Highlight	Filled	Outline	top and bottom	on
P2	Highlight	Filled	Outline	top and bottom	off
P3	Shadow (outlined)	Outline	Outline	bottom	on
P4	Highlight	Outline	Filled	top	on
P5	Highlight	Filled	Outline	top	on

Table 6.1: Visual Cue types each participant picked during the study for each of the cue categories.

Participant	Exploration Time	Search Time
P1	25min 10s	6min 12s

Table 6.2: Exploration Time for a portion of the city and Search Time of the H&M entrance of participant P1.

Participant	Exploration Time	Search Time
P2	21min 1s	4min 11s
P3	10min 45s	4min 38s
P4	32min 22s	4min 10s
P5	11min 51s	3min 2s
Mean ± SD	**19 min ± 8min 41s**	**4min ± 0min 35s**

Table 6.3: Exploration and Search Times of participants P2-P5.

five participants. Similarly, four participants also enabled *Symbol-blinking*. For the *Entrance* cues, the picked options varied slightly more. Nonetheless, the Filled *Entrance* showed to be favored slightly more. Participant P3 seemed to prefer the placement of the visual cues on the ground, as they were the only one who picked the Shadow cue for *Obstacles* and chose to have the *Symbol* cues only on the ground. The rest of the participants opted for the *Symbol* cue being on the top. Additionally, participants P1 and P2 chose to have the *Symbol* cues on both the ground and on top, which could be attributed to their limited FOV, and as such not being able to instantly see the *Symbols* when they are not directly looking at them.

6.2 Completion Time

The first measurements we analyze are the completion times of the performed study tasks. In Table 6.3 we present the time participants P2-P5 needed to *explore* the whole city and *search* for all POIs. Since P1 could not finish exploring the whole city and subsequently only performed a *Search* task on one POI, we separate their measured times from the rest, shown in Table 6.2. The *Exploration* time for participant P1 is thus referring to only a small portion of the city, containing the H&M entrance. Analogously their *Search* time also refers to finding only the H&M entrance.

From the results, we can see that the *Exploration* times varied significantly between participants, with an average of 19 minutes and a standard deviation of 8 minutes and 41 seconds. As such, the different levels of visual impairment appear to have a high influence on the *Exploration* time. Participants P2, and P4 seemed to have the biggest difficulties here, needing more than double the *Exploration* time than the rest. While P1 is not included in the mean and standard deviation calculations, we can see that their *Exploration* time for only a portion of the city is more than twice as high as the *Exploration* time of P3 and P5 for the whole city. In contrast, this overall fluctuation can no longer be seen in the *Search* time. With an average *Search* time of 4 minutes and a standard deviation of only about 35 seconds, all participants who explored the entire city, i.e. P2-P5, needed roughly the same amount of time for the *Search* task. Compared to the *Exploration* task, the level of visual impairment showed much less influence for the *Search* task for these participants. In the following, we analyze the influence of the level of visual impairment on the completion times in more detail.

Field of View (FOV)

The biggest factor influencing both *Exploration* and *Search* time seems to be the available field of view (FOV), potentially with the combination of color blindness. This can be seen in the completion times of participant P1, who has the smallest FOV of less than 5°. Although P1 has the highest self-reported residual vision, both of their completion times were significantly higher than the rest. As P1 did not finish exploring the whole city we do not have an exact time of how long they would need to explore the city in its entirety. However, since they needed 25 minutes for only a small fraction of the city, we can estimate that their *Exploration* time of the entire city would be much higher than the presented *Exploration* times of all other participants. Similarly, their *Search* time is also much higher, needing over 6 minutes to only find the H&M entrance. The influence of a limited FOV on *Exploration* time can also be seen on the the example of P2. However, this influence seems to drastically decrease for the *Search* time for P2. Despite having a FOV of only 5°-7° and even a lower self-reported residual vision than P1, the *Search* time of P2 was roughly the same as that of P3-P5. This suggests that P2 was able to attain a cognitive map, that guided their *Search* task. Hence for a FOV of more than 5°, the visual cues appear to be a sufficient support. However, for a FOV of less than 5° the visual cues appeared to not provide sufficient aid. Especially the Outline cue for walkable areas, which P1 used, could be difficult to perceive as only the borders of the paths are highlighted. This means participants with a small FOV cannot simultaneously see both highlighted borders if the path is too wide. As such, they have to constantly scan the entire ground.

Color Blindness

Additionally, while other participants possessed a slight degree of color blindness as well, P1 reported not being able to differentiate any colors, which could also contribute to the performance difficulties. Although P1 reported being able to perceive the cues based on their contrast, some cues failed to provide the intended information. For cases such as the *Shape Information* cue, the information about non-walkable areas, i.e. streets, and walls could not be provided through the cue as their difference was marked only by a different color. As such, differentiating between streets and walls was more difficult since P1 had to resort to identifying the streets through car lane markings or crosswalks.

residual vision

While a limited FOV of less than 5° presented the biggest impact overall, residual vision appears to have a significant impact on the time needed for *Exploration*. Comparing participants without an impacted FOV (P3, P4, P5), the *Exploration* time of the participant with the lowest residual vision, P4, was three times higher than for P3 and P5. In contrast, this effect is not seen in the *Search* task anymore, with P4 having the second shortest *Search* time of all participants. This suggests that, similar to P2, participant P4 was able to build a cognitive map during the *Exploration* which guided them in the POI *Search*. Hence for a residual vision of 3%, the visual cues appeared to provide sufficient aid to accomplish the task.

6.2.1 Summary of Findings: Completion Times

RQ1: Cognitive Mapping

During the *Exploration* task, participants were presented with a new scene and had to navigate without prior knowledge. The level of visual impairment makes this navigation more challenging, as we have seen by the increased *Exploration* time of participants P1, P2, and P4 who either had the lowest self-reported residual vision or the smallest FOV. Once a person is able to successfully acquire a rich cognitive map, they can use it for guidance. The varying *Exploration* times compared to the relatively similar *Search* times of P2-P5 indicate that these participants were able to acquire such cognitive maps, which helped them during the *Search* task. Despite P2 and P4 needing more than twice as long to fully *explore* the city, they were able to accomplish the *Search* task just as fast as the other participants. This means that although their low residual vision and small FOV impacted their navigation during the *Exploration* task, these factors no longer impacted their performance for the *Search* task. In contrast, the results of P1 indicate that their difficulty with accomplishing the *Search* task was due to not being able to properly form a cognitive map of the city portion they explored.

In summary, the results suggest that creating a sufficient cognitive map with the visual cues was not possible given a residual vision under 15 % combined with a FOV of less than 5°. For a FOV of above 5° and at least 3% residual vision, successfully creating a helpful cognitive map was possible.

RQ2: Visual Cues

(a) For a limited FOV and color-blindness, the information provided by the visual cues appears to not be sufficient. Especially the *Outline* cue for walkable areas, may not provide sufficient information. Since only the borders of the paths are highlighted, participants with a small FOV cannot simultaneously see both highlighted borders if the path is too wide. As such, users have to constantly scan the entire ground. Thus, in this case, more information should be highlighted by the *Shape Information* cue than just the borders of the walkable area.

(b) In addition to a limited FOV, we saw that color blindness potentially also played a role in the high completion times of P1 as well. Although P1 reported being able to perceive the

Participants	POI Search Sequence												
P1	Start	⟶	H&M										
P2	Start	⟶	WC	⟶	H&M	⟶	Cafe	⟶	Pizzeria	⟶	ATM		
P3	Start	⟶	WC	⟶	H&M	⟶	Pizzeria	⟶	ATM	⟶	Cafe		
P4	Start	⟶	WC	⟶	H&M	⟶	Pizzeria	⟶	ATM	⟶	Cafe		
P5	Start	⟶	WC	⟶	H&M	⟶	Cafe	⟶	Pizzeria	⟶	ATM	⟶	Cafe

Table 6.4: Sequence of POIs participants navigated to during the Search Task. Green marks the correctly found POIs, red the wrong POIs.

cues based on their contrast, some cues failed to provide the intended information. The *Shape Information* cue provides information about non-walkable areas, i.e. streets vs walls, only through color. As such, differentiating between streets and walls is difficult for color-blind people. Hence an alternative is needed for visualizing this information without relying on color.

6.3 Path Tracking

After analyzing the completion times we gained general information about which participants showed difficulties during the tasks. We now investigate the search task in more detail to further analyze the specific areas of difficulties.

6.3.1 POI Search Sequence

In the following, we investigate how easy it was for participants to find specific POIs. For this, we first look at the sequence of POIs the participants navigated to during the search task, specifically how often they navigated to the wrong POI, i.e. how often they mistook POIs. In Table 6.4 we show the sequence of each POI the participants navigated to. The POIs that were correctly navigated to are marked in green, while the wrong POIs are marked in red.

As we can see, only participant P5 navigated to a wrong POI once, mistaking the *Cafe* for the *Pizzeria*. After being informed about their error, they then successfully navigated to the correct *Pizzeria* location. The rest of the participants did not mistake any POI for another one. This implies that while both the *Cafe* and *Pizzeria* were highlighted in a way that made them detectable, they were not sufficiently identifiable. For the rest of the POIs, the results indicate that they were sufficiently detectable and identifiable, as they all could be correctly identified during the search.

However, the correctly found POIs do not automatically imply that a successful cognitive map was acquired. For each correctly identified POI, we can assume one of the two cases:

Participants			1. POI		2. POI		3. POI		4. POI		5.POI
P1	Start	not optimal →	H&M		-		-		-		-
P2	Start	optimal path →	WC	optimal path →	H&M	not optimal →	Cafe	optimal path →	Pizzeria	optimal path →	ATM
P3	Start	optimal path →	WC	optimal path →	H&M	optimal path →	Pizzeria	optimal path →	ATM	optimal path →	Cafe
P4	Start	optimal path →	WC	optimal path →	H&M	optimal path →	Pizzeria	optimal path →	ATM	optimal path →	Cafe
P5	Start	optimal path →	WC	optimal path →	H&M	not optimal →	Pizzeria	optimal path →	ATM	optimal path →	Cafe

Table 6.5: Paths taken by participants during their Search Task. Green arrows mark when participants took the shortest path, and red when not.

1. The participant was able to find the correct POI because its location is stored in the participant's cognitive map.
2. The location of the POI was not stored in the participant's cognitive map and the participant needed to actively search for the POI. However, they could successfully detect and identify it.

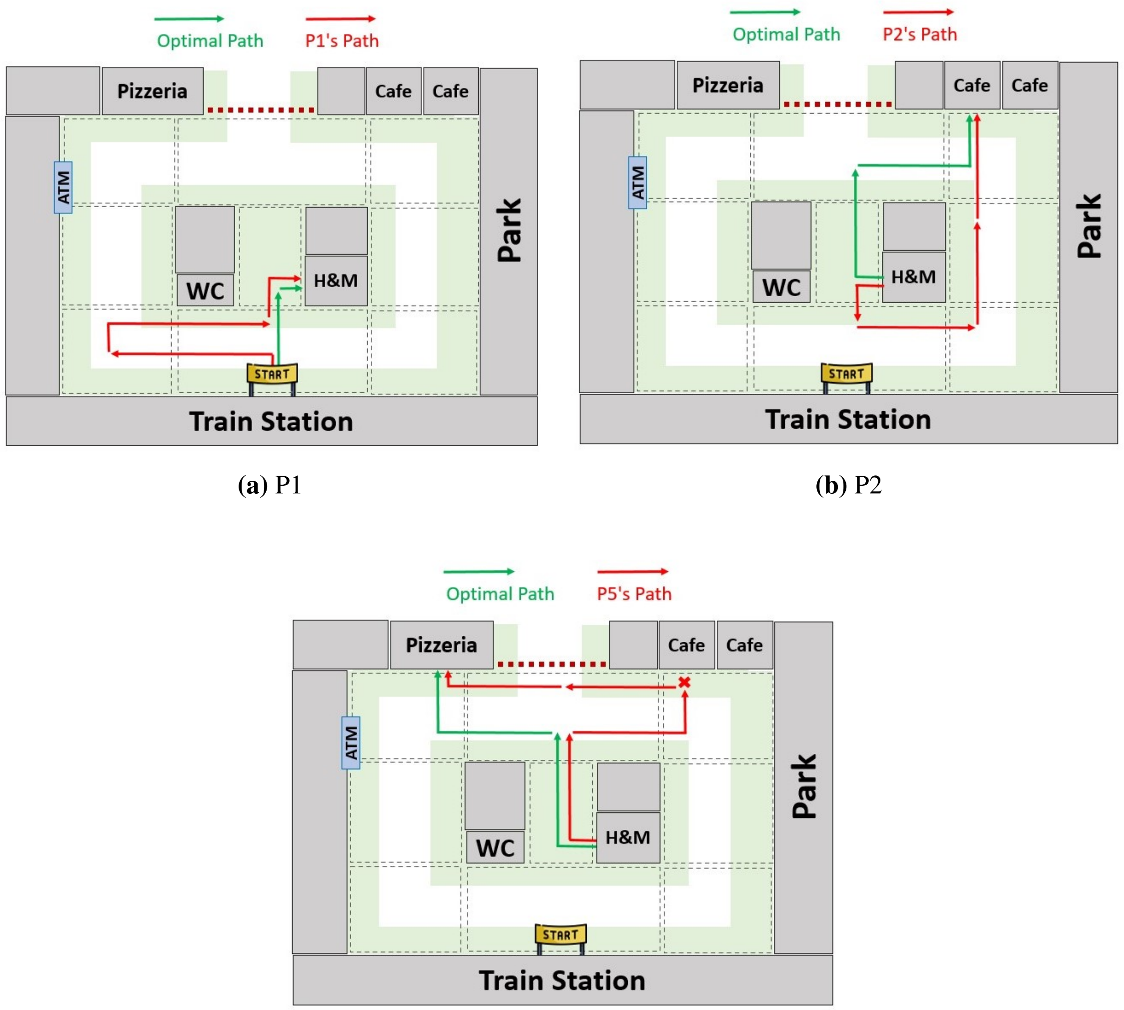
Thus we need to further analyze whether the correctly found POIs were found because participants were guided by their cognitive map, or whether they only found them after an unguided search. For this, we look at the paths participants took during the search task.

6.3.2 Shortest Path

First, we present an overview of when participants took the shortest path during their search task. In Table 6.5 we see for each POI search, whether the participants took the shortest route or not. The shortest routes are marked with green arrows and the paths that are not the shortest are marked with red arrows.

As we can see, overall the majority of the taken paths to each POI were also the shortest. While P3 and P4 took the shortest path to every single POI, participants P1, P2, and P5 each took one route throughout their whole search which was not the shortest. For the rest of the routes, P2 and P5 chose the shortest route. Since P1 only searched for one single POI, they did not have a case where they were able to navigate through the shortest path. All three cases of non-shortest paths involved the H&M entrance, indicating that this area might have caused some difficulties for participants. In the following, we investigate these non-shortest paths taken by P1, P2, and P5.

To visualize the taken paths, we divide the city layout into 9 different blocks and define the taken path by the sequence of traversed blocks. In Figure 6.1 we show the taken paths to the POIs that were not the shortest. In green, we present the optimal, i.e. the shortest, block-sequence path from the starting point to the next POI to be found, and in red the corresponding path taken by the participant. Figure 6.1a shows the path taken by P1 for their first and only target POI, the *H&M entrance*, starting at the *Train Station*. For both P2 and P5, their starting point was the *H&M* entrance and the target POI for P2 was the *Cafe*, seen in Figure 6.1b, while for P5 it was the *Pizzeria*, seen in Figure 6.1c.



(a) P1 **(b)** P2

(c) P5

Figure 6.1: Path tracking results portrayed by sequence of city blocks, for non-shortest paths taken by participants P1 (a), P2 (b), and P5 (c). The shortest paths are marked in green, and the paths taken by participants in red.

Path taken by P5

As we have seen in Table 6.4, P5 mistook the *Cafe* POI for the *Pizzeria* POI, hence why they navigated to the wrong location first. This is why they did not directly take the shortest path from the *H&M* to the *Pizzeria*. However, we can see that the path they took to the *Cafe* and from the *Cafe* to the *Pizzeria* was the shortest. This suggests that the POIs were successfully detected and the spatial layout of the city was understood during exploration. However, since P5 mistook the two POIs, this further suggests that the *Cafe* and *Pizzeria* were not sufficiently identifiable, meaning the highlighted information about the *Pizzeria* and the *Cafe* was not sufficient to make them differentiable for P5.

Contrary to P5, the non-shortest paths taken by participants P1 and P2 were not due to misidentifying the POI. As we have seen from Table 6.4, they successfully identified the correct POI for these cases.

Path taken by P2

We can see that while the path P2 took from the *H&M* entrance to the *Cafe* was not the shortest, their path did not include any turnarounds or going in circles. Instead, the path went directly to the *Cafe*, only going from the different direction. In Section 6.6 we go into further detail about what visual information the participants used for orientation and what the challenges were. Here, one of the reports by P2 was that they found the highlighted *Park* fence to be extremely helpful for orientation and that some passages in the city lacked enough unique landmarks. Which could explain why they took the path along the park instead of the shorter one. This suggests that the *Park* fence was unique enough to be used for orientation, while the optimal path did not contain enough unique and perceivable visual cues.

Path taken by P1

In contrast to P2, participant P1 did not take a direct path while searching for the *H&M* entrance. Instead, they needed to turn around and actively search for the target. While the other participants did not have problems finding the *H&M* entrance, the other non-shortest paths suggest that this area could have caused more difficulties than others. One reason why this could be the case is that the *H&M* entrance was the only POI without facing the street directly, i.e. the non-walkable area. Instead, it was located in a central square surrounded by buildings and not streets. This central square was all part of a walkable area, which is much wider than the rest of the walkable areas in the city, i.e. the pedestrian paths. Since all three participants used the Outline cue for this information, the space between the outlines was also much wider which would have made it more difficult to detect the Outline cues. This could especially be the case for P1 and P2 since they have a limited FOV and might not have been able to see both outline cues at the same time. During the subjective feedback of the participants, P1 corroborated the problem of identifying *Shape Information* and having to scan the area. As mentioned above, we go into further detail on these findings in Section 6.6.

6.3.3 Summary of Findings: Path Tracking

RQ1: Cognitive Mapping

From the tracked paths, combined with the POI search sequence we can see that four out of five participants were able to find direct routes to POIs, with almost all of them being the shortest routes. This suggests that these four participants were able to build a sufficient cognitive map that they could use for finding direct paths to each POI and they did not have to actively search for their targets. However, for the participant with the smallest FOV of less than 5°, this was not the case. From their tracked path we can see that they navigated in the opposite direction first and could not navigate directly to the target. This suggests they did not acquire a sufficient cognitive map of the explored area.

Participant	Mental Image	Layout	Detours
P1	1	1	-
P2	4	5	4
P3	5	5	5
P4	5	5	4
P5	5	5	5
Mean ± SD	**4 ± 1.55**	**4.2 ± 1.6**	**4.5 ± 0.5**

Table 6.6: Exploration Task Likert-Scores from 1-5 for the questions *"I was able to create a mental image of the city scene."; "I understood the layout of the city scene."; "I am able to find detours to given spots".*

RQ2: Visual Cues

(a) The information highlighted for the *H&M*, *ATM*, *Cafe*, and *Pizzeria* seemed to be sufficient for detection, as all participants could detect them. However, since the *Pizzeria* and *Cafe* were mistaken by P5, this suggests that their highlighted information did not make them sufficiently identifiable. Hence either the way the information was highlighted was not suitable or different/ additional information should be highlighted.

(b) Highlighting only the curbs or borders on wide walkable areas seems to be less suitable, as seen by the difficulties at the central square area. Thus additional information should be highlighted as well so that users with a limited FOV can perceive the cue without having to scan the whole area.

6.4 Perceived Task Performance & Workload

After analyzing the completion times and path tracking data on the cognitive mapping process of participants, we now look at the subjective assessments of the participants regarding their cognitive maps during each task.

6.4.1 Exploration Task

Starting with the *Exploration* task, we look at how well participants reported gaining a cognitive map after exploring the city. In Table 6.6 we present the Likert-Score each participant gave to questions about acquiring a mental image of the place, understanding the spatial layout, and being

Participant	Remembering POI	Searching POI	Success Finding POI
P1	2	2	5
P2	5	5	5
P3	4	5	5
P4	5	5	5
P5	5	5	5
Mean ± SD	**4.2 ± 1.17**	**4.4 ± 1.2**	**5 ± 0**

Table 6.7: Search Task Likert-Scores from 1-5 for questions *"I knew the location of the target POI already through the prior exploration."; "I did not need to actively search for the target POI. "; "I was able to successfully navigate to the target POI."*

able to find detours to a location. Note, that since Participant P1 did not get the chance to explore the whole city due to time constraints, they could not form a mental image of the entire city. Hence why their scores refer to only the exploration of the portion of the city they did explore. Furthermore, since their exploration was only limited to the front section of the city, there was not enough covered area for potential detours to get a score on this.

In general, the given scores indicate that participants P2-P5 were able to successfully build a cognitive map, with each of these participants giving a score between 4 and 5 for each question. As we have mentioned already, P1 was not able to explore the whole city, however, even for the portion of the city they did explore, they reported not being able to gain a mental image or understanding its layout. As such, they had difficulty with orientation.

In contrast, all participants who were able to explore the whole city, i.e. P2-P5, reported understanding the layout fully, with each participant giving a score of 5. Similar to the results shown by the *Exploration* times in Section 6.2, participants P3 and P5 showed to have the least amount of difficulties, while P2 and P4 appeared to face slightly more challenges, with P1 struggling the most. Thus, the low vision volume of P4 and the limited FOV of P1 and P2 influenced the results here as well. However, for P2, and P4 this was only very slightly the case, compared to P1.

6.4.2 Search Task

To see whether the acquired cognitive maps were helpful for guidance during the POIs search, we now look at the results of the questions we asked participants after the *Search* task. In Table 6.7 we show the Likert-Score given by each participant for being able to remember POI locations, not needing to actively search for POI, and how successful they were in finding the POI. Note, for the second question we asked the negated version "I needed to search the POIs", and afterwards, flipped

Participant	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TLX-Score
P1	5	3	1	7	3	1	3.33 ±2.13
P2	2	2	1	1	3	1	1.67 ±0.75
P3	6	8	1	1	6	3	4.17 ±2.67
P4	8	1	6	1	7	2	4.17 ±2.91
P5	1	1	1	1	1	1	1.00 ±0.0
Mean Score ± **SD**	**4.4** ± 2.58	**3.0** ± 2.61	**2** ± 2	**2.2** ± 2.4	**4** ± 2.19	**1.6** ± 0.8	**2,87**

Table 6.8: NASA-TLX Scores using a scale of 1-10 for the Search Task.

the given scores so that they now represent the statement "I did NOT need to actively search the POIs". This is so that the higher score would indicate a better cognitive map as do the rest of the scores.

All participants reported maximum success in finding the POIs, with P2-P5 not needing to search for them. Due to Participant P1 not having encountered every POI during the *Exploration* task, we could not include the unvisited POI in their *Search* task. Thus, we only let them search for the H&M, which they were able to find. However, as we see from their given score of 2 for *Searching POI*, they needed to perform an active search in order to find it. As their similar score of 2 for *Remembering POI* indicated, their active search was necessary since they could not remember its location. In contrast, the scores of the other participants P2-P5 indicate that they could remember the POI locations, with 4 being the only score lower than 5 which was given by P3. Thus in general, these results combined with the results for the exploration questions, suggest that participants P2-P5 were able to build a sufficient cognitive map during the exploration task and successfully use it during the search task.

6.4.3 Workload during Search Task

In addition to the Likert-Scores, we analyze the results of the NASA-TLX[1] questionnaire for the *Search* task to gain an insight into the overall level of difficulty participants experienced during the task. In Table 6.8 we present how each participant ranked the six questions,*Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort*, and *Frustration*. Usually, a NASA-TLX scale ranges from 1 to 20, however when answering the questions, typically we place our score visually depending on the relative position of our marking in the scale, instead of actually considering the number itself. Since the participants had to name a specific number without having the scale in front of them visually, choosing a number on a scale of 1 to 10 can be easier than using a scale of 1 to 20. Hence, we scaled it down to only 1 to 10 in order to make the score selection a little more intuitive for the participants. Additionally, we omitted pairwise comparisons used in a weighted score calculation, hence we use what is often referred to in research as "Raw TLX [Har06].

[1] https://humansystems.arc.nasa.gov/groups/tlx/

In general, with 2.87 being the mean TLX-score of all participants, the overall workload for the *Search* task can be seen as medium. Looking at the individual scores, we can see that participants P3 and P4 ranked the overall workload of the *Search* task the highest with a TLX-score of 4.17 out of 10. Whereas participant P1 ranked each subscale the lowest, giving each a 1 out of 10. However, the standard deviation of P4 is also the highest, meaning their given scores fluctuated the most depending on the subscale. While P4's higher TLX-score could be attributed to having the lowest vision volume of all participants, P3 in contrast has a vision volume almost as high as P5. Additionally, despite participant P1 showing the biggest difficulties in the tasks so far, which we attributed to their limited FOV, their overall TLX-score is lower than that of P3 and P4. Furthermore, with P2 also having a limited FOV, their score of 1.67 is the second lowest, meaning the limited FOV did not appear to influence the perceived workload. As such, we do not get a direct correlation between the overall TLX score of participants and their level of visual impairment.

When looking at the six individual subscales the biggest workload is attributed to the *Mental Demand* of accomplishing the search task, with an average score of 4.4. Similarly, the required *Effort* is deemed as the second highest, with an average of 4. As the acquisition of an allocentric cognitive map and its subsequent usage requires a level of mental effort, it makes sense that these two subscales were ranked the highest overall by participants.

In contrast, the *Frustration* and *Temporal Demand* of participants were ranked the lowest with a mean of 1.6 and 2 respectively. Since we did not include any time limits on the participants during this task, this would explain why this subscale is one of the lowest ranked.The low *Frustration* score also seems to indicate that the given *Search* task did not include anything too irritating or stressful for the participants.

Looking at the *Performance* subscale, we can see that all participants who have shown to successfully build a cognitive map in the results so far also ranked their performance as 'perfect' with a score of 1. In contrast, participant P1, who showed difficulty with acquiring a sufficient cognitive map, gave a higher score of 7. This further supports the analyzed results so far of P2-P5 being able to successfully gain and use a cognitive map, while P1 was not able to do so.

6.4.4 Summary of Findings: Perceived Performance & Workload

RQ1: Cognitive Mapping

The subjective scores given by participants regarding the ability to acquire and use an allocentric cognitive map of the virtual city are in line with the findings we have gathered from the Completion Times 6.2 and Path Tracking 6.3. These further suggest that participants P2-P5 were successful in understanding the layout of the city and attaining a mental representation of it, including the locations of POIs. As the ability to find detours requires an allocentric cognitive map, the average score of 4.5 given by P2-P5 for this question suggests that they could form such an allocentric cognitive map. Additionally, their reported ability to successfully find POIs without an active search further supports this. From the NASA-TLX scores, we can further see that the level of difficulty for this was overall medium. In contrast, P1's scores show that they could not form a sufficient cognitive map, and while they were able to find the target POI, they needed to perform an active search first.

Obstacles		**POI Objects**		**Entrances to POI**		**Symbols**		**Shape Information**	
Explor.	Search	Explor.	Search	Explor.	Search	Explor.	Search	Explor.	Search
P3	**P1**			**P4**	**P2**	**P5**	**P5**	**P1**	**P3**
	P3				**P3**			**P2**	
					P4				

Table 6.9: Votes of participants for most helpful visual cues category, for Exploration task in blue, and Search task in red. Participants could vote for more than one category.

6.5 Visual Cues Rating

So far, we focused mostly on investigating the orientation of participants by analyzing their cognitive map acquisition and usage. Now we want to go further into detail on the efficacy of each category of the visual cues. For this, we first look at the visual cues each participant reported as the most helpful one during each task. Afterwards, we present the scores given to each visual cue category for the *Exploration* task and *Search* task separately. Following this we compare the scores of the two tasks.

6.5.1 Most Helpful Visual Cues

For each cue category, we present which participants reported them as the most helpful cue in Table 6.9. In blue we show the participants who ranked this cue the most helpful for the *Exploration* task, and in red the same for the *Search* task. We gave every participant the option to choose more than one visual cue as the most helpful, hence why the total number of votes for each task is not the same. Note that Participant P1 did not encounter the *ATM Shadow* cue and the corresponding *Euro Symbol* cue, since they did not get to explore this part of the city. Hence why they could not vote for the **POI Objects** cue and their ranking of the **Symbol** cue could only be based on the *Arrow Symbols*.

Given the results, we can see that for the *Exploration* task, the cue category with the most votes is the **Shape Information**, which highlights the layout of the walkable and non-walkable areas. The two participants who voted for this cue category are also the ones who have a limited FOV, both below 7°. This suggests that for gaining a mental image of a city, having a cue that highlights the layout of the paths is especially helpful in case of a limited FOV. For the *Search* task, this category was not seen as helpful anymore by P1 and P2. Overall only one participant, P3, noted this information as the most helpful during the *Search* task.

In contrast, the cue category with the most votes for the *Search* task were the **Entrances to POIs**. Since the goal during this task was to find the POIs, i.e. the Entrances to them, this would explain why most participants ranked this cue category as the most helpful for this task. Another category that two participants voted as the most helpful for the *Search* task were also the **Obstacles**. From the reports by the participants given during the study, some obstacle objects were used as identification points for the POIs during the *Search* task. For instance, the bollards near the *H&M* entrance. We go into further detail on this in the next Section 6.6, however, it is worth mentioning here, as it explains why the **Obstacles** category is voted as the second most important for the *Search* task.

Participant	Obstacles	POI	Entrances	Symbols	Shape Info.	Mean ± SD
P1	3	-	5	5	5	**4.5 ± 0.87**
P2	4	3	5	1	5	**3.6 ± 1.5**
P3	5	5	5	5	5	**5.0 ± 0.0**
P4	5	5	5	4	5	**4.8 ± 0.4**
P5	5	5	5	5	5	**5.0 ± 0.0**
Mean ± SD	**4.4 ± 0.80**	**4.5 ± 0.87**	**5.0 ± 0.00**	**4.0 ± 1.55**	**5.0 ± 0.00**	

Table 6.10: Exploration task scores of visual cue category. Scores were given on a scale from 1-5.

While the votes of participants P1-P4 remained between the three categories **Obstacles, Entrances to POI,** and **Shape Information**, participant P5 found the **Symbols** the most helpful for both tasks. Their preference for using symbols for orientation and navigation is also further addressed in their presented reports in Section 6.6.

Lastly, the cue category **POI Objects** did not receive any votes for either of the tasks. This lack of votes could be due to the fact that we downsized the city to only contain one single POI object, the ATM. As such, the influence of this cue was limited due to its sparse occurrence.

6.5.2 Visual Cues Scores

After analyzing which visual cue categories were the *most* helpful for individual participants, we now look at *how* helpful each cue category was rated as. For this, we present the Likert-Score results for each task. Each cue category was given a score of 1 to 5 by participants, with 5 being the most helpful and 1 being the least helpful for the given task. Note that Participant P1 did not encounter the ATM POI object during both of their tasks. Hence analogously to the previous results, we do not have a score from them for the corresponding visual cues.

Exploration

Starting with the *Exploration* task, Table 6.10 shows how every participant ranked each cue category for attaining a mental map of the city. Additionally, we show the mean score over all cue categories of each participant and the mean score of each cue category over all participants, as well as the corresponding standard deviations.

Participant	Obstacles	POI	Entrances	Symbols	Shape Info.	Mean ± SD
P1	5	-	5	5	1	**4.0 ± 1.73**
P2	2-3	2	5	2	4	**3.1 ± 1.2**
P3	5	5	5	5	5	**5.0 ± 0**
P4	4	4	5	4	5	**4.4 ± 0.49**
P5	1	1	1	1	1	**1.0 ± 0**
Mean ± SD	**3.5 ± 1.55**	**3.0 ± 1.58**	**4.2 ± 1.60**	**3.4 ± 1.62**	**3.2 ± 1.83**	

Table 6.11: Search task scores of visual cue category. Scores were given on a scale from 1-5.

From the mean scores of each cue category, we can see that the *Entrances* and *Shape Information* were ranked the highest, with an average score of 5. This high score of the *Shape Information* cue correlates with the prior results we have seen of having the layout of the streets and paths highlighted as being helpful. Furthermore, *Entrance* cues also provide more structural information about the city, as it highlights where buildings are located as well as where one can usually find the logos of the corresponding buildings. Overall these two cue categories seem to be suitable for the *Exploration* task, as all participants rated them with a score of 5.

In contrast, the *Symbol* cues were overall rated as the lowest with an average score of 4. However, as we can see from the standard deviation of 1.55, the scores of the participants varied for *Symbols* much more than for *Entrances* and *Shape Information*, which both had a standard deviation of 0. While P5, P3, and P1 gave *Symbols* a score of 5, Participant P2 deemed it as not helpful overall, with a score of only 1. Here, the ones who did not give it a score of 5, i.e. P2 and P4, were participants with the lowest vision volume and limited FOV, which could have made the identification of the symbol difficult and as such made this cue less helpful. Nonetheless, P1 who had the smallest FOV still gave it a score of 5, however, their score was only based on the *Arrow Symbols*.

In general, the participants who had both the highest vision volume and no limited FOV, i.e. P3 and P5 gave a score of 5 consistently for all cues. While a low vision volume resulted in a slightly lower mean score, as we see with P4, overall their scores were close to P3 and P5. In contrast, participants with a limited FOV gave the lowest scores overall. As such the categories **Obstacles, POI Objects** and **Entrances** were seen as less helpful by participants with a limited FOV, while **Entrances** and **Shape Information** were seen as helpful regardless of visual impairment level.

Participant	Obstacles		POI Objects		Entrances		Symbols		Shape Info.		Mean	
	Exploration	Search	Exploration	Search	Exploration	Search	Exploration	Search	Exploration	Search	Exploration	Search
P1	3	5	-	-	5	5	5	5	5	1	**4.5**	**4**
P2	4	2.5	3	2	5	5	1	2	5	4	**3.6**	**3.1**
P3	5	5	5	5	5	5	5	5	5	5	**5**	**5**
P4	5	4	5	4	5	5	4	4	5	5	**4.8**	**4.4**
P5	5	1	5	1	5	1	5	1	5	1	**5**	**1**

Table 6.12: Comparison of Exploration & Search task scores of each cue category.

Search Task

In Table 6.11, we show the corresponding scores given by participants for the *Search* task. Here, we also see a parallel to the results of Subsection 6.5, in which the **Entrance** cues were seen as the most helpful, followed by the **Obstacle** cues. Contrary to the *Exploration* task, the **Entrances** and **Shape Information** did not get a consistent score of 5. Especially the **Shape Information** showed to be a lot less helpful here. This further suggests that participants already acquired an understanding of the structure of the city from exploration. So far we have seen that participant P5 was the one with the least amount of reported difficulties and the lowest search time overall. Their score of only 1 for each category also suggests that the cues were not that important once the cognitive map was acquired.

Exploration vs Search

In Table 6.12, we further show the scores we just presented in direct comparison for each category, with blue marking the *Exploration* task, and red the *Search* task. Here we can see that in almost every category the participants gave a higher score for the *Exploration* task. With the only noteworthy exception being P1 rating **Obstacles** higher for the *Search* task. As we have stated in Subsection 6.5, P1 used bollards obstacles for identifying the target POI during the *Search* task, which explains why they ranked it high for this task. In general, the overall mean scores of each participant also decreased in the *Search* task, meaning every participant rated the cues as less important in the *Search* task.

In Table 6.13, we further see the mean scores for each cue category for the *Exploration* task in blue and *Search* task in red. Here, we can also see that for each category their mean rating decreased in the *Search* task. This shows that overall the visual cues were deemed more important for the *Exploration* task, than the *Search* task. From this table, we can also see that **Entrances** were overall the best rated, followed by the **Shape Information**, making them overall the most important cues, which corresponds with the results seen so far.

Task	Obstacles	POI Objects	Entrances to POI	Symbols	Shape Information	Mean SD
Exploration	4.4	4.5	5	4	5	**4.58 ± 0.4**
Search	3.5	3	4.2	3.4	3.2	**3.46 ± 0.41**
Mean	**3.95**	**3.625**	**4.6**	**3.7**	**4.1**	

Table 6.13: Comparison of Exploration & Search mean task scores of each cue category.

6.5.3 Summary of Findings: Visual Cues Rating

RQ1: Cognitive Mapping

Generally, the visual cues were seen as less helpful for the *Search* task than the *Exploration* task. This suggests that once the participants explored an unfamiliar city with the help of visual cues, the importance of those cues might decrease for subsequent navigation through the city. As such, using visual cues to explore a place first virtually could help with orientation when navigating the real place without visual cues.

RQ2: Visual Cues

From the results, we can gather that overall the **Entrances** cues were received the best, followed by the **Shape Information**. The **Shape Information** cues were seen as the most helpful for the *Exploration* task, to understand the layout of the paths and streets which forms a basis for gaining a mental image of the city. Meanwhile, **Entrance** cues were shown to be more important for the *Search* task, where participants needed to find the entrances of POIs. The cue categories **POI Objects** and **Symbols** received conflicting ratings. Especially for participants with a limited FOV or lower vision volume, these cues seemed to be less beneficial. This could be due to difficulties perceiving the Symbol shapes and the POI object cue not giving enough identification information about the POI object. Similarly, **Obstacles** cues also showed differing results, however, they were found to be useful during the *Search* task for recognizing a target POI. Participants with a limited FOV generally also gave lower and more differing scores overall, suggesting that the cues were less suited for a limited FOV in general.

6.6 Qualitative Feedback

The last results we present are the findings made from the open questions we asked the participants after each task regarding their experience using the visual cues. From the answers given by the participants, we uncovered four broad themes involving the visual cues as well as a fifth theme regarding the challenge of teleportation. We present each theme and its underlying aspects in the following.

6.6.1 Colors

The first broad theme is the usage of color in the visual cues. Due to their salient nature, strong colors allowed participants a preview of the scene, which was regarded as very helpful by many. On the other hand, visual cues that only colored the objects in one color failed to make objects identifiable and additionally posed unsuitable for color-blind participants. In the following, we go into more detail on each of those aspects, as reported by participants.

Preview

Similar, to the findings of our formative interviews prior to designing our visual cues, participants of the study reported the color of the visual cues as the most helpful visual feature. Specifically, participants P3 and P4 explained that it helped them extend their perception range by giving them a preview of objects and structures in a distance. Instead of only seeing things that are in close proximity, colored highlights on distant information allowed them to gain more layout information. P3 described that being able to see that, for instance, there are obstacles on the sidewalk they are walking towards, can help them adjust their walking and be prepared in advance. Similarly, P5 also reported how helpful it is for obstacles to be highlighted by color, such as benches or street poles, as this is something they struggle with in their daily life.

Color Blindness

While participants P2-P5 benefited from the usage of different colors, participant P1 had difficulties with cues that relied solely on providing information through color due to their color blindness. This was the case with the Outline cue for *Shape Information*. Since the information about walkable areas, non-walkable areas, and walls is provided through color, participant P1, who is color blind, could not recognize which borders of the path were streets and which were walls. While they could recognize the curbs themselves which they reported as the most helpful feature of all, they could not differentiate between streets and walls. This resulted in P1 struggling with understanding the layout of the environment and thus led to a poor orientation. As such, they stated that being provided with a suitable cue that shows them the streets would be extremely helpful.

Obstacle Identification

Having the obstacles highlighted with a bold color, helped participants recognize some of the obstacle objects that had unique shapes. As such, P5 reported being able to identify benches or trashcans. Although colors helped participants detect that *something* was there, in many cases a color Highlight cue of objects was not enough to make them identifiable. This was the case for objects that either did not have a unique shape or in the case of too many objects standing close to each other, they obscured each other's outlines. For instance, the chairs and tables placed in front of the Pizzeria and Cafe were difficult to identify by most. This made it especially difficult for P5 to differentiate between the two locations. While P2 and P4 regarded these obstacles as useful for identifying the corresponding POI, they reported that they needed a different form of cue to easily identify the obstacle objects themselves. They further added that having the whole object colored, resulted in details inside the object getting lost. Similarly, P1 also mentioned not being able to identify the obstacles in the center square, consisting of plant beds next to benches. As such, participants P1, P2, and P3 wished for these objects to be better perceivable.

6.6.2 Logos, Signage, and Symbols

The second discussed topic were logos, signage, and symbols. These were regarded by participants as important for identifying POIs. These Points of Interest were then used for orientation. However, most of the logos and signage were shown to be difficult to read. In the following, we go further into detail on the role of POIs, their identification through logos and symbols, and the mentioned limitations.

Points of Interest (POIs)

Participants P2-P5 reported that they memorize specific POIs and use them for orientation, with P5 mentioning the POI cue as the most helpful of all. For instance, the main station was reported useful for orientation, as they memorized the locations of the POIs in relation to the main station. As such, both P2 and P5 noted that they memorized that the H&M entrance was located on the right side of the central square when starting at the main station. Similarly, P4 also mentioned using the main station as an orientation point, as well as the Pizzeria.

Identification of POIs

Logos and Signage were reported as the most helpful features for the identification of POIs by P2 and P4. Especially the H&M logo was mentioned by P4 as useful. Similarly, to identify the main station, P2 reported the helpfulness of the DB logo. P5 found the euro Symbol a great idea for identifying POI and rated it as the most important visual cue during their exploration. They added that they wished the city contained more Symbols as it would help them identify the POIs better. Especially because the signage of e.g. the Pizzeria and the Cafes was hard to read. For instance, they suggested adding a knife and fork Symbol to the Pizzeria, or a clothes hanger Symbol to the H&M store to make it easier to categorize the presented POIs. Furthermore, participants P4 and P5 wished the main station was more detectable. They explain that the DB logo was only seen from the center of the city, but once they walked towards the main station from the sides there was no visual cue for identification. As a result, they could not immediately identify it as the main station once they faced the outer sides. Here, they wished to be provided with some form of additional cue.

Readability

Although P5 found the euro symbol the most helpful, they also added that due to the size of the Symbol, it was difficult to recognize the shape when they were not standing close enough. Similarly, Participants P4 and P2 also reported difficulties recognizing the shape of the symbol. For this, participant P5 mentioned the idea of having the Symbol cues change in size depending on the distance to the user. Thus, when the user is standing far away, the Symbol would be displayed in a large size in order to attract the attention of the user better and provide the needed information even from a distance. Once the user gets closer, the Symbol would become smaller so that it does not obstruct the view too much anymore. Additionally, they added that the Symbol should turn based on the user's orientation, so that the user faces the symbol from the front, as it can be difficult to identify the shape from the size. Similarly, the signage of the Pizzeria and the Cafes was too small to read for almost all participants.

6.6.3 Unique Landmarks

Unique landmarks formed the third discussed theme. As reported by P3, P4, and P5 unique obstacles such as the menu boards or chairs and tables in front of the Cafes and the Pizzeria served as helpful identification information for the POIs. Although P4 reported not fully being able to identify the obstacle objects themselves, they still served as a unique feature to recognize the POIs. Other unique features of POIs also served as an aid for orientation. For instance, the highlighted park fence was reported by P2 as helpful for orientation which was further seen in the path tracking results from Section 6.3. Furthermore, the awning at the Pizzeria entrance was also used by P3 for the identification of the POI and a subsequent orientation point for further navigation. Although not unique in itself, the bollards placed in the center square were memorized by P1 as being near the H&M entrance and thus served as unique identification points. These then helped them find the H&M in the Search task. Similarly, while *Entrances* themselves were not unique specifically, having entrances highlighted helped P4 for identification of the Cafes, as they remembered that they had two adjacent doors in close proximity. Thus, not only was it helpful for the main purpose of helping users find the entrance, but it can also be used as an identification point.

Lack of Unique Landmarks

Despite the mentioned useful unique landmarks so far, participants P1 and P2 classified the biggest missing information as being not enough unique landmarks overall. P1 explained that due to their difficulty understanding the layout, all paths looked the same. They continued that enough unique landmarks could have helped them understand their location and improved their orientation. Similarly, P2 also reported facing the biggest difficulties during the tasks when not enough unique landmarks or features were present. As we have already discussed in Section 6.3, this could have been the reason for P2 taking the longer path to the Cafe, which contained more unique landmarks during the search task, such as the highlighted park fence.

6.6.4 Walkable Area

The last discussed category which involved the visual cues was the presented *Shape Information* cue providing information about walkable and non-walkable areas. The participant who noted it as most important to have information about walkable areas and streets was P1 who also has the smallest FOV with under 5°. Similarly, P2 who also has an affected FOV of 5° - 7° also found the curb highlight extremely helpful during the exploration task.

One problem we have seen with the Outline *Shape Information* cue so far was the usage of color to convey information about walkable and non-walkable areas and walls. Besides for people with color blindness, this cue also showed difficulty for participants with a limited FOV. Participant P2, who has a limited FOV, noted that the *Shape Information* is only provided when they are standing on a walkable area. Currently, the Outline cue shows the user where the non-walkable area is located only in relation to the walkable area. Meaning the user has to walk on the walkable area in order to know where the street is in relation to them. As a result, participants with a limited FOV, i.e. P1 and P2, reported often not knowing where they were standing. Similarly, identifying and differentiating walls and streets was difficult for them. As a result, P2 reported having to use crosswalks for identification of the street. Because of these challenges, P1 reported difficulty with orientation as they could not immediately identify their location. Both discussed wanting some form of visual marking on the streets to facilitate its identification.

Teleportation

Our last discussed topic does not directly involve the visual cues, but it had an influence on the overall experience of the participants during the tasks. The biggest challenge mentioned by all for both tasks had to do with the teleportation locomotion. Although all participants managed to use the teleportation sufficiently, it led to additional orientational difficulties. As P4 described, it was difficult to maintain orientation in case they needed to turn around, especially after being too close to a wall. Additionally, due to the controllers not being properly recognized by the sensors, the teleportation stopped working randomly, leading to confusion about why they could not see the teleportation ray. While this did not directly have anything to do with the visual cues, it could have had a negative effect on their overall cognitive mapping process and acted as an additional disturbance factor.

6.6.5 Summary of Findings: Visual Cues

After presenting the qualitative feedback given by the participants, we now present the insights we gathered from those results for our research question (**RQ2**). More concretely, we focus for each visual cue category on **(a)** how important and helpful the currently highlighted information was and what missing information should ideally be highlighted as well. And **(b)** whether the way the information was highlighted was helpful.

Obstacles

RQ2(a): In Chapter 4 we argued that the most important job of visual cues for *Obstacles* is to make them detectable, however, our study results showed that some obstacles should also be identifiable. Especially, since some of the obstacle objects also served as identification points for POIs, such as the chairs and tables in front of the Cafe and Pizzeria.

RQ2(b): While the shadow cue does not have any effect on how identifiable the obstacle is, the Highlight cue was able to provide at least the shape of the obstacle object. Thus, if the shape of the obstacle was unique enough then the object could be identified, such as for free-standing benches, or street lights, as reported by P5. However, identification was difficult for obstacle objects that did not have a very unique shape, such as the plant beds, or multiple obstacles placed next to each other which obscured the shape outline of each other. This was the case for the chairs and tables located in front of the Pizzeria and Cafe, which most participants reported as difficult to recognize. As such, the Highlight cue should be modified in a way that facilitates object identification.

Points of Interest (POI)

RQ2: Having POIs highlighted in general was regarded as really helpful. However, most POIs were difficult to identify from a distance. The main station was only identifiable if participants stood next to the DB logo, but once they faced the outer sides of the main station, there was no visual cue for identification. Therefore, there should be more information highlighted in order to make the main station identifiable from all locations. Similarly, for the POIs where the signage was too small to read, i.e. Pizzeria and Cafes, there should be additional identification information highlighted as well. As such more Symbol cues should be provided, however, they should be modified such that their shape is easier to recognize.

Entrances

RQ2: In general, the *Entrance* visual cues showed the most positive feedback, and all participants found their presence helpful during exploration and could recognize the highlighted information. As such, there was no feedback given on any missing information or a different way this cue could be designed.

Shape Information

RQ2(a): Having the curbs highlighted was seen as the most helpful by participants with a limited FOV, i.e. P1, and P2, when exploring a city. In contrast, the participants who showed the least difficulties throughout the study, P5 ranked them as the least important from the cue categories. Nonetheless, P5 did find the information highlighted by this cue helpful for the exploration task.

RQ2(b): While the participants without severe color blindness and an unaffected FOV (P3-P5) found the visual cues for this category suitable for their needs, P1 and P2 reported some difficulties. For P1, who is color-blind, the cue failed to provide the necessary information about which border is the street and which is the wall. As a result, they could not differentiate where the streets were and where the walls were, meaning the structure of the city was more difficult to grasp. Furthermore, for participants with a limited FOV, *Shape Information* is only provided when they are standing on a walkable area. Currently, the Outline cue shows the user where the non-walkable area is located only in relation to the walkable area. Since streets are much wider than pedestrian paths, participants with a limited FOV could not immediately recognize where the walkable path is located or that they are standing on the street. As such, the *Shape Information* cues should be extended to also include a form that directly informs users when they are located on the non-walkable area and where the walkable area is located to them.

7 Conclusion

To support spatial orientation for visually impaired people, our work focused on creating visual cues facilitating exploration. Using a user-centered approach, we designed different visual cue types for the categories: *Obstacle, Points of Interest (POI), Entrance,* and *Shape Information*. In a user study with five visually impaired participants, we then evaluated their efficacy for cognitive mapping of a city scene in VR.

Our user study indicated that with the help of our visual cues, four out of five participants were able to successfully acquire and use a cognitive map of the presented virtual city. However, for the participant with a self-reported vision of 10% - 15% and the smallest FOV of less than 5°, the visual cues could not provide the sufficient help.

Even with a small number of participants, we saw a lot of variety in terms of what participants preferred or needed, and as such, almost all designed cue types within each category were shown to be useful. The preferences of participants for each category also varied. While each category proved to be helpful for different participants, we could also see that some categories were deemed as more important by the majority. As such, most participants reported the *Shape Information* cues as most helpful during exploration, while *Entrance* cues seemed to be preferred by most during the search task. Although the visual cues received positive feedback overall, there was also shown to be room for adjustments for different needs. Especially for a limited FOV and colorblindness, the category *Shape Information* did not provide a suitable visual cue type. Providing *Obstacle* cues only for detection also showed to be insufficient. Most participants expressed a desire to also identify the obstacle objects not just detect them. Similarly, *POIs* cues also showed limitations in providing identification information due to the Symbol cues being too small. In contrast, all participants were satisfied with the presented *Entrance* cue types.

Overall, while our visual cues presented several limitations, they also showed to be a promising starting point for facilitating orientation through visual feedback. In the following, we first present possible design modifications to the current visual cues, in Section 7.1. Following this, in Section 7.2 we discuss the limitations of our user study and how these limitations should be addressed in future studies. Lastly, Section 7.3 provides an outlook for the future of visual cues facilitating orientation for visually impaired people.

7.1 Design Implications

In the previous chapter, we discussed what information should be highlighted by the visual cues and whether the way they highlight this information is suitable. We discussed this based on the feedback gathered from users during the user study. In the following, we present design ideas, some of which were discussed with the participants to improve the mentioned limitations.

7.1.1 Obstacles

The main modification to be made for Obstacle cues, as shown by the results, is to make the objects easier to identify.

Identification

Highlight Cue with Edges & Outlines: In cases of multiple obstacles next to each other, the Outline of each object should be made more visible so the shape of the object can be seen. Furthermore, for objects that do not contain a unique shape, the whole object should not be colored with one color, instead only the important details such as the edges should be highlighted. The downside of this would be that this might make the object less detectable from a distance. A solution for this would be to have obstacles that are distant be highlighted as a whole, as we have done so far, and once the user comes closer, the cue changes to the edge and outline highlight to make it identifiable. Another approach would be to highlight the object in one color, as done so far, and additionally provide the edges in another color, similarly to the combined cue of Outline and Filled for Shape Information.

7.1.2 Shape Information

For Shape Information we have two cases for which the cues should be extended or modified, for colorblindness, and for a limited FOV.

Colorblindness

Dashed or Dotted Outline Cue: To allow the distinction between the street border and wall border, the outline should be modified so that it provides information through shape instead of color. For instance, the street border outline could be displayed as a dashed or dotted line instead, similarly to how we marked street crossing with the Outline cue so far.

Pattern Cue: Similarly to the Outline cue, here we have to use a different shape to provide the relevant information. Inspired by the created cue by Nair et al. [NZS+24], a checkered pattern could be placed on the walkable area. This cue could however lead to some visual clutter when used with the Shadow cue for obstacles.

Limited FOV

Moving Shadow: To provide Shape information for a limited FOV, without users having to scan the ground area for the outlines, we need to place the cue in a spot where the user can immediately find it. One idea would be to provide a marked area on the ground where the user is standing, similar to the Shadow cue, which moves with the user's position. Depending on whether the user is standing on a walkable area or a non-walkable area, the shadow marking would inform the user about it through either color or shape.

7.1.3 Points of Interest (POI)

The last category for modification, are the POIs cues, which consist of the Symbols and the cue for the POI objects. Both cues should be modified to make identification easier.

Identification

Edge Highlight: Similar to the changes for obstacle cues, the edges of POI objects could be additionally highlighted so the user can perceive their shape. This could additionally make them more detectable. However, this might not be enough for identification, hence why the Symbol cues need to be used as well.

Symbols: Since the euro symbol was difficult to identify by participants if they were not close enough, the Symbol cues should be modified to make the identification easier. For this, participant P5 described the idea of having the Symbol be larger when the user stands in a distance from it and once they get closer the Symbol would decrease in size. Additionally, the Symbol should turn based on the user's orientation, so that the user faces the symbol from the front, as it can be difficult to identify the shape from the size. Additionally, more Symbol cues should be added to allow easier identification of POIs, especially since the signage was too small to read for most participants. In the case of larger POIs, such as the main station, the provided Symbol cue, i.e. the DB banner, should also be provided from every view, so that users do not have to walk to the center to see the logo.

7.2 Limitations and Future Work

While we gained a variety of meaningful insights from participants, the study also comes with a number of limitations affecting the results. In the following, we examine these limitations and discuss how they could be addressed by future studies.

Limited Number of Participants: The first shortcoming of our study is the limited number of participants. Although the backgrounds of the participants were generally diverse, with different diagnoses, ages, and genders, five participants are not enough to represent a broader spectrum. The visual acuity differs immensely across individuals with impaired vision, and as such the corresponding needs vary greatly as well. Even individuals with the same form of visual impairment can have very different visual capabilities. As a result, we cannot draw definite conclusions on which cues are beneficial for which diagnosis. To gain a fuller insight into one form of visual impairment, more participants with the same diagnosis are needed. Furthermore, it is also important to cover more forms of diagnoses, as the spectrum of visual impairments is very broad. This could help us uncover the need for additional cue forms and information that should be highlighted.

Lack of Comparisons: Our evaluation of *how* effective and helpful our visual cues are was only based on qualitative feedback. While some participants were able to perceive the virtual city without visual cues, this was not the case for all. As a result, we could not directly compare the task performance of using no cues versus using cues. Thus, we could not evaluate their level of efficiency, only whether using them resulted in a successful task performance or not. Therefore, this should be investigated in future studies by letting participants perform the same type of tasks with and without visual cues. Furthermore, we also did not have quantitative data for the comparison of cue categories, since all participants used each cue category. Hence we could not directly compare the efficacy of cue categories based on task performance. We only relied on qualitative feedback from participants. This could be further investigated by testing task performance for each cue category separately.

VR Locomotion: As we have gathered from the qualitative feedback, the teleportation locomotion was shown to additionally negatively influence the orientation. Especially when participants teleported far away, it was difficult to understand the spatial relations of the old and new positions. Additionally, the teleportation often failed which led to some irritation. When participants needed to turn around at a large angle, they typically used the Snap-Turn feature, which could have made it difficult to maintain orientation. Furthermore, we could not fully test the potential of Obstacle cues for mobility, as participants did not have to directly avoid them during the navigation. However, due to smooth locomotion causing too much motion sickness, we had to opt for teleportation instead and accept these shortcomings. As such, investigating these cues in a VR setting with real life walking could help overcome the challenges caused by teleportation. For this, a large enough space would have to be provided to ensure safe walking for participants.

Limited Time: Although we did not have a direct time limit for the studies, typically concentration and performance decrease by the 1.5h mark, hence we did not want to exceed this time frame too much. Due to the selection and customization of the visual cues taking some time, there was not much time left for the exploration and search tasks. Finding the right balance between tasks being too challenging and too easy can be difficult with a large range of visual capabilities. To make the exploration and search not too time-consuming or challenging, we opted for the smaller city prototype containing only a small number of POIs. For participants with a higher self-reported remaining vision, this small city scene was shown to be relatively easy to comprehend. As such, we should further investigate how the results change in a larger and more complex city scene. This could potentially show the need for additional visual cues that we have not discussed so far. Additionally, since we did not have time to let participants fully test out each cue type, we only had them pick the ones they preferred. Having participants perform the given tasks with each cue type could additionally provide more insight into the suitability of different visual cue types for different visual impairment forms.

Feeling Pressured: Lastly, since participants gave scores for the evaluation per dialogue instead of filling out a questionnaire themselves, the participants could have potentially felt pressured to give better scores. However, we did not have the means to provide the participants with an accessible way to independently read and answer the questionnaires in the limited timeframe. Therefore, future studies should provide an accessible way for participants to give their answers privately without the presence of the study conductor.

7.3 Outlook

So far we discussed a number of ideas for how future studies could address the limitations of our work. Lastly, we want to give an outlook on how visual cues could facilitate orientation for visually impaired people in the future.

VR Training for Real World: In our user study results, we have seen that participants reported all visual cues as less important during the search task compared to exploration. This suggested that once participants acquired a sufficient cognitive map, they did not need to rely on the visual cues as much. As such, VR could be used as a pre-planning aid prior to visiting unfamiliar places. If whole cities were provided in VR, similar to Google Street View [1], users could familiarize themselves with their layout with the help of visual cues. This way they could acquire a cognitive map without the hazards of the real city. Upon arrival, their acquired cognitive map could then help guide their navigation.

Extention to AR: So far we mainly focused on the benefits of using VR, however, it also comes with its limitations. While it enables safe training, it cannot provide in-situ assistance. As such, with visual cues in-situ users would be provided with support even after training in VR. This way, obstacle cues could be extended to include moving objects as well, thus not only facilitating orientation but also mobility.

Inclusion of Non-Visual Cues: Lastly, although we argued that visual stimuli are most suitable for providing spatial information, including non-visual feedback in addition could provide a richer experience. Supporting the visual cues with auditive and haptic cues could help users perceive the information even better. This could be especially useful for people with very limited remaining vision who might have difficulties perceiving the current visual cues.

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Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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