# CHARLES UNIVERSITY IN PRAGUE

FACULTY OF HUMANITIES

Department of Psychology and Life Sciences

Bc. Oliver Kobián

# Effect of movement method and environment size on navigation and spatial memory

Diploma thesis

Prague 2024

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Supervisor: Mgr. Lukáš Hejtmánek Ph.D.

Prague 2024

## Declaration:

I declare that I have done this thesis independently. All sources and literature used were properly cited. The thesis has not been used to obtain another or the same degree

In Prague on . . . . . . . . . . Signature……………..

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I would like to thank my supervisor Mgr. Lukáš Hejtmánek Ph.D. for his guidance of my work, consultation, helpfulness, and his valuable advice and comments. I would also like to thank my friends and family for their support.

# Abstract

This diploma thesis focuses on locomotion methods in virtual reality, specifically on their effect on navigational abilities and spatial memory. In the theoretical part of this thesis firstly the topic of navigation, spatial memory, optic flow, spatial scale, virtual reality, and locomotion methods in virtual reality are described. In the empirical part, an experiment is presented. In this experiment, we studied two locomotion methods – Teleportation and Teleportation with optic flow, and their effect on navigation and spatial memory. We also examined the effect of spatial properties on these abilities – two sizes of environments were compared – small and large and also two types of complexity of environments – vista spaces and environmental spaces. The experiment had two parts, in the first part participants were looking for various objects and in the second part they were tasked to point at these object's locations with one reference point. Results showed significant differences in navigation duration and pointing duration between the examined locomotion methods – Teleportation with optic was faster. However, the effect of the locomotion method was not shown in the pointing accuracy and navigated distance. Also, no significant difference was found in cybersickness between the two LMs. Participants also navigated faster in vista environments than in environmental environments and they also pointed more accurately. The environmental size did not seem to affect the pointing accuracy, but participants pointed faster in small environments.

**Keywords:** virtual reality, locomotion methods, spatial memory, navigation, optic flow

# Abstrakt

Tato diplomová práce se zaměřuje na metody pohybu ve virtuální realitě, konkrétně na jejich vliv na navigační schopnosti a prostorovou paměť. V teoretické části práce je nejprve popsáno téma navigace, prostorové paměti, optického toku, velikosti navigovaného prostředí, virtuální reality a metod pohybu ve virtuální realitě. V empirické části je představen experiment. V tomto experimentu jsme zkoumali dvě metody pohybu - teleportaci a teleportaci s optickým tokem a jejich vliv na navigaci a prostorovou paměť. Také byl zkoumán vliv prostředí na tyto schopnosti - porovnávány byly dvě velikosti prostředí - malé a velké a také dva typy komplexity prostředí – vista prostředí a enviromentální prostředí. Experiment měl dvě části, v první části účastníci hledali různé objekty a ve druhé části měli za úkol ukázat na umístění těchto objektů za pomocí jednoho referenčního bodu. Výsledky ukázaly signifikantní rozdíly v délce navigace a délce ukazování mezi zkoumanými způsoby pohybu – teleportace s optickým tokem byla rychlejší. Vliv metody pohybu se však neprokázal u přesnosti ukazování a navigované vzdálenosti. Rovněž nebyl zjištěn významný rozdíl v pohybové nevolnosti mezi oběma metodami pohybu. Účastníci také rychleji navigovali v prostředí vista než v prostředí environmentálním a také přesněji ukazovali. Velikost prostředí neměla vliv na přesnost ukazování, ale účastníci ukazovali rychleji v malých prostředích.

**Klíčová slova**: virtuální realita, metody pohybu,prostorová paměť, navigace, optický tok

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# Abbreviations

| | |
|---|---|
| **AR** | Augmented reality |
| **HMD** | Head-mounted display |
| **LM** | Locomotion method |
| **MR** | Mixed reality |
| **PC** | Personal computer |
| **VE** | Virtual environment |
| **VR** | Virtual reality |
| **XR** | Extended reality |
| **USB** | Universal serial bus |
| **RAM** | Random-access memory |
| **LCD** | Liquid crystal display |

# 1 Introduction

Choosing the right locomotion method (LM) is a very important aspect of any virtual reality (VR) experience, especially in psychological experiments. VR can be a great tool to study various cognitive functions such as navigation and memory, however, the various LMs used can impair our navigational abilities and spatial memory in VR. In this diploma thesis, I will present an experiment comparing two different LMs - Teleportation and Teleportation with optic flow in various types of environments. The main goal of the presented experiment is to study the impact of these methods and the impact of the navigated environment on navigation and spatial memory.

In the first chapter of the theoretical part navigation in general and various navigation strategies and types of cues that humans use are explained. Afterwards, other cognitive processes that are important for spatial cognition are explained such as spatial memory, and spatial updating. A chapter about the importance of optic flow in navigation and in navigation in VR then follows. Throughout the theoretical part, the importance and use of VR in studying these processes is also described. In the conclusion of the theoretical part VR and its advantages and disadvantages are discussed. The last chapter focuses specifically on the problem of LMs in VR and focuses more on the two LMs used in the experiment, which is then presented in the empirical part of this thesis. In this experiment, two LMs and their impact on navigation and spatial memory are studied – Teleportation and Teleportation with optic flow. Other than the impact of the LMs also the impact of the type of environment is studied. Firstly, the effect of the scale of the environment and secondly the effect of the environmental complexity.

# 2 Theoretical section

Throughout the theoretical section, I will try and explain various topics closely related to the topic of the presented study in the empirical part. In the experiment the effects of locomotion methods and environmental properties on navigation and spatial memory in VR were studied, So in the first chapter, I will discuss navigation overall more broadly as a foundation on which I will build in the following chapters about spatial memory, spatial scale, and optic flow. The last chapter will focus more on VR and locomotion methods in VR.

## 2.1 Navigation

Almost every day we need to travel to work, school, the doctor's office, or even from our bedroom to the kitchen. This coordinated movement from one point in the environment to another is called navigation (Montello, 2005). Almost every species needs to navigate in some way and this skill is very important for their survival. Multiple cue sources such as path integration, external cues, or magnetic cues are used and combined for successful navigation (Brodbeck & Tanninen, 2012), and many body systems and cognitive processes are involved in navigation - for example, our abilities to perceive, remember, and reason in space and place (Montello, 2005). In human navigation, vision and visual cues are the most important but we can also rely on auditory cues, self-movement cues coming from one's body, and many more.

In the following chapter, the various navigation strategies and theories and how they work mainly in humans will be explained.

### 2.1.1 Navigation strategies

There are various navigation strategies that we use depending on the context of the situation, type of environment, individual preference, etc. These strategies also differ in the type of cues they use. There are two types of cues or inputs used for navigation - idiothetic and allothetic. The navigational strategy is then based on an interaction and combination between these two types of cues (Knierim et al., 1998).

**Allothetic cues** are the external cues of the environment. This is the information coming from the surrounding environment which is picked up by the different sensory modalities (visual, auditory, olfactory, and haptic) (Jain et al., 2017). The agent can locate their position by using external cues encountered while moving. These cues are stable and reliable and can be used as a reference for long periods (Whishaw et al., 2001). Allothetic navigation therefore works based on the position estimation depending on the perceived distance from these external cues (Wiener et al., 2011).

**Idiothetic cues** on the other hand are internal cues coming from the body of the navigator. This self-referential information is generated when the navigator moves (Jain et al., 2017). The main example of these types of cues is proprioception which is the sense of position of the navigator's body. Another type of idiothetic cue is the sensory or optic flow which is generated during movement (Jain et al., 2017). The third type of idiothetic cue is vestibular information. These idiothetic cues provide the navigator the ability to estimate their speed by monitoring changes in stimuli caused by the movement (Whishaw et al., 2001).

### 2.1.2 Path integration

Path integration (also called dead reckoning) is a navigational strategy that mainly uses idiothetic cues. It is the ability to return to the starting point of a journey using only internal body-based cues. The navigator continuously estimates their position according to a reference point (for example nest) using the signals coming from their own locomotion (Etienne & Jeffery, 2004). Also to successfully path integrate animals have to keep a continuous sense of their direction (Etienne & Jeffery, 2004). During path integration, the navigator continually records the information generated during the movement and calculates this information to generate the homing vector which is the vector back to the starting location (home, nest, etc.) (Fujita et al., 1990).

Although path integration can be sufficient using only idiothetic cues, using external cues from the environment can help to correct or update this heading direction or even initiate path integration (Whishaw et al., 2001). In navigation, landmark cues and motion cues from path integration continuously interact (Etienne & Jeffery, 2004) but path integration becomes very important when there is no landmark information (Wiener et al., 2011), or when vision is otherwise obstructed.

#### 2.1.2.1 Path integration in humans

To study path integration in humans the triangle completion task (also called return-to-origin task) is used the most often. In this task, blindfolded participants are sent along two edges of a triangle, and after reaching the end of the path they walk to the starting point to complete this triangle (Wiener et al., 2011). The subjects show their understanding of the relationship between the starting and drop-off points through path integration along the intervening path. In this task, the navigator keeps track of the starting point concerning their location (Loomis et al., 1998). Results from studies using the path completion task show that humans are not able to navigate using path integration alone. The subjects in the triangle completion studies usually make systematic errors, underestimate large turns, and overestimate small turns, also short distances tend to be overestimated and longer distances underestimated (Dorado et al., 2019).

For example a study by Loomis et al. (1993) compared adventitiously blind individuals, congenitally blind, and blindfolded sighted individuals in the triangle completion task. Here all the studied groups performed poorly with many errors. Also, no significant difference between the groups was found. The subjects made systematic errors turning not enough in larger turns and turning too much where smaller turns were needed.

Another more recent study was conducted by Dorado et al. (2019) in VR. They compared the path completion task with available locomotion (VR treadmill - this method translates body movements from reality to the virtual world) and without it (touchpad condition - the locomotion was controlled only by the motion tracking controller) in different VR displays. Here independently of the display type the subjects systematically underestimated the direction and distance of the starting location. However, the added motor cues in the treadmill condition improved the performance.

#### 2.1.2.2 Error in path integration

Path integration is an effective navigation strategy, especially as a homing mechanism but it also has its limitations. As implied in the previous section both random errors and systematic errors may happen (Rodrigo, 2002). Estimation of self-motion comes from multiple sensory modalities and relies on different kinds of information such as proprioceptive and vestibular information and visual flow. However, the integration of these cues is susceptible to errors (Stangl et al., 2020). The dead-reckoning system also cannot correct these errors in any way, so errors accumulate over time. The greater the traveled path the less accurate the estimation of the homing vector will be (Wehner & Srinivasan, 1981).

Also, the internal signals will always be affected by noise (Etienne et al., 1996). Noise will impact the displacement estimates leading to errors in determining positional uncertainty. Direction errors originate when using a fixed landmark and rotation errors (which accumulate over time) occur during the integration of angular velocity to determine direction (Heinze et al., 2018). Path integration memories and their maintenance are also prone to the same type of error (Heinze et al., 2018).

Because of these errors path integration is the most precise and reliable over short journeys. This is why the use of external (allothetic) cues and landmarks is important in navigation and often can complement path integration - reliance on landmarks is needed to have a more accurate performance (Dorado et al., 2019). However, with more available self-generated cues, the position estimation becomes more precise (Etienne et al., 1996). Path integration is also a fundamental component in building cognitive maps as it allows us to associate the external environmental cues with positional estimates and also plays a crucial role in the transfer to route knowledge and wayfinding (Stangl et al., 2020).

### 2.1.3 Landmarks

The second class of navigation strategies uses allothetic cues - the external cues of the environment. One example of these cues is landmarks, which are cues in the environment that are stable and have some informative and salient features (Jain et al., 2017; Stankiewicz & Kalia, 2007). The more informative or unique the object in the environment is, the more memorable it will be and the more likely be used as a landmark (Stankiewicz & Kalia, 2007). These objects should also preferably be stable in the environment as this can also influence their salience as landmarks (Chan et al., 2012). Landmarks can be acquired by olfaction and audition or by other means although humans mainly use their vision to recognize them (Montello, 2005).

### 2.1.4 Beaconing

A very simple landmark-based navigation strategy is called beaconing. In this strategy, a single distal landmark in the environment can serve as a navigation point by acting as a beacon. The place of the beacon shows the target location or the direction of the location. Beaconing (or beacon following) is a form of visually guided navigation in which the navigator only needs to monitor their location with respect to the beacon ignoring other environmental information (Jain et al., 2017).

### 2.1.5 Route following

A little more complex although still a fairly simple navigation strategy using landmarks is route following. This strategy uses multiple landmarks or routes to navigate to the goal as opposed to the beaconing strategy (Jain et al., 2017). It is a strategy of navigating along a more complex route and the movement changes at specific landmarks as it works as a basic stimulus-response learning (Geva-Sagiv et al., 2015). It is for example employed when driving a car (Geva-Sagiv et al., 2015) or while hiking and following some kind of marker on the trail (Van Der Ham & Claessen, 2017).

### 2.1.6 Cognitive maps

The most complex navigation strategy is called the cognitive map. This term was first used in 1948 by Tolman. During his experiments on rats, he found that the learning of the rats was not simply a stimulus-response connection but instead, the rats seemed to build up a kind of a map in their nervous system (Tolman, 1948). The cognitive map is, simply put, an internal representation of the space, and most adults have a number of these maps, which allow them to successfully navigate on a day-to-day basis (Stankiewicz & Kalia, 2007). The process of cognitive mapping is therefore storing, encoding, and manipulating the experienced spatial information (Golledge et al., 2000). This assumes the ability to store information in memory about the environment in which the navigator makes spatial decisions (Kitchin, 1994). Cognitive maps are constructed from the information that is gained from exploring the environment and storing spatial relations and attributive data. The construction of cognitive maps happens gradually from different pieces of information gained during navigation. These maps then allow the navigator to function and analyze environmental and geographic information (Kitchin, 1994). It is essential to know and provide spatial relations between two different locations “without necessarily knowing how to get there” (Meilinger, 2008, p. 345).

#### 2.1.6.1 Neural basis of cognitive maps

The concept of cognitive maps gained significant support with the discovery of various types of specialized cells in the brain that contribute to spatial navigation. The first and most significant was the discovery of place cells in the rodent hippocampus by O’Keefe & Dostrovsky (1971). These cells fire when an animal approaches specific locations within the environment. The firing pattern signals an animal's location and seems to be a crucial component of the cognitive map. O’Keefe and Nadel (1978) further proposed that the hippocampus provides the neural basis for the spatial map and that this spatial map is organized in an Euclidean coordinate system encoding landmarks and goals based on their allocentric locations (Epstein et al., 2017).

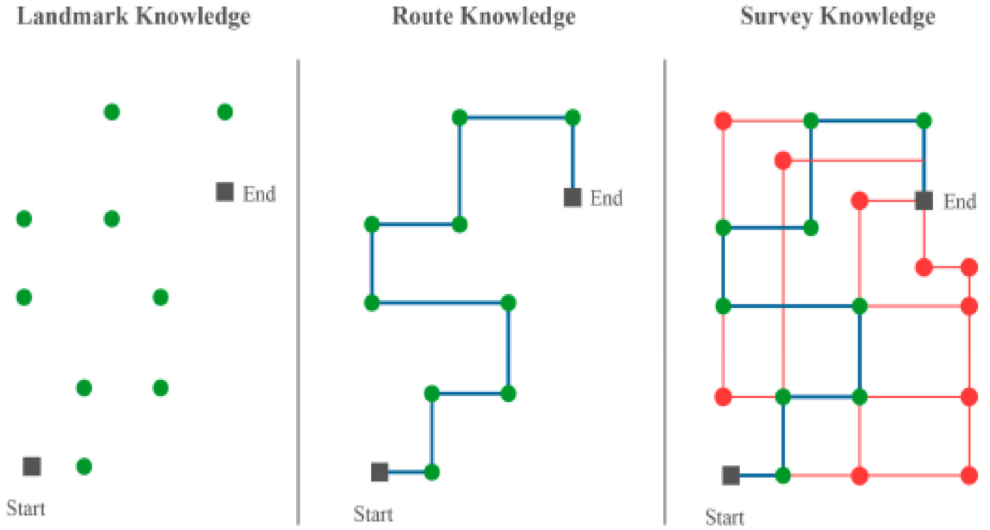
Subsequent discoveries revealed additional cell types contributing to the navigation system. Firstly the grid cell in the medial entorhinal cortex “fire in a regular hexagonal lattice of locations tiling the floor of the environment” (Epstein et al., 2017, p. 1504). They are believed to underlie path integration (Grieves & Jeffery, 2017) and are also thought to encode distances as the navigator moves through the environment (Epstein et al., 2017). Secondly, the head direction cells distributed across various brain structures, fire according to the orientation of the navigator's head. And thirdly the border cells are located in the entorhinal cortex and boundary cells in the subiculum which fire “when the navigator is at set distances from navigational boundaries at specific directions” (Epstein et al., 2017, p. 1504). Place cells, head direction cells, and grid cells are thought to be the basis of the cognitive map although so far many more types of cells have been discovered in various brain regions (such as object cells, goal cells, etc.) and the question of how spatial cognition in the brain is supported is not yet completely answered (Grieves & Jeffery, 2017).

### 2.1.7 Landmark, route, and survey knowledge

Several theories have proposed methods for using visual information, particularly landmarks, to learn an environment. In 1975 Siegel and White postulated a model of spatial knowledge called Landmarks, routes, and surveys. Cognitive maps are thought to be learned by acquiring these three elements of the environment by unifying landmarks and routes with survey information (Tversky, 1993).

In this model landmarks are the base components of spatial representations. Route knowledge is the knowledge of "spatial layout from the perspective of a ground-level observer navigating the environment" (Shelton & Gabrieli, 2002, p. 2711). It can be defined as a place-action association and through route knowledge we can navigate a known path from one place to another (Chrastil, 2013). It is the path sequence connecting the previously learned landmarks in the environment (Quesnot & Roche, 2014). The Survey knowledge also includes information on the layout of the environment and how these individual routes fit together (Chrastil, 2013). Having the survey knowledge one is aware of the relationships between the spatial components of the space, and should be able to estimate distances between points of interest, give directions, and take shortcuts in the learned environment (Quesnot & Roche, 2014).

*Figure 1 Graphical representation of Landmark, route, and survey postulated by Siegel and White (1975)*



**Source:** *(Quesnot & Roche, 2014)*

## 2.1.8 Hierarchical models

Hierarchical models expand on these models even further. According to Poucet (1993), spatial representations can hardly be described as maplike Euclidean representations of space. Humans do not use a mathematical formula that would take a map and put it in a mental representation; the information is more likely to be gathered and reorganized completely differently (Tversky, 1992). One of the proposed models for reorganization of the information is the hierarchical theory which suggests that various regions of an environment are stored in different branches of a graph-theoretic tree. The mental representation is organized such that "increasingly more detailed spatial knowledge is given at lower and lower levels of the hierarchy" (McNamara, 1986, p. 90). According to Tversky (1992), people use categories instead of (or in addition) to the Euclidean information in a map of the environment. We group locations on maps together and the landmarks into higher-order categories. These can be higher geographical categories (countries) or smaller conceptual categories (types of buildings) and these categories can also distort memory and make the memory loading more difficult. Tversky (1992) summed it up followingly:

> People infer the direction of entities in a category from the overall direction of the category, thereby distorting the direction of cities in a state in the overall direction of the state. People are faster to make judgments of direction when cities are in two different states or categories than when they are in the same state. And when the two cities are in the same state, the farther apart they are, the easier it is to judge which is more north or east. Categorization also affects distance estimates. People estimate distances between entities in the same category as relatively smaller than distances between entities of different categories. (p. 133)

The hierarchical model works based on information clustering. According to Hirtle & Jonides (1985) the judgments across clusters are promoted and also biased by the relationships between categories, the judgment can be promoted by priming within a cluster, and cluster boundaries also influence distance judgments. Therefore learning about an environment involves an incorporation of local perspectives into place representations, creating maps of regions, and calculating an overall reference direction for each map (Poucet, 1993).

#### 2.1.8.1 Hierarchical model studies

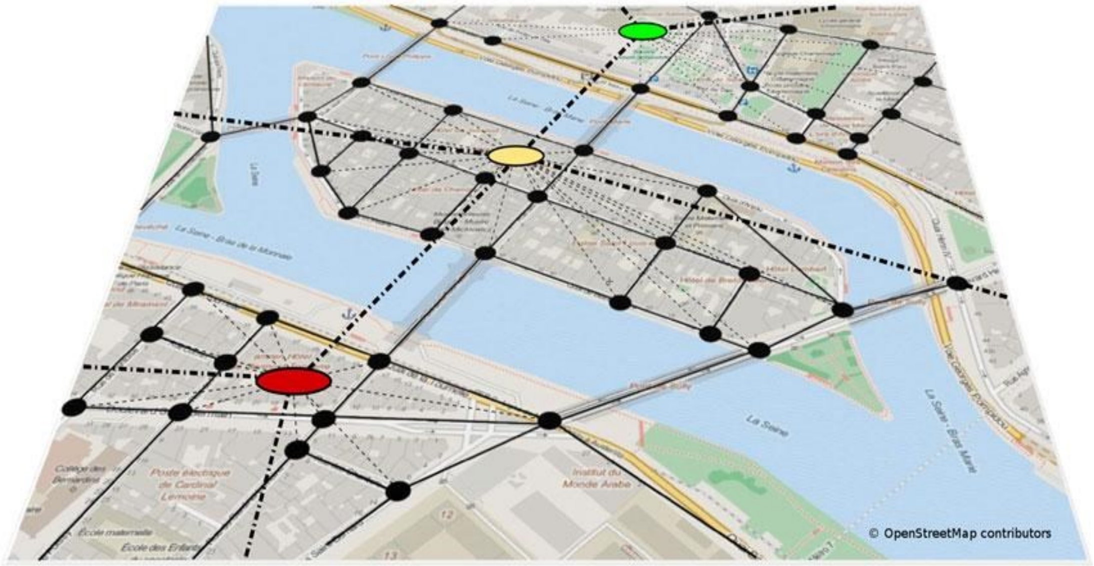
The hierarchical model is supported by numerous studies showing systematic errors in errors in memory and judgment of environmental knowledge. For example in a study by Stevens & Coupe (1978), the first experiment was designed to study distortions in spatial memory. In this task, the knowledge about the direction between locations was studied. They chose pairs of locations whose direction was different from the direction of their superordinate units. It was confirmed that there is a systematic tendency to alter the direction estimates toward the direction of the higher relationships. Based on these findings the authors proposed a hierarchical superordinate structure in which we store the spatial relations. We store the locations of the states and then the cities by the state. So, the state acts as a superordinate category, and when we try to determine directions from one city to another, we first consider the state's overall direction. This can then distort our judgment.

In another similar study by Wilton, (1979) again pairs of towns (from the U.K. and Scotland) were compared based on their directions. Here they found a decrease in reaction time the further apart the towns were therefore pointing to a necessity to access more detailed representations when the towns are closer together. This model was further proven in the second experiment where they compared reaction times in guessing the direction of either two English towns or a pair of Scottish and English towns (all the Scottish cities are north of the English towns). Again, the reaction times proved to be shorter in the latter condition further proving the hierarchical model. Subjects firstly access information about the locations of the towns only roughly (in this case as being in England or Scotland). Only if this information is not sufficient, they then access the more specific information which would slow their reaction time.

#### 2.1.8.2 Cognitive graphs

Further expanding on the cognitive maps and hierarchical models are **cognitive graphs**. In this theory, the spatial memory and the stored cognitive maps are thought to be represented as graphs. In the graph, the individual landmarks, single vista spaces, and specific sensory inputs correspond to nodes and the movement vectors connecting the landmarks correspond to edges and they mostly represent the action to move between these nodes (Meilinger, 2008; Wiener & Mallot, 2003; Wolbers & Wiener, 2014). Several places can also be linked to create different regions which allows the hierarchical spatial knowledge to form (Wolbers & Wiener, 2014).

*Figure 2 Graphical representation of Hierarchical graph-like representation of an environmental scale space. The nodes represent single vista spaces, and the different colors represent the hierarchic structure.*



***Source:*** *(Wolbers & Wiener, 2014)*

Successful navigation depends on a combination of idiothetic and allothetic cues and also on a combination of various navigation strategies. There are also many more theories and approaches that I did not describe in the previous chapter as the theory is so extensive. Here I tried to outline the basics of navigation strategies and theories. In the following chapter, I will talk more about spatial memory as a very important cognitive process in navigation and especially in creating cognitive maps.

## 2.2 Spatial memory

The ability of cognitive mapping and other navigation processes is facilitated by spatial memory. This is the ability to remember visited places and keep track of one’s location as well as retrieving the information when needed for navigating and constructing spatial representations (Colombo et al., 2017; Olton, 1977). Spatial memory and remembering the locations of objects is a very important component in large-scale navigation. The location can be coincident with a landmark, it can be remembered as a triangulation from an array of objects or the location can be perceived (encoded) in the direction of a distal landmark (Jacobs, 2003). Spatial memory encodes and stores spatial relationships. The acquired spatial information reduces the navigator's uncertainty of their position with respect to geographical objects. This information includes sensory characteristics of a location and can also include the speed of the movement and its direction (Fagan et al., 2013).

Fagan et al. (2013) also state another type of memory that can influence animal movement - **attribute memory**. This type of memory stores useful information about the locations and the spatial information such as types of food and quality of resources linked to the specific location. Valuable or otherwise important locations may be stored in the memory with more resolution signifying its importance (Fagan et al., 2013).

### 2.2.1 Reference frames

Spatial information and navigation rely on two reference frames - allocentric and egocentric. Space is encoded in memory according to these reference frames. When encoding location, it can be relative to one's body (egocentric) or independent from one's body (allocentric). The spatial memory encoding of an object's position is therefore either egocentric or allocentric (Jacobs, 2003).

#### 2.2.1.1 The egocentric reference frame

The egocentric reference frame relies on relationships between the subject and objects and leads to the creation of self-centered representations. In this reference frame, the navigator is the center of reference and all the landmarks are stored as relative to their position (Colombo et al., 2017). Orientation while using an egocentric reference frame integrates information from a first-person perspective relative to the position of the navigator (Gramann et al., 2010).

#### 2.2.1.2 The allocentric reference frame

The allocentric reference frame, on the other hand, works with object-to-object relations (world-centered representation) and here the navigator is one point of representation instead of the central point (Colombo et al., 2017). Orienting and navigating using this reference frame transforms these relationships into map-like representations. Here the angular and metric relationships remain consistent irrespective of the navigator's heading (Gramann et al., 2010).

To successfully navigate we do not rely on a single one of these reference frames but rather switch and combine between them according to the environmental requirements (Colombo et al., 2017). The use of either appears to depend on various factors: “the amount of self-motion between presentation and retrieval; the size and intrinsic spatial structure of the environment; and the extent of prior experience within it” (Burgess, 2006, p. 556). However, it seems that small-scale tasks are more likely to use egocentric reference frames and larger-scale tasks are more likely to employ allocentric representations (Byrne et al., 2007).

### 2.2.2 Spatial updating

To successfully navigate we also need to maintain a sense of where we are and where the objects and other features of the environment are (Montello, 2005). The process responsible for this is called spatial updating. It is a cognitive process that automatically computes the spatial relationships between the navigator and the environment based on the information about their movement. As we move the egocentric locations of objects constantly change based on our movements therefore this process is essential for perceiving the positions of objects relative to one's body and for maintaining situational awareness (Wolbers et al., 2008). It is especially important when we walk with little vision and in navigating complex environments (Wolbers et al., 2008).

People update through various cues. Firstly, the visual system detects self-motion through optic flow patterns and changes in the landmark's position. And secondly, proprioception cues provide the navigator with information about velocity and acceleration (Klatzky et al., 1998). The spatial updating process seems to be automatic and we constantly update our positions as we move (Martin & Thomson, 1998; Riecke et al., 2007).

#### 2.2.2.1 Spatial updating in VR

Studies show us that VR can be a great tool to study spatial updating even though in VR the body-based cues are usually missing and the cues to assess self-motion other than the optic flow are also usually reduced (Borodaeva et al., 2023). For example, a study by Wan et al. (2009) compared spatial updating in real and virtual environments (VE) and specifically examined how spatial updating works when subjects are placed in superimposed real and VEs. Participants were put in a virtual kitchen and a real room and were tasked to learn the locations of targets and to navigate through these environments. They were then asked to face these remembered targets blindfolded. The results of the two experiments showed that the participants updated the two superimposed environments simultaneously. These results suggest that even VEs can be treated like real environments when visual stimuli are available. So it seems that visual cues alone are capable of supporting spatial updating to a certain extent. VR can therefore be a good tool to study this process.

In a more recent study by Borodaeva et al. (2023), the self-motion cues possibly used in spatial updating were manipulated and real walking with passive locomotion was also compared. The static visual cues also varied in the second experiment - either only the boundary was available, five landmarks or both were available in different conditions. Their results suggested that increased optic flow and real walking did not improve spatial updating further proving that only a little optic flow is needed for spatial updating to work properly. However, the environmental richness in the form of landmarks and borders significantly improved updating. So the richness of the environment seems to be a good method to support spatial updating in VEs.

Spatial memory is an important aspect of navigation and navigational behavior. It is a crucial ability for the survival of many species - in our memory, we can for example store the locations of food sources and attributes of these sources and we also remember dangerous places. This ability also directly facilitates our cognitive mapping abilities and participates in most of the other navigational processes.

In the following chapter, I will outline the types of spatial scales and types of environments and how these aspects of our surrounding environments can impact our navigational behavior and spatial memory. I will also address the use of VR in spatial scale and spatial properties research.

## 2.3 Spatial scale

Environmental properties can also greatly affect our navigation abilities and even what type of navigation strategy will be employed. Specifically, the scale and complexity of the environment in which we travel. In 1993 Montello proposed a novel classification of psychological spaces that integrated the differences from other theories and also added some novel terms. He named the environment categories figural, vista, environmental, and geographical. Figural spaces are projectively smaller than the body and no locomotion is needed for it to be perceived. These could be some small objects which can be manipulated by hand. Vista spaces are projectively larger than the navigator but most relevant information in vista space can be acquired from a single viewpoint (Ekstrom & Isham, 2017). So again practically no locomotion is needed to apprehend these types of spaces. Examples can be single rooms without any high obstacles obscuring vision but also whole town squares and similar “larger” environments which can be seen from any one point in the environment. Environmental spaces are projectively larger than the navigator and cannot be apprehended from a signal viewpoint in the environment (Montello, 1993). These could be apartments, whole buildings, or cities. In this case, locomotion and exploration are needed to gain all the necessary information about the environment (Ekstrom & Isham, 2017). And the geographical environments are projectively much larger than the body and we cannot apprehend them even via locomotion (Montello, 1993). An example of a geographical environment would be an aerial view from an airplane.

Although it makes sense to think of environmental spaces as large-scale spaces the distinction between vista and environmental spaces does not always have to be in its scale. The main difference is in the opaque borders dividing the environmental space which separates the environment into multiple vista-like spaces. We can see an example of this in Figure 3 where both of the environments are of the same size however one is vista and the other is environmental.

*Figure 3 Example of the same-sized vista (a) and environmental environments (b)*

***Source:*** *(Ekstrom & Isham, 2017)*

### 2.3.1 The effect of spatial properties on navigation

Navigation and other spatial processes are different in vista and environmental spaces as well as in different scales of environments. The main difference between vista and environmental spaces is the needed locomotion to gain the necessary information about the environmental space. As the vision is obstructed by borders the target locations in environmental spaces are obscured while in the vista space, they lie within the sensory horizon. So the information in environmental spaces cannot be acquired instantaneously but needs to be experienced over time during exploration (Wolbers & Wiener, 2014). Navigating larger environmental spaces also takes more time and involves different processes such as localization, planning, monitoring, and replanning.

Studies also suggest that environmental representations are accessed sequentially - representations of environmental scale-spaces are fragmented into independent vista units (Brockmole & Wang, 2002; Wolbers & Wiener, 2014). This means that response time is increased the more complicated and larger the environment is (Meilinger et al., 2016). The information about the larger environmental environments seems to be stored in more reference frames and the vista representations also have to be linked (Wolbers & Wiener, 2014), supporting the idea of hierarchical graph-like representations. Also, distances tend to be underestimated in a single unit as opposed to the same distance but separated by borders (Kosslyn et al., 1974).

To learn the structure of the larger environments one must build a cognitive map of the environment. To do so the observations need to be combined over extended periods (Kuipers & Levitt, 1988). Another difference between large and small-scale environments is in spatial updating. This process seems to concentrate more on the immediate environment and less on distant targets exceeding the current space. And for larger traveled distances, there is also a higher risk of computational error (Meilinger et al., 2016).

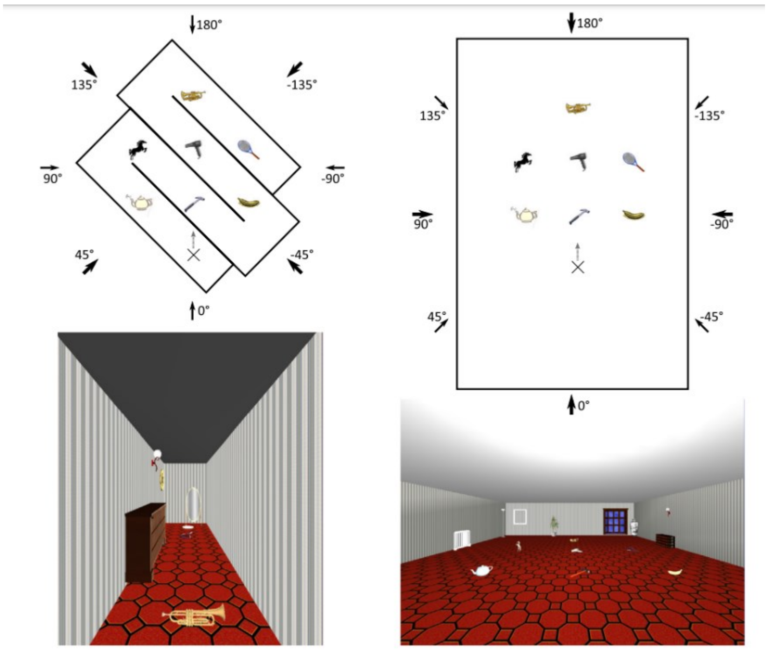
### 2.3.2 Spatial scale in VR

Again, VR can be a great tool to study the effect of scale on human navigation. In VR we can access large environmental spaces from much smaller real environments. Various LMs allow travel through much larger environments from room-tracked areas making it easier to study navigational behavior in larger spaces.

In a study by Nguyen et al. (2008), the effect of scale change on distance perception was studied in VR. The participants were put in a virtual tunnel with targets ranging in distance and various types of scale changes were implemented. The procedure consisted of an adaptation phase, where the participants made 20 distance judgments and received feedback. In the test phase, the scale changed, and they completed another 10 estimates now without feedback. Throughout the two conducted experiments various conditions were implemented - the scale of the tunnel was changed, the scales of all aspects, the scale of the targets, and the scale of the separation of the targets. When all aspects were scaled, participants going from the large to small tunnel perceived the same distances as longer and participants going from the small to the large tunnel perceived the distances as shorter. When only the tunnel was scaled participants perceived the distances as the same. Meaning that not all scale changes have the same effect in the distance perception.

Another very interesting study by Meilinger et al. (2016) explored memory in vista and environmental spaces. Participants were tasked with learning the same layout of objects, either in a vista space or across multiple corridors in an environmental space. In their experiment, they tested the participants in visual pointing after learning the object layout either in a vista or in an environmental space. In the environmental condition, the latency of retrieving the objects from memory increased with greater corridor distance. However, this effect was not observed in the vista condition; objects were retrieved equally quickly regardless of distance. Moreover, memory for environmental space appeared to be structured based on the learning experience rather than the inherent layout structure. This suggests that the processes involved in perceiving vista and environmental spaces likely differ. To further prove this in the second experiment participants in the second experiment memorized the same object layout but presented in the order as it was in the environmental space. This again did not get similar results as found in environmental space learning.

*Figure 4 Layout design from a VR study by Meilinger et. al (2016). On the left we can see the environmental condition and on the right the vista condition.*



***Source:*** *(Meilinger et al., 2016)*

In this chapter, I tried to outline the effect of environmental properties on navigation and other spatial processes. Navigational researchers should be aware of these effects and account for them in the interpretations of their results. VR can be a great tool for researching this topic since the environmental properties are easily manipulated and we also can simulate and test much larger environments than would be possible in reality. In the following chapter, I will address the topic of optic flow and its role in navigation.

## 2.4 Optic flow

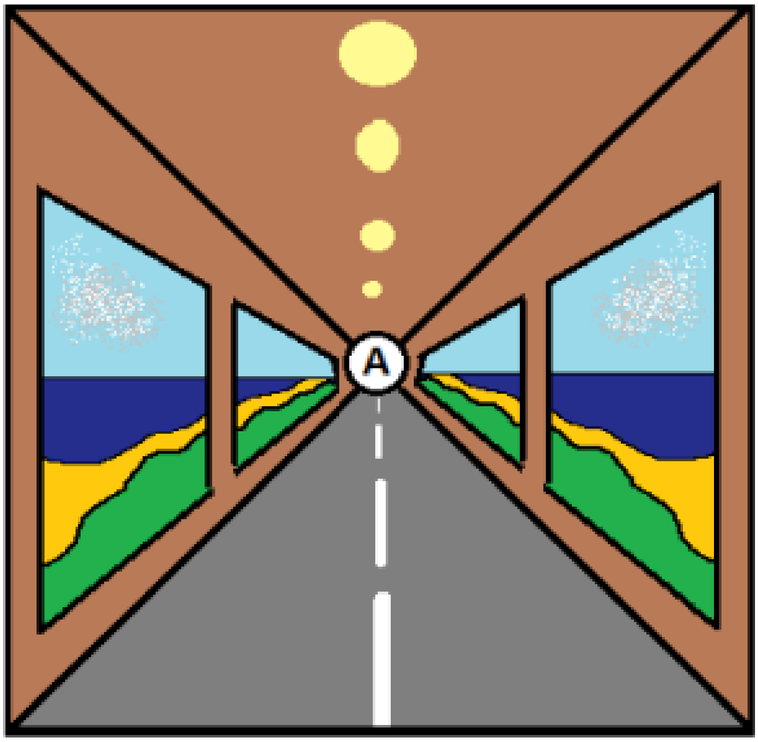
Human navigation is controlled mainly by our vision. Not only can we process landmarks but with vision we can also assess our self-motion. While moving through an environment a motion pattern is created at the eye. This pattern moves relative to the environment. It is the apparent motion of objects and textures in the visual field that is relative to the navigator's movement (Lappe et al., 1999; Warren, 2008). This phenomenon is known as optic flow and was proposed in 1950 by James J. Gibson. It is a form of visual streaming and occurs because "the image of the same object(s) are constantly changing with regards to which area of the retina they stimulate" (Forrester et al., 2016, p. 328). We fix our gaze on an object and as we go forward the information from objects in the background informs us about our location in the environment (Forrester et al., 2016). According to Koenderink (1986) optic flow provides information about ego-motion, information which sustains egocentric orientation, sustains segmentation and aggregation, and provides exteroceptive information providing the spatial structure of the environment.

### 2.4.1 Optic flow strategies

Gibson (1950) also proposed that we use optic flow to control the direction of locomotion. This is termed the **heading strategy**. "The visual motion in the 'optic array surrounding a moving observer' radially expands out of a singular point along the direction of heading" (Lappe et al., 1999, p. 329) and this point is called the Focus of expansion (FOE). This is the point from which the optic flow seems to come, and optic flow always travels away from this point (Fig. 5). Moving through an environment probes the visual input at the eye which transforms radially and the focus of expansion is aligned with the destination which the navigator is heading towards (Turano et al., 2005). Optic flow seems to be used to perceive and also regulate self-motion. If we were to navigate a straight path without any rotation the focus of expansion would indicate the direction of travel. So if we align our heading we can correctly steer towards a target in the environment (Li & Niehorster, 2014).

Other strategies are explaining the control of locomotion through optic flow. There is the **path strategy** according to which we can use path and not heading to control locomotion (Wann & Land, 2000). If we were steering towards a target we could accomplish the task by adjusting the curvature of our path to a predetermined value and maintaining it constant, ensuring that the trajectory aligns with the target (Li & Cheng, 2011). There is also the **tau-Equalization strategy** according to which “to steer toward a goal, we can also steer to render the simultaneous closure of two gaps: the target heading angle () and the distance of the target along the heading direction” (Li & Niehorster, 2014, p. 766).

*Figure 5 Visual representation of FOE. Point A represents the point from which the optic flow travels*



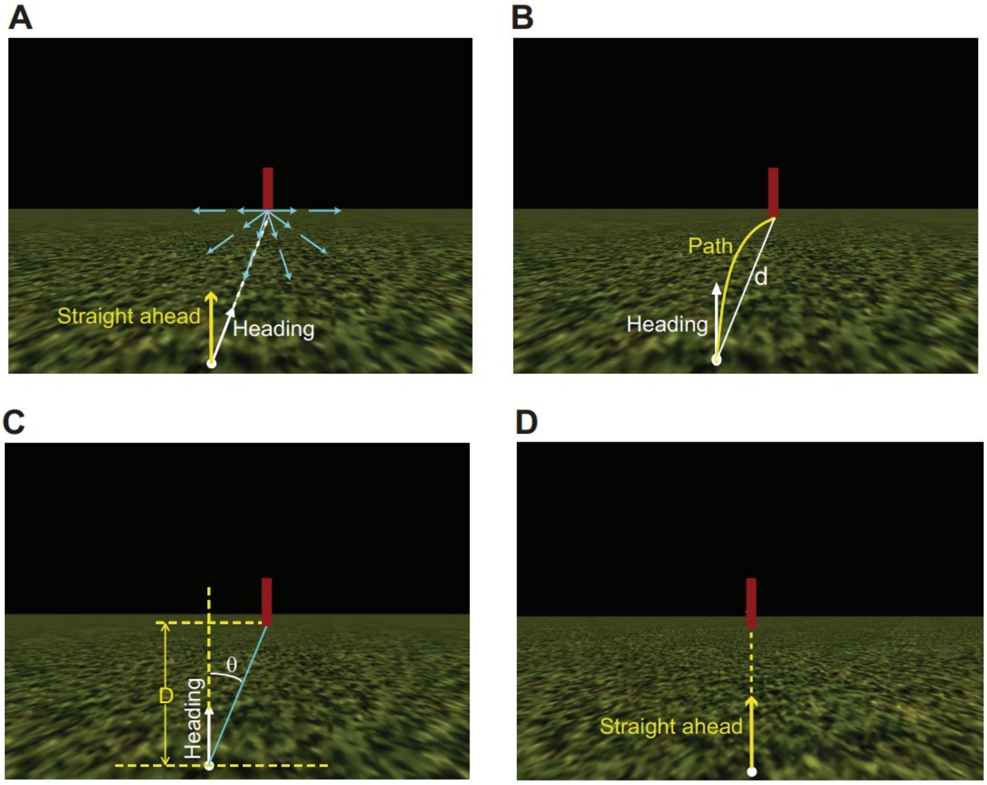
**Source:** *http://www.eyesonjason.com/vs_p8_self_motion_and_optic_flow.html*

### 2.4.2 Egocentric direction

People can also walk in the direction of a target without visual cues (Turano et al., 2005). In opposition to the optic flow strategies controlling locomotion is the egocentric direction strategy. This strategy relies only on an egocentric direction. According to this strategy, people do not rely on information from optic flow but instead can steer to a goal using just its egocentric direction (Li & Niehorster, 2014; Rushton et al., 1998). This strategy mainly relies on the perceived direction of the target. The direction is gained from its location on the retina and the information about eye positions. It works simply by visually fixating on the target and traveling towards it (Turano et al., 2005). If we would center the goal straight ahead we would travel in a straight line toward it (Li & Niehorster, 2014).

Evidence for the egocentric strategy comes from studies with displacing prisms. Rushton et al1998) showed that if displacing prisms were put in front of the subjects' eyes, they made a curved path toward the goal. Therefore, it seemed that the subject used only the egocentric direction of the goal and did not rely on optic flow.

*Figure 6 Optic flow strategies (A. Heading strategy, B. Path strategy, C. Tau-equalization strategy, D. Egocentric strategy)*



***Source:*** *(Li & Niehorster, 2014)*

Although it is agreed that optic flow can guide the control of locomotion towards a goal (Li & Niehorster, 2014) the effect of optic flow depends on the salience of the visual context (Turano et al., 2005). Therefore, the more prevalent the optic flow cues the more precise the control of locomotion and the more precise the estimation of self-motion is. However, it seems that both the egocentric direction and optic flow strategies guide locomotion. If the optic flow is not available or is otherwise obstructed, we will tend to focus on the egocentric strategy more. But with all the cues available these strategies seem to complement each other and not exclude one another.

### 2.4.3 Optic flow in VR

The availability of optical flow cues can be easily manipulated in VR which makes it a great tool to study the effect of optic flow on navigation. In a VR study by Cardelli et al. (2023) the optic flow cues were manipulated by changing the texture of the floor (either optic flow was rich or not available at all from self-motion). Here the available optic flow affected spatial updating - the ability was impaired when the optic flow was not available. So it showed that only visual cues are relevant for spatial updating of the objects in the environment. Mainly in the absence of vestibular and proprioceptive cues the optic flow provides information about self-motion and the optic flow provided by the ground had a dominant role in the estimation of self-motion and hence the ability to update spatial relationships (Cardelli et al., 2023).

A very influential study in VR by Warren et al. (2001) tested the egocentric strategy versus the optic flow strategy by manipulating the available optic flow. Their findings confirmed that humans rely on both optic flow and egocentric direction to orient toward a target. When the available optic flow was reduced the participants relied more on the egocentric direction and with greater optic flow the behavior tended to be more dependent on the optic flow. According to the authors these two strategies work in a complementary manner.

A study by Riecke et al. (2002) studied path integration using only visual information on a 180° screen. In one of the experiments, the participants were able to correctly update rotations only from optic flow and also to reproduce distances. Their results showed that path integration using only visual cues is sufficient for simple navigation.

Optic flow also promotes faster spatial learning and better spatial memory (Kirschen et al., 2000). According to Redlick et al. (2001) optic flow gives a consistent sensation of self-displacement and if the visual cues were strong, we could rely only on optic flow to navigate. And finally, the availability of the optic flow also affects distance estimations (Mossio et al., 2008; Redlick et al., 2001).

In conclusion of this chapter, we can say that optic flow is a very important cue in navigation for assessing self-motion. And even more so in VR where other self-motion cues such as proprioception or vestibular cues are neglected or completely missing. VR can be a great tool in studying the effects of optic flow on navigation as we can easily manipulate its properties and availability. In the following chapters, I will focus on VR and its uses, advantages, and disadvantages specifically on navigation and navigation methods in VR.

## 2.5 Virtual reality

Virtual reality is a technology that simulates virtual 3D environments and usually also enables some kind of interaction with the environment. It can be used to simulate real environments or to create completely novel ones. VR can also be used to simulate the behavior of other 3D objects and entities  (Hudson et al., 2019). This simulation is computer-generated and requires a special type of hardware. In the case of non-immersive VR, only a PC and monitor are needed. So any video game played on a PC would be a non-immersive VR - this type of VR can also be called Desktop VR. For immersive VR experiences, a special device called the Head-mounted display (HMD) is needed. This headset includes two small high-definition monitors for each eye for stereoscopic vision of the environment. These HMDS usually also include sound and haptic inputs that can be added by wearing special gloves.

These HMDs can be either tethered or standalone. Tethered headsets require a connection to a PC and are therefore a display device streaming the content from the PC. HTC VIVE is an example of this kind of headset. The advantage of these headsets is that they are more powerful since the computations are provided by the PC. However, the use of these headsets can sometimes be clumsy due to the restricted movement caused by the length of the cable from the PC. Also, the PC needs to be powerful enough to run VR applications therefore the cost is much higher.

The standalone headsets have all the necessary components inside them - these headsets can stream VR experience anywhere. An example of these HMDs is the headset from Meta such as the Meta Quest 3. Although these types of headsets also have a way to connect to the PC and become a display device. The main advantage of these headsets is that they can be used anywhere, and the PC is not needed. The setup of these headsets is also much simpler. However, this comes with the cost of much less computation power than the tethered HMDs.

Another type of extended reality is Augmented reality (AR). AR combines elements of VR and the real world. Here the simulations are overlaid to the real world, and it also provides real-time interaction with the world. There are many types of AR and HMDs are not always needed - one example of augmented reality is for example a popular mobile game Pokemon Go, where players use their smartphones to locate, capture, and train virtual creatures called Pokémon that appear in the real world. AR provides digital elements over the real objects, unlike VR where the environment is fully digital. There is also Mixed reality (MR) which also allows interaction with the superimposed objects. The umbrella term for these three categories is Extended Reality (XR).

### 2.5.1 Immersion and presence

One of the core aspects of VR is *immersion* (Zheng et al., 1998). Immersion is the feeling of being in the virtual world - basically how strong the illusion of virtuality is. Immersion instills a sense that we have left the real world and are now part of the virtual world (Mestre et al., 2006) The higher the quality of the environment the higher the immersion will be. It also depends on the available cues, again the more cues available the more the environment will feel like the real world. Slater (2018) gives an example of this - if a VR system allows the perception of the whole body it will have a higher level of immersion than looking at a screen.

A similar term is *presence.* Immersion is the technical and objective aspect of VR while “presence is a psychological, perceptual and cognitive consequence of immersion” (Mestre et al., 2006, p. 2). According to a review by Wilkinson et al. (2021), presence is the feeling of being in another place – it is a detachment from reality and an attachment to virtual reality. The main difference is that immersion can be objectively assessed. And presence would be the human reaction to immersion which differs from person to person (Slater, 2003).

It could seem impossible that we would perceive VR as real or that the illusion of realness could be strong enough. However, the illusion can be strong enough to trick the brain into thinking that the virtuality is in fact real. I think that Slater (2018) summed it up beautifully:

> On the subject of presence, the authors in their section the ‘challenge of presence’ use the word ‘belief’ – that it seems impossible that people would believe the virtual world to be the real thing. However, presence is not about belief. Of course no one, not even when they are standing by a virtual precipice with their heart racing and feeling great anxiety, ever believes in the reality of what they are perceiving. The whole point of presence is that it is the illusion of being there, notwithstanding that you know for sure that you are not. It is a perceptual but not a cognitive illusion, where the perceptual system, for example, identifies a threat (the precipice) and the brain-body system automatically and rapidly reacts (this is the safe thing to do), while

> the cognitive system relatively slowly catches up and concludes ‘But I know that this isn’t real’. But by then it is too late, the reactions have already occurred. (p. 432)

### 2.5.2 Use of Virtual reality

The first and most prevalent use of VR that comes to mind is in the gaming industry. VR can simulate any imaginary environment and in combination with immersion and intractability of the environments, this can add a whole new dimension to playing video games. However, VR can be a great tool in many other fields. It can be a great tool in creating various simulators. For example, it can be used for infantry training in urban tactics by using virtual city and virtual enemies and friendly troops (Bowman & McMahan, 2007). Another example of such a use is in the medical field where doctors can visualize various scenarios and complex data and even simulate surgical procedures. Other uses can be in flying simulators for pilot training, education, wheelchair training, tourism, and many more. VR can also be used as a form of exposure therapy for anxiety disorder treatments (Powers & Emmelkamp, 2008), panic disorders (Carl et al., 2019), PTSD, phobias, and more. Throughout this work, I also tried to outline the usability of VR in cognitive psychology and navigation research. VR is an amazing tool for studying cognitive processes, especially spatial cognition.

### 2.5.3 Advantages and disadvantages of VR

However, as with any other technology VR has its advantages but also disadvantages. In the following section, I will describe the most important advantages and disadvantages of using VR in psychological research.

#### 2.5.3.1 Controllability

One of the main advantages of using VR in psychological research is the full controllability of the environment. Environmental influences and other distractors can disrupt the course of an experiment in reality. VR on the other hand provides full controllability of the environments and distractors. And not only does VR provide controllability of the environment it also provides full control of the stimulus and the availability of cues.

In VR it is also possible to precisely record the participants' performance. The behavior of the participants can therefore be recorded in detail and we can choose which aspects are important for us and which of them to record. Thanks to this the replicability of VR experiments is also fairly easy. And finally, VR allows us to present in other ways unethical or otherwise impossible situations (Annett & Bischof, 2010).

#### 2.5.3.2 Motion sickness

One of the main disadvantages and biggest problems of using VR is the possible VR motion sickness. Also called VR sickness or cybersickness, this phenomenon is similar to car sickness or sea sickness. It occurs due to the conflicting information our body gets from the virtual locomotion. Since in VR, the projected space is usually larger than the available space in reality various LMs for movement through the environments are implemented and often no or little movement is needed to navigate the VE. However, this causes a sensory conflict of our visual and vestibular system and can cause symptoms such as nausea, sweating, dizziness and even vomiting (Kennedy et al., 2010).

A large study on 1132 subjects by Stanney et al. (2003) examined the effects of VR sickness. Subjects were put in VR for 15 to 60 minutes. The main finding was that the symptoms of sickness increased the longer the subjects were subjected to VR. 13% of the subjects had to terminate the experiment prematurely and the dropout rate increased with the longer durations. Also, participants with prior experience with VR motion sickness in other scenarios were more prone to experience VR sickness. Other factors affecting the rate of sickness were the level of navigational control, gender (males experienced less motion sickness), and to some extent participants' BMI. According to Pan and Hamilton (2018), other factors affecting VR sickness can be eye strain, image latency, and high-contrast images.

With VR motion sickness also comes the ethical aspect of VR studies. Participants have to be acquainted with the risk of the potential VR sickness beforehand. Researchers should also try to prevent the risk as best as they can. The impact of the aforementioned factors can be for example reduced by changing the environment design or the intensity of the optic flow (Pan & Hamilton, 2018).

Subjects should also have some possibility of a break during longer procedures as the time spent in the virtuality increases the risk of sickness.

#### 2.5.3.3 Navigation without movement

As mentioned in the chapter about motion sickness in VR we usually do not need to physically move to navigate - we use various LMs. In the case of motion sickness, this can be a disadvantage however this is also a huge benefit, especially in neuroscience. VR can be a great tool for understanding neural functions as it largely increases the tools available to measure neural activity while navigating. For example, functional magnetic resonance, fluorescent imaging, and magnetoencephalography can be used which would not be possible in freely moving subjects (Minderer et al., 2016). This helps to understand neural processes in human navigation.

Overall VR can be a great tool for research in psychology, but we also need to be prepared to face some of its disadvantages. However, if we take these disadvantages into account there are some ways to prevent them or to at least mitigate them.

### 2.5.4 Is navigation in VR real navigation?

Another important question that every researcher studying navigation in VR should ask is: “Is navigation in VR navigation?” Virtual reality has come a long way in the past decades and is constantly being improved. The set-ups are even more realistic and immersive however navigating in the VE via motion tracking controller is not entirely the same as walking and navigating in real life. In the following section, I will try to outline some of the main differences and also similarities and how to interpret the results of navigation studies in VR.

Montello (2005, p. 263) stated: “... one should be restrained in interpreting metaphors such as “traveling through cyberspace.” Like all metaphors, the application of the navigation metaphor has limitations. Real navigation involves real places or spaces on the earth, and real movement of the body.” VR navigation depends heavily on visual information and to some extent on auditory and tactile information while real navigation relies more on motor, proprioceptive, and vestibular information. These types of cues are mostly not present in VR (Taube et al., 2013). So it would seem that navigation in VR is a different process than real navigation.

Many studies specifically reflect on this topic. A study by Ruddle & Lessels (2006) examined the effect of available cues for sufficient navigation. Participants were given varying levels of cues: only visual information, visual information combined with walking, or visual information with rotations only. Their task was to search for targets within a virtual room, which could be either photorealistic or impoverished in visual detail. The group that walked performed nearly perfectly irrespective of the visual fidelity. These results show the importance of body-based cues even if the visual scene is not rich.

However, in a study by Riecke et al. (2010), the participants performed search tasks in VR with rotations and translations controlled either by physical motion or by joystick. Here the benefit of full physical motion still showed however allowing body rotations was enough for performance benefit when compared to the joystick condition. And the rotation performance was almost the same as the walking performance. These results suggest that only rotations could prove sufficient for navigation in virtual reality.

Another study by Hejtmanek et al. (2020) compared real walking, navigating on a desktop, and immersive navigation with HMD with an omnidirectional treadmill and how these conditions affect the transfer of spatial information to real-world navigation. Participants navigated the UC Davis Center for Neuroscience in one of these three conditions and after that, they navigated the Center in reality. Results showed that participants in the real walking condition learned the most information at first, however in all the conditions participants improved over time. Also both the virtual conditions showed less transfer to real-world navigation and the omnidirectional treadmill condition proved to be slightly better than the desktop condition. These results show that real-world navigation is superior although the spatial knowledge can also be learned and transferred from VR effectively.

So even though VR can be an amazing tool to study navigation we should keep in mind that it is not entirely the same as real navigation and it has distinct differences that should be considered when interpreting research findings or using VR for practical applications. The main similarities would be in spatial representations - both VR and real navigation involve mental representations and navigation through environments. Also, the involved cognitive processes are similar. The main difference would be the mostly missing full physical movement through space and different sensory feedback (mainly tactile, olfactory, and proprioceptive cues).

### 2.5.5 Locomotion methods in VR

Movement through the VE is enabled by various LMs. LMs allow us to exceed room-scale tracking and move through bigger environments in the virtual world (Soler-Dominguez et al., 2020). The best LM in terms of presence, immersion, and available cues would be real walking - mapping the user's movement one-to-one with their avatar in the virtual world. This LM imitates real walking and provides most of the cues that are available while navigating in reality. However, this method is not always possible due to the restricted physical space of the tracked area (Prithul et al., 2021). Locomotion is a very important aspect of VR because it is a common task to move in VEs - navigation is not always the goal of VR applications but in almost every case some kind of locomotion is needed (Bozgeyikli et al., 2016). So finding the right LM that would be safe and also provide sufficient cues for navigation is one of the major challenges for VR researchers and developers (Al Zayer et al., 2020).

There are many different types of LMs and many different navigation metaphors. Boletsis and Chasanidou (2022) proposed a typology of LMs in VR. This work followed a previous paper by Boletsis (2017) and expanded the then-proposed typology even more. According to the authors, LMs have three classification categories. The first one is the Interaction type or how the user controls the navigation. For example, motion controllers are often used to trigger navigation and some methods use body movements as a way to trigger navigation. Second is the motion type which can be continuous or non-continuous. And third is the Interaction space - whether the LM surpasses the physical environment or not (Boletsis, 2017). Through a systematic review of available user studies the authors determined five categories of VR locomotion - motion-based, motion-based teleportation, roomscale-based, controller-based, and controller-based teleporting (Boletsis & Chasanidou, 2022).

Motion-based LMs utilize body movement to locomote in VR, an example of this method is the very prevalent Walking-in-place method which translates physical movement in place to movement in the virtual world. Motion-based teleportation is similar but the LMs under this category are non-continuous. Room-scale-based methods allow real walking but are constrained to a limited space of the tracked area. The controller-based methods are continuous methods used with a controller. And finally, controller-based teleporting is again used with a controller but is non-continuous (Boletsis & Chasanidou, 2022).

In this work, I will be focusing on the controller-based teleportation methods. Before moving to the empirical part of this work I will first introduce two LMs that will be used in our experiment - teleportation and teleportation with optic flow.

#### 2.5.5.1 Teleportation

Teleportation is one of the most used LMs in any use of virtual reality. It is an instantaneous movement through space - the user specifies the location by pointing (usually with the motion tracking controller) and after that, the user's viewpoint instantly changes to the specified destination (Prithul et al., 2021).

This LM is very popular and is used in many VR experiences. This is due to the relative safeness of this LM. Due to the instant viewpoint change, there are no optic flow cues available. This can be an advantage because optic flow cues simulate self-movement and the absence of vestibular and proprioceptive cues from movement while navigating in VR can cause VR motion sickness (Prithul et al., 2021). Another advantage of teleportation is that it is easy to learn, and it has a high immersion factor. However, the absence of optic flow cues during navigation can also be problematic. Teleportation is often found to be disorienting in comparison to other LMs.

For example, in a study by Coomer et al. (2018) four LMs were compared - teleportation, joystick, arm-cycling, and point-tugging. Using a search task experiment they found that teleportation was indeed a safe LM, however, participants with teleport traveled the longest distances, took the longest time, and also made the most mistakes. The arm-cycling method proved to be the best in spatial orientation and also in VR motion sickness.

Another study by Paris et al. (2019) compared four game-like LMs - teleporting, grappling, skiing, and magic carpet. For their evaluation, they used a triangle completion task. Here continuous methods (with optic flow) outperformed the discrete methods and the greatest error in path integration was found in teleportation.

In a study by Christou & Aristidou (2017) Gaze-Directed, Pointing, and Teleport LMs were compared in a navigation task. Participants navigated to goals pointed to them on a map and on the way they also had to collect tokens. Here the teleportation showed the least VR motion sickness and was not significantly disorienting. It also had the fastest completion time however most tokens were missed using teleportation.

And in a study by Langbehn et al. (2018) joystick locomotion, redirected walking and teleportation were studied. Participants navigated to several predetermined goals and after that pointed in the direction of these targets. Here the redirected walking group was best in recollecting the spatial layout. Again, teleportation proved to be the safest method however the redirected walking also did not increase VR motion sickness significantly. In terms of preference, participants preferred teleportation and redirected walking over the joystick locomotion.

#### 2.5.5.2 Teleportation with optic flow

The second LM used in the experiment is teleportation with optic flow. This LM is quite similar to the classic teleportation and has the same controls. However, the main difference is in the presence of optic flow. In this LM instead of the instant viewpoint change the navigator gains sort of a tunnel vision and the movement through space can be seen.

I am not aware of any studies using this LM. However, there are few studies examining similar methods. For example, a study by Bhandari et al. (2018) evaluated LM called Dashing - a teleportation method that retained some optic flow and compared it to classic teleportation. In a pointing task, participants performed better using the dash method. However, this study did not use a classic VR HMD but only a mobile VR platform.

In another study by Bolte (2011), LM called the jumper metaphor was studied and compared with real walking methods and teleportation. The jumper metaphor allows real walking while navigating shorter distances but if the navigator wants to travel a larger distance this LM predicts their planned location and virtually jumps to the target while keeping the optic flow. Results showed that real walking was the best while drawing blind maps, but the jumper metaphor proved to be better than classic teleportation.

A study by Adhikari et al. (2023) examined an LM called Hyperjump which adds jumps every half a second on top of the continuous movement. Participants navigated a virtual city with and without HyperJump. The task was to follow waypoints to new landmarks and point back to previous landmarks. HyperJump was integrated into two continuous locomotion interfaces: one controller-based and the other leaning-based. With the added HyperJump, participants traveled significantly faster while remaining on the desired course without compromising their spatial knowledge.

#### 2.5.5.3 Bachelor’s thesis

The experiment presented in the empirical section directly follows up on my bachelor’s thesis (Kobián, 2022) where we examined the same two LMs in four small apartment-like environments. Participants completed four testing trials of search, return to origin, and pointing tasks - two for each LM. We found no significant difference in traveled distance in the navigation task and also no difference in pointing accuracy in the spatial memory pointing task. The only significant difference was in the time needed to finish the search task - teleportation with optic flow proved to be faster in finishing the navigation task (finding four objects and returning to the starting point). Also, no significant difference was found in the motion sickness caused by these LMs and the overall sickness scores were low which would suggest that the LM Teleportation with optic is a relatively safe method.

Overall, it seemed that the added optic flow caused some sort of an improvement, especially in the navigation time but overall, we expected a bigger effect of optic flow to show. This could be because of the effect of the tested environments. Firstly, the layouts of the environments were not unified. And secondly, the environments were small-scale. This is why in the current experiment we will also test the effect of environments and if the effect of the added flow will be more pronounced in larger and more complex environments.

# 3 Empirical section

## 3.1 Goals of the study

The goal of the presented study is to compare two LMs - teleportation and teleportation with optic flow in various types of environments. Specifically in small-scale and large-scale vista and environmental spaces. Teleportation is the most used stationary LM. This method does not generate optic flow. Due to this fact, this LM is considered as one of the safest methods however it can also be disorienting when compared with other LMs. Teleportation with optic flow is a relatively novel LM not yet used in navigational studies. This method was chosen because it could solve some of the problems of classic teleportation such as disorientation and impaired spatial memory. Adding limited optic flow could lead to better spatial orientation without substantially increasing VR motion sickness (as was shown in my bachelor's thesis).

In the first experiment, in my bachelor's thesis, participants navigated in small environmental apartment-like environments. In the current experiment, the impact of environmental scale and environmental complexity on navigation behavior and spatial memory will be examined as the navigated environment can have a profound effect on our spatial abilities. The scale of the navigated environment can distort our spatial memory as for larger traveled distances there is also a bigger risk of a computational error. Not only the scale but also the complexity (vista or environmental spaces) of the environment can have a significant effect on our spatial abilities as the response time of spatial memory is increased the more complicated and larger the environment is.

We want to find out if the added optic flow in the LM Teleportation with optic flow will have a bigger effect in more complicated environments and if navigation and spatial memory will be better than with the classic Teleportation in these environments.

## 3.2 Hypotheses

**Hypothesis 1:** We expect that with the LM teleportation with optic flow participants will navigate faster and travel shorter distances (**H1a**) and they will also point with a better accuracy in the spatial memory (pointing) task **(H1b**).

**Hypothesis 2:** We expect to find differences in navigation and spatial memory acquired in the different sizes and complexities of environments.

**Hypothesis 2a**: Firstly, we expect participants to acquire better spatial knowledge in small environments, which will be demonstrated by better pointing accuracy

**Hypothesis 2b**: We expect the participant in the vista environments where all of the information will be available from any one point in the space (regardless of the size of the space) – participants should have better spatial understanding demonstrated by better pointing accuracy.

**Hypothesis 3:** Based on our previous results, we expect no significant difference in motion sickness for the two tested LMs. Both LMs should have low motion sickness scores.

## 3.3 Methods

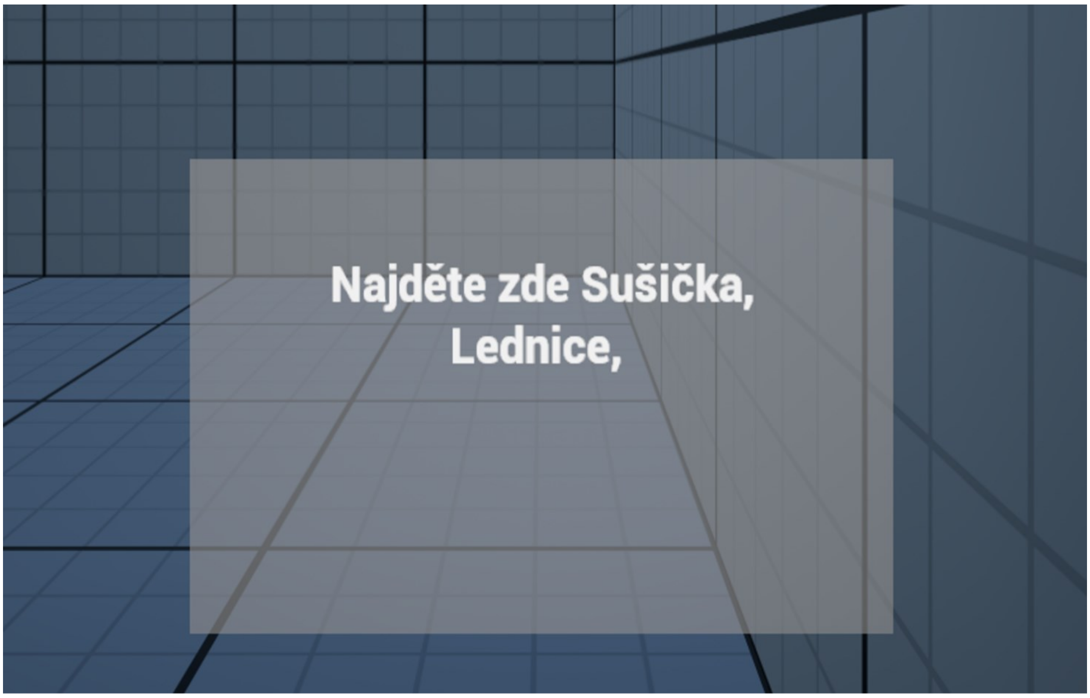
The procedure consisted of an experiment in VR and a few questionnaires During the VR experiment, participants searched for various objects in environments varying in size (small and large) and complexity (vista and environmental) using two different locomotion methods (Teleportation and Teleportation with optic flow). After locating the objects, participants were tested on their acquired spatial knowledge with a pointing task. Participants filled out two questionnaires for each of the LMs; one assessed the rate of the caused simulator sickness and the second assessed the LM preference.

### 3.3.1 Experiment

The experiment consisted of several trials (eight per participant), each repeated in a different environment using varying LM. The goal of each trial was to find and memorize locations of four objects in an environment and then demonstrate the acquired spatial knowledge by pointing to their locations from a novel place.

Firstly, participants were tasked with finding four objects in the environment. The names of these objects were displayed as a banner at the start of the experiment (see Fig. 7). If participants forgot the items, administrator could manually show the banner again.

*Figure 7 The banner with the instructions in the learning environment (translation: Find here: Dryer machine, Fridge)*



Najděte zde Sušička,
Lednice,

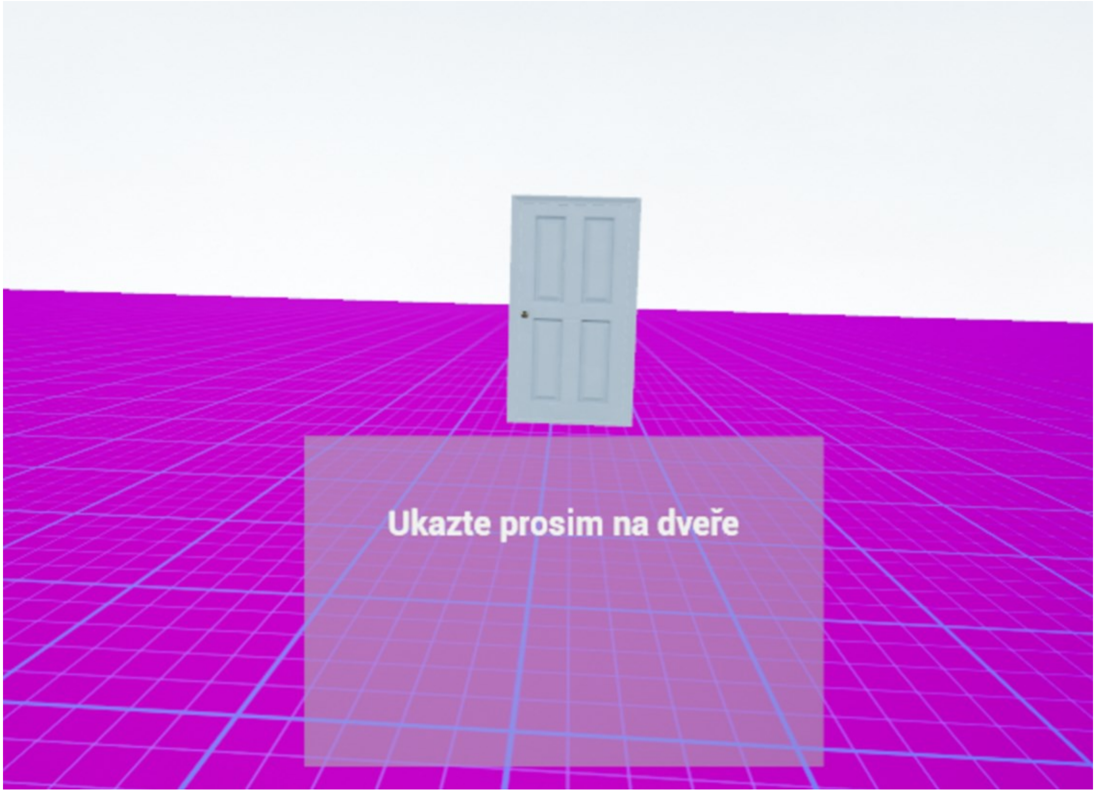
To successfully „find“ the object, participants needed to „touch“ it with one of the controllers. After touching the object confirming sound was played and the banner with the remaining objects appeared again.

After finding all four objects they were tasked to travel back to the starting point - the entrance doors. This objective was again shown as a similar banner text. After making their way back to the entrance door the pointing phase started. The environment around them disappeared, and they were relocated to a different location (which was constant for all of the participants and was always in the middle of the environment) and only the entrance door remained to provide a reference point (Fig. 8).

Participants' task was to try and point to the locations of objects based on the location of the entrance door. The pointing was done using the joystick (similar to the movement) on the right motion controller and the participants had to press the key twice to confirm their choice.

First, they were asked to point to the entrance door (Fig. 8) and after that to the found objects in a predetermined order. After finishing one of the trials, text informing the participants appeared. After that, the administrator played the following level through the PC.

*Figure 8 The empty environment with only the door as a reference point (translation: "Please point at the door")*



We measured the time needed to finish the task and the traveled distance in the navigation task. In the pointing task, the error of the reported direction we measured - the angle error of the reported direction relative to the real direction of the object and also the difference of distance between the target and pointing. Through the questionnaires, we measured the rate of VR motion sickness of the participants and the LM preference.

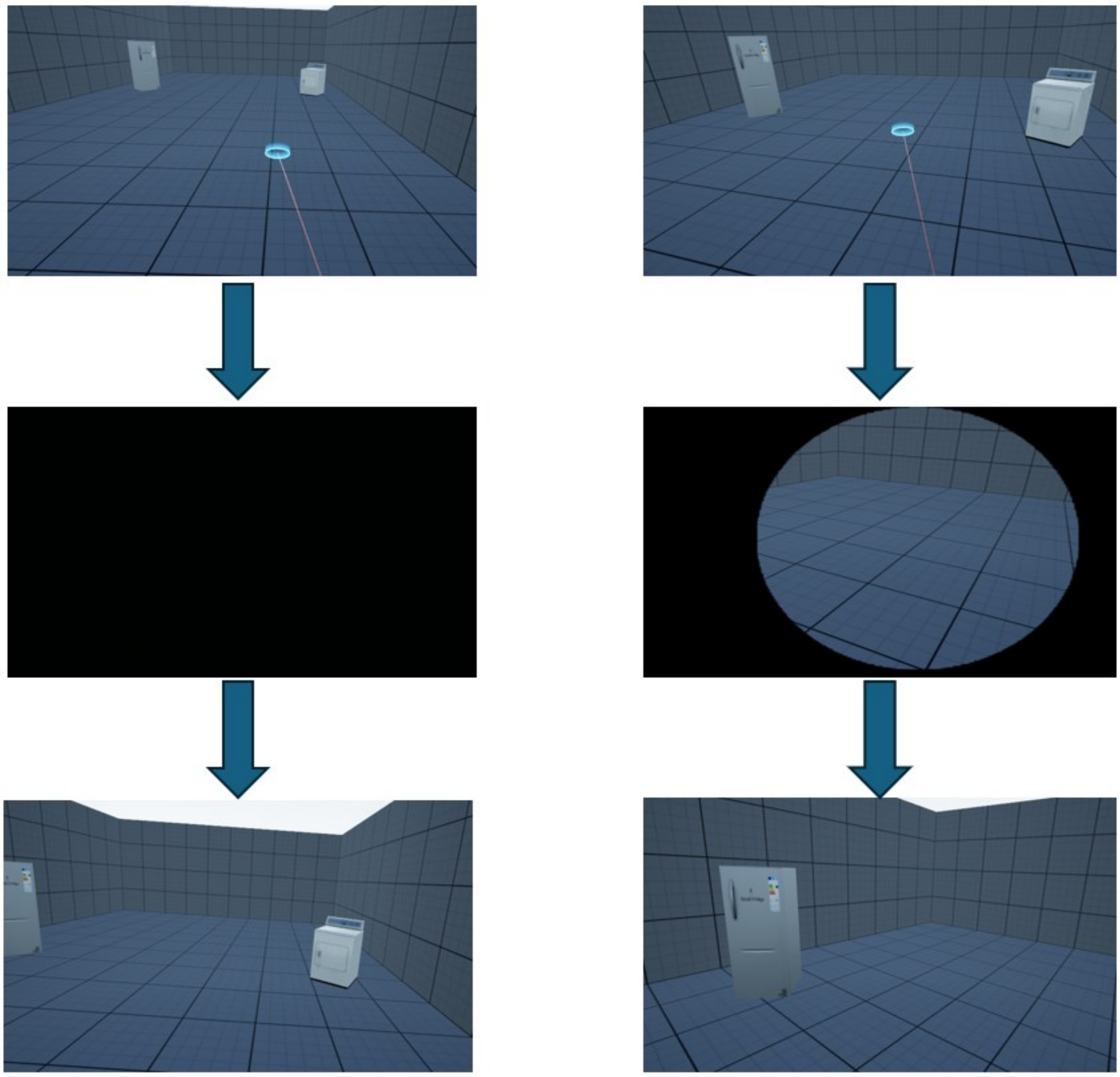
### 3.3.2 Locomotion methods

Two LMs were examined - teleportation and teleportation with optic flow.

**Teleportation** (Fig. 9 *left*) is an instantaneous movement through space. Classic point and teleport method was implemented. In our case, the pointing is done by pressing the joystick on the right controller. After pressing the joystick, a line appears with a blue circle at the end. Aiming this green line allows the navigator to choose their destination. After releasing the joystick, the screen goes black and they appear on this chosen spot. The black screen takes longer the further the navigator wants to move. This is a stationary LM which means that the user does not have to move in reality, and only physical rotations are needed.

**Teleportation with optic flow** (Fig. 9 *right*) is a novel LM combining elements of teleportation and optic flow cues. The controls are exactly the same as in teleportation - by pressing the joystick green line appears which points to the intended goal location. However, after releasing the joystick instead of an instantaneous change of viewpoint the navigator gains sort of a tunnel vision, and the movement through space can be seen and the navigator does not lose the optic flow cues as in teleportation. This is again a stationary LM and only physical rotations are needed.

*Figure 9 Teleportation (left), Teleportation with optic flow (right)*



### 3.3.3 Environments

I designed eight environments for this experiment plus one simple testing environment. The environments differed in size and complexity (vista and environmental condition). Four environments were small (36 m$^2$) four were large (144 m$^2$) and there were pairs of environments of the same size that had the same context (or stylization) but different complexity of the space (vista spaces and environmental spaces). The main difference between the vista and the environmental condition was in the division of the space. In the vista condition (Fig. 10), all of the environment can be seen from any one point but in the environmental condition (Fig. 11), the space was divided so the navigator was not able to see the whole space. The four large environments had the same layout as well as the four small environments. The difference was in the context of the environments and the division of space.

*Figure 10 Example of a large vista environment*

```
RecastNavMesh-Default (Static)
AgentRadius 35.0, AgentHeight 144.0
CellSizes 38.0/19.0/19.0, CellHeights 10.0/10.0/10.0, AgentMaxStepHeight 35.0/35.0/35.0 (low/default/high)
Region part Watershed, Layer part Watershed

NavData count: 1
MainNavData: RecastNavMesh-Default
Using cluster links
```

*Figure 11 Example of a large environmental environment*

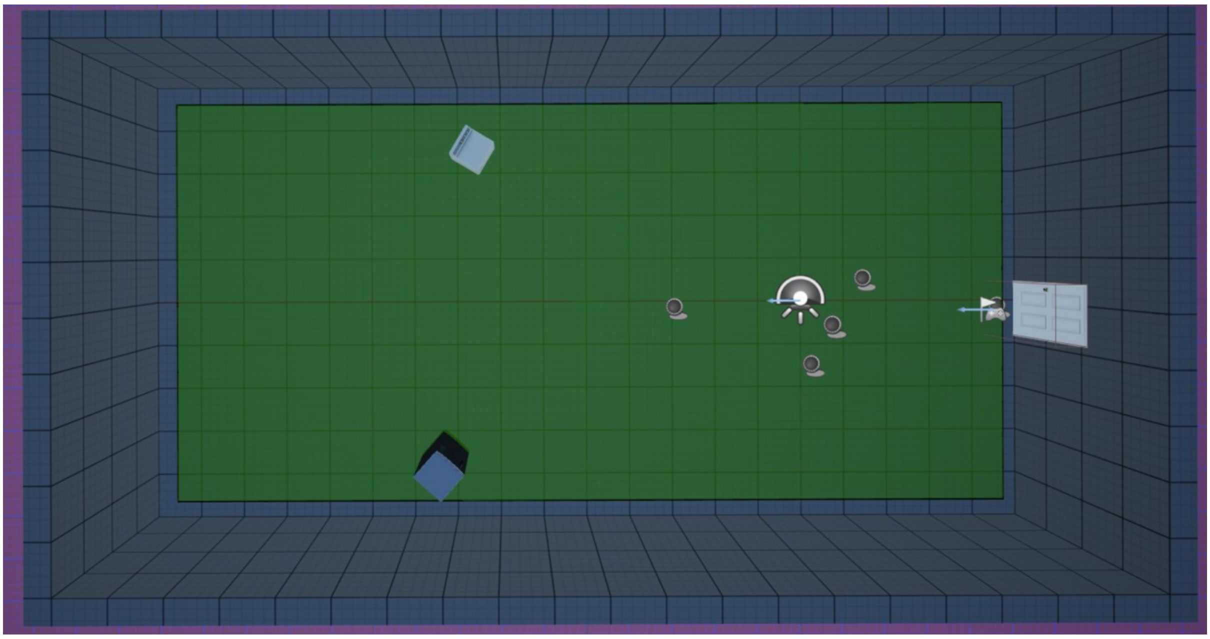
```
RecastNavMesh-Default (Static)
AgentRadius 35.0, AgentHeight 144.0
CellSizes 38.0/19.0/19.0, CellHeights 10.0/10.0/10.0, AgentMaxStepHeight 35.0/35.0/35.0 (low/default/high)
Region part Watershed, Layer part Watershed

NavData count: 1
MainNavData: RecastNavMesh-Default
Using cluster links
```

In Figure 12 you can see the Learning environment. This is a much-simplified version of the other environments and was used for the participants to try and test the

LM and also the experimental task. Here participants looked only for two objects – a Dryer machine and a Fridge.

*Figure 12 Learning environment*



In Figure 13 you can see the first context pair of the large environments. In the vista condition participants were tasked to find a Cash register monitor, a Small tree in a flowerpot, a Fire extinguisher, and a Recycling bin. In the environmental condition, they were tasked to find a Wall-mounted first aid kit, a Stepladder, a Yellow wet-floor sign, and a Vending machine for drinks. As said above both these environments had the same layout.

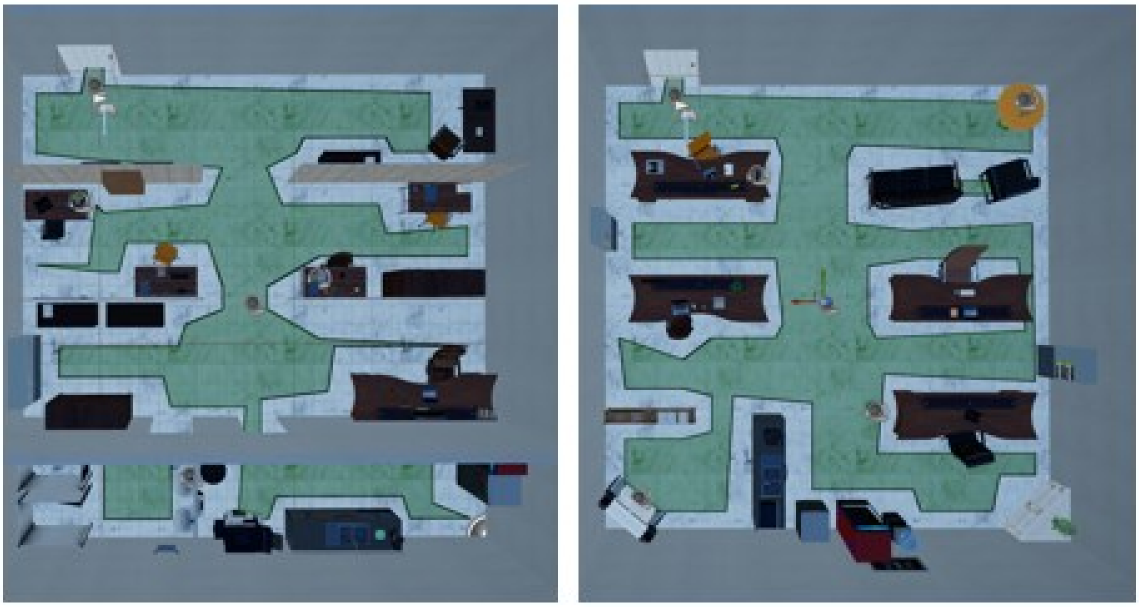
*Figure 13 Large space context 1. On the left is the vista environment and on the right is the environmental environment*

In Figure 14 you can see the second context pair of the large environments. In the vista condition participants were tasked to find a Manual forklift, Advertisement ballons, a Fire hose, and a Hand shopping cart. In the environmental condition, they were tasked to find a Shopping cart, a Mop, a Wooden box, and a Two-wheel pushcart. Again both environments had the same layout which was also the same as the layout in the previous environments.

*Figure 14 Large space context 2. On the right is the vista environment and on the left is the environmental environment*

In Figure 15 you can see the first context pair of the small environments. In the vista condition participants were tasked to find a Trash bin, a Phone, a Printer for drawings, and a Water bottle. In the environmental condition, they were tasked to find a Bottled hand soap, a Copier, a Calculator, and a Table flower. Both environments had the same layout.

*Figure 15 Small space context 1. On the right is the vista environment and on the left is the environmental environment*



In Figure 16 you can see the second context pair of the small environments. In the vista condition participants were tasked to find a Kettle, a Crib, a TV, and a Lamp. In the environmental condition, they were tasked to find a Laptop, a Bunk bed, a Toilet, and a Cooker. Again the layout was the same as in the first context pair.

*Figure 16 Small space context 2. On the right is the environmental environment and on the left is the vista environment*

#### 3.3.3.1 Questionnaires

We used two questionnaires for other assessments. To assess the motion sickness caused by the different LMs the Simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) was used. This questionnaire measures the rate of motion sickness caused by the simulator in this case by virtual reality.

To assess the LM preference, the Virtual reality locomotion experience questionnaire (VRLEQ) was used (Boletsis, 2020). This questionnaire combines the System Usability Scale (SUS) (Brooke, 1996) survey and the Game Experience Questionnaire (GEQ) (IJsselsteijn et al., 2013). However, since our interest is in the LM preference we used only the second part of the questionnaire which assesses the perceived usability of the LM.

At the end of the procedure, participants filled out one more questionnaire - this was a questionnaire containing two demographic questions (age and sex) and two questions about their experience with VR.

### 3.3.4 Procedure

Firstly, the participants were familiarized with the course of the experiment and the risks that VR can cause (VR motion sickness and epilepsy). After that, they read and signed the informed consent. The VR headset then needed to be set up for the individual participant. The HMD needs to fit right so it does not fall or otherwise move during the procedure.

The first part of the experimental procedure was a learning trial for the first selected LM. Here the participants tried and learned the LM by completing a simpler version of the test itself. Although participants could physically move a little bit (in and approximately 2x2 meters around them), they were instructed to use the virtual LM and to only use physical movements to turn around. In the learning trials, the participants were tasked with finding two objects and then returning to the start and pointing to the locations of those items.

The experimental procedure was then repeated four times for the first LM. After finishing the four trials for the first LM, the first part of the questionnaires followed. Here the participants filled out the Simulator sickness questionnaire (Kennedy et al., 1993) and the Virtual reality locomotion experience questionnaire (Boletsis, 2020).

After filling out these questionnaires the procedure was repeated for the other LM. First came the learning trial where the participants tried and learned the LM and after that four testing trials followed. After completing the trials for the second LM, a series of questionnaires again followed. Firstly, the same two questionnaires were used – Simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) and Virtual reality locomotion experience questionnaire (VRLEQ) (Boletsis, 2020) and here also a short demographic questionnaire followed with other questions about their experience with VR.

#### 3.3.4.1 Conditions combination

We implemented a within-subject design so the participants were subjected to all eight conditions - eight different environments with two different LMs. The order of the LMs alternated. The order of environmental conditions was randomized. In both LMs, all conditions had to be filled. Meaning that for both LMs there had to be one small vista and environmental environment and one large vista and environmental environment. The contexts were also randomized.

*Table 1 An example of randomization (LN = Large environmental space, SN = small environmental space, SV = small vista space, LV = large vista space). Every environment had an assigned number 1-8 (1-4 were large environments and 5-8 were small environments).*

| Locomotion method | Type of environment | Context sequence |
|---|---|---|
| Optic flow/Teleport | LN,SN,SV,LV//SV,LN,LV,SN | 3,7,6,1//8,2,4,5 |
| Teleport/Optic flow | LN,SN,SV,LV//SV,LN,LV,SN | 2,5,8,4//6,3,1,7 |
| Optic flow/Teleport | LV,SV,LN,SN//LN,LV,SN,SV | 1,8,2,5//3,4,7,6 |
| Teleport/Optic flow | LV,SV,LN,SN//LN,LV,SN,SV | 4,6,3,7//2,1,5,8 |
| Optic flow/Teleport | SN,LV,LN,SV//LV,SN,LN,SV | 7,4,2,8//1,5,3,6 |

### 3.3.5 Ethical aspects

The main risk of any research and use of virtual reality is the potential risk of VR motion sickness. The symptoms are quite similar to classic motion sickness which can include headache, loss of balance, bad movement coordination, stomachache, puking, etc. To try to prevent this phenomenon participants were informed about the potential risk of VR motion sickness through informed consent which they needed to sign to participate in the study. I tried to prevent the cybersickness as best as possible.

I asked the participants throughout the experimental procedure if they were feeling any mentioned symptoms and if so, the procedure would have been immediately stopped. Participants could also stop the experiment at any time if they were feeling unwell. However, no problems arose during the procedures and none of the participants experienced serious problems of VR motion sickness.

In very rare cases (1:4000) the use of VR has been connected with the possibility of instigating epileptic seizures in vulnerable populations. But according to Fisher et al. (2022) VR and 3D images should be benign unless they contain specific provocative content. In our case, there was no flashing or provocative content so the experience was safe. Nonetheless, this potential risk was stated in the informed consent and this information also was explicitly stated before starting the experiment. Epilepsy was also our only inclusion criterion.

We gathered no sensitive information about the participants. Part of the project was a short questionnaire, where the participants were asked about basic demographic information - their age and sex. This information is in no way connected to the name of the participants and no further information was gathered.

### 3.3.6 Participants and materials

15 subjects aged 18-29 (4 males and 11 females, mean age: 21.2, SD = 2.5) participated in the study. The participants had little to no experience with VR. 4 of the subjects never used VR, one of them had only one experience with VR, eight of the participants used VR two to ten times and only one of them had more than ten experiences. None of the participants were regular users of VR.

The experiments took place at the Cyberspacelab laboratory at Kampus Hybernská 998/4. Both examined LMs are stationary, and the participants did not need to move in reality, and they needed to only turn so the spaces of our laboratory were sufficient enough. One full session took approximately 45 minutes to finish.

#### 3.3.6.1 Hardware and software

Meta Quest 2 HMD connected to a PC via a cable VR link was used. This HMD is a standalone headset with the possibility to connect to a PC via USB or Wi-Fi. Our experiment was run on a PC and the HMD was connected to it via USB. The HMD uses processor Qualcomm Snapdragon XR2 SoC with 6 GB RAM. It has a fast-switch LCD with a resolution of 1832×1920 per eye. The refresh rate of the HMD is 72 Hz. It also includes an integrated speaker that enables surround sound and a microphone. The controllers are third-generation Oculus Touch. The experiment was run on a PC with the following specifications - AMD Ryzen 5 5600 6-Core Processor 3.50 GHz, 32.0 GB RAM, and NVIDIA GeForce RTX 3080 graphics card.

The experiment was programmed in Unreal Engine 5. I modeled and built the individual environments using various asset packs from the Unreal Engine marketplace - *Big office, Supermarket, Office scene, Clothing and shoe store, Industry props pack 6, HQ residential house, and Houseplant pack*. My supervisor Mgr. Lukáš Hejtmánek PhD programmed the experiment and the data logging.

## 3.4 Results

### 3.4.1 Analysis

The data were processed in the statistical program JASP version 0.18.3. The alpha value for all of the analyses was 0,05.

I used linear mixed effects models to analyze the effects of LM, environmental size, and complexity on navigation and spatial memory. To account for repeated measures and participant-specific effects, a random intercept for each participant in the models was included.

### 3.4.2 Navigated distance

In the first part of the experiment, we measured the navigated distance – the distance the participants traveled from the beginning of the trial to find all four objects and to return to the starting point. Table 2 shows the descriptives of the navigation distance split by LM, environmental size, and complexity.

*Table 2 Descriptive statistics of the navigated distance (the distance participants navigated to finish the navigation task) split by LM, size of the environment, and by the complexity of the environment. All rows have 60 observations.*

| | | **Navigated distance** | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **Std. Deviation** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 9526.209 | 9730.922 | 3957.993 | 6644.259 | 11895.340 |
| | Teleportation | 9270.211 | 9894.307 | 4118.334 | 6560.943 | 12337.935 |
| **Environement size** | Small | 6585.808 | 6610.218 | 1173.085 | 5819.743 | 7202.689 |
| | Large | 12247.53 | 13015.01 | 3225.757 | 10618.67 | 14405.256 |
| **Environment complexity** | Vista | 8523.845 | 9033.394 | 3734.841 | 6000.194 | 10915.062 |
| | Environmental | 9669.319 | 10591.835 | 4178.035 | 7016.654 | 12872.750 |

To analyze the effects of LM, size of the environment, and complexity of the environment on the navigation distance (the distance traveled to find the four objects and return to the starting point) I used a mixed effects model and included random intercept for participants. The fixed effects were the LM, environmental size, and environmental complexity, the interaction between LM and environmental size, and the interaction between LM and environmental complexity. The residuals were approximately normally distributed.

The fixed effects estimates and interactions can be seen in Table 3. The LM did not have a significant effect on navigation distance (β = -81.693, t = -0.388, p = 0.699), but the complexity of the environment (vista or environmental condition) did (β = -779.221, t = -3.698, p < 0.001) and participants navigated shorter distances in the vista condition. The size of the environment had unsurprisingly a significant effect on navigation distance (β = -3202.397, t = -15.200, p < 0.001) in small environments participants navigated shorter distances. As can be seen in Table 3 none of the interactions were significant.

*Table 3 Fixed effects estimates for the reported model (navigated distance). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 9812.615 | 223.092 | 14.000 | 43.985 | < .001 |
| Locomotion method (OF) | -81.693 | 210.690 | 100.000 | -0.388 | 0.699 |
| Environment complexity (V) | -779.221 | 210.690 | 100.000 | -3.698 | < .001 |
| Environment size (Small) | -3202.397 | 210.690 | 100.000 | -15.200 | < .001 |
| Locomotion method (OF) ✻ Environment complexity (V) | -165.517 | 210.690 | 100.000 | -0.786 | 0.434 |
| Environment complexity (OF) ✻ Environment size (S) | 124.780 | 210.690 | 100.000 | 0.592 | 0.555 |

### 3.4.3 Navigation duration

We also measured the navigation duration during the first part of the experimental task – the duration it took the participants to find all the objects and return to the starting point. Table 4 shows descriptives of the navigation duration split by LM, environmental size, and complexity.

*Table 4 Descriptive statistics of the navigation duration (the duration it took participants to finish the navigation task) split by LM (a), size of the environment (b), and by the complexity of the environment (c). All columns have 60 observations.*

| | | **Navigation duration** | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **Std. Deviation** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 74.218 | 82.118 | 26.790 | 64.931 | 96.036 |
| | Teleport | 88.526 | 95.912 | 35.723 | 71.507 | 107.390 |
| **Environement size** | Small | 77.197 | 81.240 | 25.033 | 60.162 | 98.549 |
| | Large | 88.526 | 95.912 | 35.723 | 71.507 | 107.390 |
| **Environment complexity** | Vista | 79.101 | 83.673 | 31.638 | 63.443 | 93.543 |
| | Environmental | 88.871 | 93.479 | 31.022 | 68.978 | 105.849 |

To analyze the effects of LM, size of the environment, and complexity of the environment on the navigation performance (the duration it took participants to find all the objects and return to the starting point) I a used mixed effects model. The model includes random intercepts for participants. The fixed effects were the LM, environmental size, and environmental complexity, the interaction between LM and environmental size, and the interaction between LM and environmental complexity. The residuals were approximately normally distributed.

The fixed effects estimates and interactions can be seen in Table 5. The LM had a significant effect on navigation time (β = -6.459, t = -2.44, p = 0.016) participants navigated faster with the LM Teleportation with optic flow. Also, the size of the environment had a significant effect on navigation time (β = -7.336, t = -2.777, p = 0.007), and participants navigated longer in the large environments. The complexity of the environment (vista and environmental condition) did not have a significant effect on the navigation time (β = -4.903, t = -1.856, p = 0.066). None of the interactions had a significant effect (see Table 5).

*Table 5 Fixed effects estimates for the reported model (navigation duration). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 88.576 | 3.382 | 14.000 | 26.187 | < .001 |
| Locomotion method (OF) | -6.459 | 2.642 | 100.000 | -2.444 | 0.016 |
| Environment omplexity (Vista) | -4.903 | 2.642 | 100.000 | -1.856 | 0.066 |
| Environment size (Small) | -7.336 | 2.642 | 100.000 | -2.777 | 0.007 |
| Locomotion method (OF) ∗ Environment complexity (V) | -1.303 | 2.642 | 100.000 | -0.493 | 0.623 |
| Locomotion method (OF) ∗ Environment size (S) | 3.135 | 2.642 | 100.000 | 1.186 | 0.238 |

### 3.4.4 Pointing duration

In the pointing task we measured the pointing duration – the time it took the participants to point to all the objects. Table 6 shows descriptives of the pointing duration split by LM, environmental size, and complexity.

*Table 6 Descriptive statistics of pointing duration (the duration it took participants to finish the pointing task) split by LM, size of the environment, and the complexity of the environment. All columns have 60 observations.*

| | | **Pointing duration** | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **Std. Deviation** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 28.136 | 28.778 | 11.534 | 19.441 | 35.117 |
| | Teleport | 29.662 | 32.476 | 14.900 | 21.104 | 38.717 |
| **Environment size** | Small | 25.309 | 27.299 | 11.775 | 18.795 | 31.229 |
| | Large | 33.050 | 33.956 | 14.171 | 22.075 | 41.369 |
| **Environment complexity** | Vista | 28.465 | 30.429 | 13.620 | 19.875 | 37.352 |
| | Environmental | 29.406 | 30.825 | 13.282 | 19.567 | 38.681 |

To analyze the effects of LM, the size of the environment, and the complexity of the environment on the pointing duration I used a mixed effects model. The model includes random intercepts for participants. The fixed effects were the LM, environmental size, environmental complexity, the interaction between LM and environmental size, and the interaction between LM and environmental complexity. The residuals were approximately normally distributed.

Table 7 shows the fixed effect estimates. After navigating with the LM Teleportation with optic flow participants finished the pointing task faster ($\beta = -1.849$, $t = -2.515$, $p = 0.014$). The size of the environment also affected pointing duration ($\beta$

= -3.329, t = -4.527, p < 0.001) with participants pointing faster in the small environments. Other effects were not significant as can be seen in Table 7.

*Table 7 Fixed effects estimates for the reported model (pointing duration). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 30.627 | 2.773 | 14.000 | 11.043 | < .001 |
| Locomotion method (OF) | -1.849 | 0.735 | 100.000 | -2.515 | 0.014 |
| Environment complexity (V) | -0.198 | 0.735 | 100.000 | -0.269 | 0.788 |
| Environment size (S) | -3.329 | 0.735 | 100.000 | -4.527 | < .001 |
| Locomotion method (OF) ∗ Environment complexity (V) | -0.539 | 0.735 | 100.000 | -0.734 | 0.465 |
| Locomotion method(OF) ∗ Environment size (S) | -1.180 | 0.735 | 100.000 | -1.605 | 0.112 |

## 3.4.5 Angle error

In the pointing task, we measured the angle error - the difference between the real position of the pointed object and the angle at which the participant pointed. Firstly, it was necessary to compute these values in absolute terms, given that the logged results included both positive and negative values, and the focus was on the angle error. In Table 8 the descriptives of the absolute angle error split by LM, environmental size, and complexity can be seen.

*Table 8 Descriptive statistics of the absolute angle error (the pointed angle error in absolute values) split by LM, size of the environment, and the complexity of the environment. All columns have 240 observations.*

| | | **Absolute angle error** | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **Std. Deviation** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 14.541 | 24.761 | 31.015 | 6.313 | 27.481 |
| | Teleport | 14.087 | 23.599 | 27.394 | 6.950 | 26.030 |
| **Environment size** | Small | 13.697 | 22.034 | 25.004 | 6.459 | 26.650 |
| | Large | 14.953 | 26.325 | 32.842 | 6.583 | 27.990 |
| **Environment complexity** | Vista | 12.524 | 23.422 | 31.195 | 5.277 | 24.336 |
| | Environmental | 15.839 | 24.938 | 27.181 | 8.024 | 29.007 |

To analyze the effect of LM, the complexity of the environment, and the size of the environment mixed effects model was used. The model includes random intercepts for participants. The fixed effects were the LM, environmental size, and environmental complexity, the interaction between LM and environmental size, and the interaction between LM and environmental complexity. The residuals were approximately normally distributed.

Table 9 shows the fixed effects estimates and their interactions. Surprisingly none of the predictors had a significant effect on the angle error.

*Table 9 Fixed effects estimates for the reported model (absolute angle error). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 24.180 | 2.989 | 14.000 | 8.091 | < .001 |
| Locomotion method (OF) | 0.581 | 1.252 | 460.000 | 0.464 | 0.643 |
| Environment complexity (V) | -0.758 | 1.252 | 460.000 | -0.605 | 0.545 |
| Environment size (S) | -2.145 | 1.252 | 460.000 | -1.713 | 0.087 |
| Locomotion method (OF) ✻ Environment complexity (V) | -0.158 | 1.252 | 460.000 | -0.126 | 0.900 |
| Locomotion method (OF) ✻ Environment size (S) | -0.893 | 1.252 | 460.000 | -0.713 | 0.476 |

### 3.4.6 Target error

We also measured the target error in the pointing task - the difference between the real position of the object and the pointed distance. Firstly, it was necessary to compute these values in absolute terms, given that the logged results included both positive and negative values, and the focus was on the pointed error. In Table 10 the descriptives of the absolute target distance error split by LM, environmental size, and complexity can be seen.

*Table 10 Descriptive statistics of the absolute target error (the difference between the real position of the object and the pointed distance in absolute values) split by LM, size of the environment, and by the complexity of the environment. All columns have 240 observations.*

| | | **Absolute target error** | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **SD** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 238.111 | 282.055 | 223.118 | 407.509 | 104.482 |
| | Teleport | 230.396 | 294.127 | 261.949 | 403.698 | 92.126 |
| **Environment size** | Small | 194.669 | 272.724 | 243.680 | 373.549 | 81.646 |
| | Large | 258.040 | 303.458 | 242.110 | 423.452 | 115.057 |
| **Environment complexity** | Vista | 199.252 | 248.409 | 217.759 | 353.922 | 81.646 |
| | Environmental | 275.818 | 327.773 | 260.558 | 472.006 | 125.038 |

To analyze the effect of LM, the environment complexity and size I used mixed effects model. The model includes random intercepts for participants. The fixed effects were the LM, environmental size, and environmental complexity the interaction between LM and environmental size, and the interaction between LM and environmental complexity. The residuals were approximately normally distributed.

Table 11 shows the fixed effects estimates and their interactions. Participants pointed with better accuracy in the vista environments (β = -39.682, t = -3.922, p < 0.001). Other predictors and interactions did not have a significant effect as can be seen in Table 11.

*Table 11 Fixed effects estimates for the reported model (absolute target error). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 288.091 | 26.661 | 14.000 | 10.806 | < .001 |
| Locomotion method (OF) | -6.036 | 10.117 | 460.000 | -0.597 | 0.551 |
| Environment complexity (V) | -39.682 | 10.117 | 460.000 | -3.922 | < .001 |
| Environment size (S) | -15.367 | 10.117 | 460.000 | -1.519 | 0.129 |
| Locomotion method(OF) ✻ Environment vcomplexity (V) | 2.713 | 10.117 | 460.000 | 0.268 | 0.789 |
| Locomotion method (OF) ✻ Environment size (S) | 10.217 | 10.117 | 460.000 | 1.010 | 0.313 |

### 3.4.7 Summary of the experiment results

The LM had a significant effect on the traveled duration but not the traveled distance in the navigation part of the experiment. Participants navigating with Teleportation with optic flow were faster overall. Also, they pointed significantly faster after using Teleportation with optic flow. However, the effect of the LM did not show in the pointing task. Neither in the pointed angle difference nor in the target distance error did the LM have a significant effect.

The size of the environment significantly affected the traveled duration and also the traveled distance. Participants spent less time and traveled shorter distances in smaller environments. However, an interesting effect of environmental size was shown in the pointing duration, here participants took less time pointing in small environments. And interestingly the size of the environment did not affect the angle error and target distance error in the pointing task.

The complexity of the environment had a significant effect on the navigated distance but not on the navigation duration. Participants in vista environments navigated shorter distances. However, it seems to not affect the pointing duration. In the pointing task, the complexity did not significantly affect the angle error but it proved to have a significant effect on the target distance error – in vista environments, participants pointed more accurately.

## 3.4.8 Questionnaires

### 3.4.8.1 SSQ

For the results from the SSQ questionnaire I firstly calculated the individual sub-scores (Nausea, Oculomotor, and Disorientation) and the total. Since some of the sub-scores were not normally distributed I used the Wilcoxon signed-rank paired samples test to compare the two LMs in the different scores. In Table 12 the descriptive statistics of the various scores for the two LMs can be seen.

*Table 12 Descriptive statistics of the various scores for both of the locomotion methods*

| | **Median** | **Mean** | **Std. Deviation** | **Minimum** | **Maximum** |
|---|---|---|---|---|---|
| **ssq nausea opticflow** | 85.860 | 90.312 | 23.051 | 66.780 | 133.560 |
| **ssq nausea teleport** | 85.860 | 83.952 | 13.588 | 66.780 | 114.480 |
| **ssq oculomotor opticflow** | 83.380 | 85.401 | 25.540 | 53.060 | 136.440 |
| **ssq oculomotor teleport** | 75.800 | 79.843 | 21.414 | 53.060 | 121.280 |
| **ssq disorientation opticflow** | 125.280 | 141.984 | 35.372 | 97.440 | 194.880 |
| **ssq disorientation teleport** | 125.280 | 129.920 | 41.649 | 97.440 | 264.480 |
| **ssq total opticflow** | 115.940 | 115.691 | 28.639 | 78.540 | 164.560 |
| **ssq total teleport** | 100.980 | 107.213 | 22.021 | 82.280 | 164.560 |

Table 13 shows that none of the differences between the different scores were significantly different for LMs.

*Table 13 Results of Wilcoxon signed-rank tests for the various scores*

| **Measure 1** | | **Measure 2** | **W** | **z** | **p** |
|---|---|---|---|---|---|
| **ssq nausea opticflow** | - | **ssq nausea teleport** | 45.000 | 1.067 | 0.303 |
| **ssq oculomotor opticflow** | - | **ssq oculomotor teleport** | 43.500 | 0.934 | 0.371 |
| **ssq desorientation opticflow** | - | **ssq desorientation teleport** | 65.000 | 1.363 | 0.182 |
| **ssq total opticflow** | - | **ssq total teleport** | 61.000 | 1.083 | 0.295 |

### 3.4.8.2 VRLEQ

To compare the scores of the VRLEQ questionnaire (LM preference) I used paired samples student’s t-test. Firstly, I calculated the summation score. No significant difference was found between teleportation scores (M = 25.200, SD = 10.325) and teleportation with optic flow scores (M = 21.800, SD = 9.329) (t = -1.942, df = 14, p = 0.073).

### 3.4.9 Additional analysis

I did one additional analysis to see if participants underestimated or overestimated pointed distances in the various conditions. For this, I used the original values of target error. In Table 14 descriptives of the target error split by LM, environmental size, and complexity can be seen.

*Table 14 Descriptive statistics of the target error (the difference between the real position of the object and the pointed distance) split by LM, size of the environment, and by the complexity of the environment. All columns have 240 observations.*

| | | Target error | | | | |
|---|---|---|---|---|---|---|
| | | **Median** | **Mean** | **Std. Deviation** | **25th percentile** | **75th percentile** |
| **Locomotion method** | Teleportation with optic flow | 72.413 | 91.008 | 348.356 | -130.079 | 310.898 |
| | Teleport | 126.717 | 146.296 | 366.057 | -53.906 | 342.779 |
| **Environment size** | Small | 187.570 | 233.338 | 281.772 | 14.624 | 373.549 |
| | Large | -16.600 | 3.966 | 388.682 | -283.510 | 243.904 |
| **Environment complexity** | Vista | 82.891 | 96.845 | 316.174 | -74.945 | 291.640 |
| | Environmental | 133.249 | 140.459 | 394.922 | -116.691 | 385.583 |

To analyze the effect of LM, the environment complexity and size I used mixed effects model. The model includes random intercepts for participants. The fixed effects were the LM, environmental size, and environmental complexity the interaction between LM and environmental size, the interaction between LM and environmental complexity, and the interaction between environmental size and complexity. The residuals were approximately normally distributed.

Table 15 shows the fixed effects estimates and their interactions. After navigating with LM Teleportation participants were more likely to overestimate the pointed distance more than with LM Teleportation with optic flow. ($\beta$ = -27.644, t = -2.091, p = 0.037). Participants also overestimated pointed distances in small environments. ($\beta$ = 114.686, t = 8.677, p < 0.001). Another significant effect was the interaction between environmental complexity and environmental size ($\beta$ = -26.121, t = -1.976, p = 0.049) the effect of vista complexity on the outcome was reduced when the level size was small. Also, the interaction between LM and environmental size proved to have a significant effect (β = 28.075, t = 2.124, p = 0.034) the effect of LM Teleportation with optic flow on the outcome was increased when the level size was small. These interactions suggest that the effects of environmental complexity and LM on the outcome are moderated by the environmental size, indicating a more complex relationship between these variables.

*Table 15 Fixed effects estimates for the reported model (target error). (OF = Teleportation with optic flow, V = Vista, S = Small)*

| **Term** | **Estimate** | **SE** | **df** | **t** | **p** |
|---|---|---|---|---|---|
| Intercept | 118.652 | 47.323 | 14.000 | 2.507 | 0.025 |
| Locomotion method (OF) | -27.644 | 13.217 | 459.000 | -2.091 | 0.037 |
| Environment complexity (V) | -21.807 | 13.217 | 459.000 | -1.650 | 0.100 |
| Environment size (S) | 114.686 | 13.217 | 459.000 | 8.677 | < .001 |
| Environment complexity (V) ✻ Locomotion method (OF) | 22.495 | 13.217 | 459.000 | 1.702 | 0.089 |
| Environment complexity (V) ✻ Environment size (S) | -26.121 | 13.217 | 459.000 | -1.976 | 0.049 |
| Locomotion method (OF) ✻ Environment size (S) | 28.075 | 13.217 | 459.000 | 2.124 | 0.034 |

In Table 16 the estimated marginal means for this model can be seen.

*Table 16 Estimated marginal means for the reported model (target error)*

| | | | | | **95% CI** | |
|---|---|---|---|---|---|---|
| **Locomotion method** | **Complexity** | **LevelSize** | **Estimate** | **SE** | **Lower** | **Upper** |
| OpticFlow | Vista | Small | 208.336 | 57.338 | 95.956 | 320.716 |
| Teleport | Vista | Small | 162.484 | 57.338 | 50.103 | 274.864 |
| OpticFlow | Environmental | Small | 259.203 | 57.338 | 146.823 | 371.583 |
| Teleport | Environmental | Small | 303.331 | 57.338 | 190.951 | 415.711 |
| OpticFlow | Vista | Large | -24.944 | 57.338 | -137.324 | 87.437 |
| Teleport | Vista | Large | 41.504 | 57.338 | -70.877 | 153.884 |
| OpticFlow | Environmental | Large | -78.562 | 57.338 | -190.942 | 33.818 |
| Teleport | Environmental | Large | 77.865 | 57.338 | -34.515 | 190.246 |

## 3.5 Discussion

In the navigation part of the experiment, participants navigated significantly faster while using the LM Teleportation with optic flow however no significant effect on the traveled distance was found between the two LMs. In small environments, participants navigated significantly faster and traveled significantly shorter distances. In vista environments, participants also navigated significantly faster however there was no difference in the distance traveled. In the pointing task, participants pointed faster after using the LM Teleportation with optic flow. Participants also pointed faster in small environments. However, neither the LM nor the environmental size had a significant effect on pointing accuracy. Here only environmental complexity showed a significant effect on pointing accuracy – in vista environments, participants pointed with better accuracy although there was no significant difference in angle error between vista and environmental environments. We expected that with LM Teleportation with optic flow, participants would navigate faster and travel shorter distances than with LM Teleportation. Teleportation is often found disorienting compared with other LMs and the added optic should cause an improvement in navigation abilities. In the navigation task, while using LM Teleportation with optic flow participants navigated faster however in the traveled distance there was no difference between the two methods. These results are consistent with the results from my bachelor's thesis where the same effect was shown (teleportation with optic flow proved to be faster but the traveled distance was similar) (Kobián, 2022). So it would seem that there is some effect of the added optic flow on the navigation performance. But even though participants finished the navigation task faster with the added optic flow they traveled similar distances as with classic teleport.

We expected that participants would point with better accuracy in the pointing task (configurational memory) after navigating using Teleportation with optic flow, as the added optic flow should promote faster spatial learning and better spatial memory. These results are again consistent with the results from my bachelor’s thesis where there was no difference in the angle error for those two LMs. However here the experimental design was slightly different, and participants were also pointing at the object’s locations not only in their direction. Even here no significant effect of the LM was proven as the pointed target distance difference was not significantly affected by the LMs. In this study, we added different types and sizes of environments compared to the first study conducted in my bachelor’s thesis. Even with the added effect of environments, the added optic flow did not increase the pointing accuracy. These results combined with the results from my bachelor's thesis would suggest that adding optic flow does affect spatial memory and retention of the visited objects minimally although, we expected the effect of the added optic flow to manifest in the spatial memory task more. Adding optic flow to noncontinuous LMs should improve the spatial memory of the navigator. Optic flow should promote faster spatial learning and better spatial memory (Kirschen et al., 2000). For example, in a study by Bhandari et al. (2018) a similar method was used and also compared with classic teleportation and participants performed better in the pointing task with the added optic flow. Teleportation is also often found more disorientating than while using other LMs (Coomer et al., 2018; Paris et al., 2019; Prithul et al., 2021) which should show in the pointing precision. Another metric measured in this experiment was the time it took participants to point to all four searched objects. Here the participants pointed faster after using Teleportation with optic flow. These results could suggest at least some effect of the added optic flow on the participants' spatial memory. From these results, it would seem that after navigating with LM Teleportation with optic the information access from spatial memory was faster than after navigating with classic Teleportation.

The second hypothesis concerned the properties of the environments and their impact on navigational abilities and spatial memory. This was the main difference of this project from my bachelor's thesis. We expected participants to acquire better spatial knowledge in small environments, which should have been demonstrated by better pointing accuracy. This was the main difference of this project from my bachelor's thesis. We expected participants to acquire better spatial knowledge in small environments, which should have been demonstrated by better pointing accuracy. The environmental size was a significant predictor of the navigated duration and distance. Here unsurprisingly participants navigated faster and shorter distances in small environments. However, what is an interesting finding is that the environmental size did not affect the pointing accuracy in the spatial memory task – there was no significant difference in pointing angle error and target distance error in small and large environments. In theory in smaller environments, participants should point with better accuracy as there is less information, and for larger traveled distances, there is also a higher risk of computational error (Meilinger et al., 2016). Interestingly though there was an effect on the duration it took participants to point – in small environments, participants pointed faster.

We expected there to be an effect of the environmental size on spatial memory in the pointing task. There was an effect of environmental size on the duration of pointing, which could mean that the size did affect spatial memory in some way. It could mean that the information from the smaller environment was accessed faster but there were no significant differences in pointing accuracy in large environments compared to the smaller ones.

Here the results regarding environmental complexity seem to be more conclusive. We expected participants to have better pointing accuracy in vista environments. Participants traveled significantly shorter distances in the vista environments, but the navigation duration was not significantly affected by the environmental complexity. In the pointing task, there was no significant effect of angle error based on the complexity of the environment. However, the environmental complexity proved to be a significant predictor of the target distance error – in the vista condition participants were more precise in their pointing. Also, no significant effect on the pointing duration was observed. In the vista condition participants navigated shorter distances. This result is in accordance with the literature – the information in environmental spaces cannot be acquired instantaneously but has to be experienced over time during the exploration (Wolbers & Wiener, 2014; Ekstrom & Isham, 2017) but in the vista spaces most of the information about the environment can be accessed from any one point in the environment (Montello, 1993; Ekstrom & Isham, 2017). In the pointing task, there was an effect of the environmental complexity on the pointed distance error but not on the angle error. This suggests at least partial distortions in spatial memory after navigating the environmental environments which is in accordance with the literature. The spatial representations of environmental spaces are fragmented into independent vista units (Brockmole & Wang, 2002; Wolbers & Wiener, 2014) which could impair recalling the visited objects. However, interestingly there was no effect of the complexity on the pointing duration even though response time should have increased the more complicated and larger the environment (Meilinger et al., 2016).

Another interesting result was that participants overall overestimated the pointed distances in small environments and also overestimated the distances more after using LM Teleportation than after using Teleportation with optic flow. Also, the interaction between LM and environmental complexity proved to be a significant predictor. Here the effect of LM Teleportation with optic flow on the outcome was increased when the level size was small, meaning that participants overestimated the distances even more after navigating with Teleportation with optic flow in small environments.

Lastly. we expected no significant difference in cybersickness for the two tested LMs. The simulator sickness scores did not differ between the two LMs. Also for both of the methods the scores were low overall and during the measurement, there were no problems with VR cybersickness – none of the participants experienced higher levels of cybersickness. Here these results were expected. The classic teleportation method is considered one of the safest methods not causing VR motion sickness (Christou & Aristidou, 2017; Langbehn et al., 2018; Prithul et al., 2021).

The added optic flow in the second LM could affect the cybersickness negatively however in the first study in my bachelor's thesis there was also no significant difference in the simulator sickness scores between the two methods. Although overall all the sub scores and the total score were lower for the classic teleportation, no statistically significant difference was shown. Another factor that might have influenced the simulator sickness scores is the time spent in VR. Longer durations spent in VR can increase the chance and severity of cybersickness (Stanney et al., 2003). However, in this experiment, participants spent approximately 10-15 minutes in VR for one testing block they also had a short break to fill out the questionnaires between them. Maybe if the time spent in VR was longer the effect of the added optic flow would be more significant on cybersickness because even here the cybersickness scores were overall lower for classic teleportation although not significantly.

Lastly for the locomotion preference questionnaire. Here no significant difference was found between the two LMs. However, the scores were overall lover for Teleportation with optic flow indicating that participants preferred Classic teleportation.

## 3.6 Limitations and future research

One of the potential limitations of this study is that the distinction between small and large environments might have not been large enough. The size of the environment did not affect the pointing precision significantly. There were differences and in small environments participants were more likely to overshoot the pointed distances and also pointed significantly faster than in large environments but the overall pointing and angle error between the environments was not significantly different. Small environments were 36 $m^2$ and large environments were 144 $m^2$. We expected there to be a significant effect of the environmental size on pointing precision and even though the estimates showed better pointing accuracy (in angle error and also in target distance error) for small environments this effect was not significant. This could mean that I should have built the large environments even larger.

As with any technology VR is not perfect and there were also some minor technical difficulties with the application and with the HMD. Mainly the USB connection via the VR airlink was somewhat problematic because it was not charging the HMD connected to the PC properly, so I had to use two different Meta Quest 2 headsets and always keep one of them charging separately. This also meant I had to set up the HMDs separately for each participant. However, these technical issues were not significant and there was only one instance of a "crash" right at the beginning of one of the testing trials for one of the participants.

Future research could address the potential limitation discussed above. Future studies could use even larger environments to test their effect on spatial memory and also to see if the added optic flow in LM Teleportation with optic flow would have a bigger effect in even larger environments than the classic Teleportation on navigation and spatial memory.

Another potential future research could examine the effect of Teleportation with optic flow on cybersickness more in-depth. In the presented study and even in my bachelor's thesis the time spent in VR for the experimental block was relatively short. Here for both of the examined LMs the simulator sickness scores were relatively low however for classic Teleportation, they were even lower. Future research could address this by prolonging the time spent in VR and examining the effects on cybersickness, navigation, and spatial memory.

# 4 Conclusion

This diploma thesis focused on the impact of locomotion method and environmental properties on navigation and spatial memory. The goal of the presented study was to compare two locomotion methods (Teleportation and Teleportation with optic flow) and also to study the effect of environmental size and complexity on navigation and spatial memory. We implemented two sizes of environments – small and large, and two types of complexities of environments – vista and environmental.

Only one of our hypotheses was confirmed – cybersickness did not differ significantly between the two locomotion methods. There was not enough evidence to confirm our other hypotheses which concerned the effect of the locomotion method and environmental properties. Firstly, participants navigated faster using the locomotion method Teleportation with optic flow but the effect of the added optic did not show in pointing accuracy in the pointing task. Participants also pointed faster after navigating with Teleportation with optic flow. Secondly spent less time pointing in small environments, but the size of the environment did not affect participants' pointing accuracy in the pointing task. Also, participants in vista environments navigated shorter distances. The complexity of the environment did not significantly affect the angle error but it proved to have a significant effect on the target distance error – in vista environments, participants pointed more accurately.

Although the differences between the two compared LMs were not sufficient enough to prove our hypotheses the differences in some factors were still apparent, suggesting that Teleportation with optic flow could in some cases be a better alternative to classic Teleportation. Teleportation with optic flow could potentially be used as an alternative to other locomotion methods in navigation studies in virtual reality and even in other virtual reality experiences.

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