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DOCTORAL THESIS

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Virtual environments as a tool to study human navigation

Využití virtuálních prostředí ke studiu lidské navigace

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Writing a thesis is easy. It only takes six months. The problem is, it is the last six months.

I have been told this truthful joke countless times during the last few months when I was completing this thesis. It is necessary to say that it did not take me six months to finish. It took me on a journey spanning five years and two continents. And although it was me who eventually made it appear on paper, it is a product of a collaborative work of many talented and passionate people.

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Abstract

Navigation is one of the most common forms of cognitive processing, which is natural for all animal species. But the neuroscientific inquiry into navigation in human subjects has been hindered by the requirements of monitoring methods, which usually require subjects to be completely still. Virtual environments allow scientists to study navigation even while the subject remains unmoving, and offer other benefits such as full control over the experimental procedures or precise behavioral recordings.

This thesis offers a basic overview of the biology of navigation and presents why navigation is an interesting cognitive process to investigate. It then presents virtual environments, explores how they can help neuroscientists to study navigation and outlines their limitations. Lastly, the literary review tries to address the question if navigation in virtual environments is comparable to navigation in the real world.

The empirical part presents five original studies of human navigation and virtual environments. These studies focus on differences of real world and virtual navigation, investigate neural pathways and brain regions involved in spatial processing, and offer examples of how virtual environments can help conduct studies otherwise impossible to do in the real world. One study provides an example of how studying navigation in a virtual environment can be interesting for psychiatry. Overall, this thesis demonstrates several benefits of VEs and the transferability of navigation results obtained in the VEs to the real world.

Keywords: virtual environments, virtual reality, navigation, spatial knowledge

Abstrakt

Navigace je jedním z nejběžnějších kognitivních procesů, který lze pozorovat u všech zvířecích druhů. Protože zobrazovací metody obvykle vyžadují, aby subjekt během experimentu zůstal bez hnutí, bylo studium navigace u lidí pomocí neurovědeckých metod dlouhou dobu obtížné. Virtuální prostředí dávají vědcům nástroj, pomocí kterého lze sledovat navigační chování u lidí i přesto, že se nehýbají. K tomu navíc přináší i další výhody, jakými je například úplná kontrola experimentálních stimulů a možnost přesného záznamu participantova chování.

Tato disertační práce podává základní přehled biologických podkladů navigace, a předkládá, proč je právě navigace zajímavým kognitivním procesem vhodným ke studiu. Dále pak prezentuje, jak mohou být virtuální prostředí pro studium navigace prospěšné a jaká jsou jejich možná úskalí. Nakonec se pokouší o zodpovězení otázky, zdali je navigace ve virtuálních prostředích srovnatelná s navigací v reálném prostoru.

Empirická část disertační práce prezentuje pět originálních vědeckých publikací, které studují virtuální prostředí a navigaci u lidí. Tyto studie se zaměřují na rozdíly mezi navigací ve virtuálním a reálném prostoru, mozkové dráhy a oblasti zapojené do prostorové kognice, a nabízí ukázky, jak virtuální prostředí umožňují uskutečnit studie, které by bez nich vzniknout nemohly. Jedna studie také poskytuje příklad toho, jak studium navigace ve virtuálních prostředích může být nápomocné v psychiatrické péči. Tato disertační práce popisuje řadu výhod virtuálních prostředí ve výzkumu navigace a přenositelnost výsledků v nich získaných pro naše porozumění navigaci v reálném světě.

Klíčová slova: virtuální prostředí, virtuální realita, navigace, prostorová orientace

Contents

Abbreviations and definitions

AD	Alzheimer's disease
ADL	activities of daily living
BGA	broadband gamma activity (50-150Hz)
CA	cornu Ammonis
EC	entorhinal cortex
EEG	electroencephalography
fMRI	functional magnetic resonance imaging
FPS	frames per second
HD cell	head direction cell
HMD	head mounted device
iEEG	intracranial electroencephalography
LFP	local field potential
MCI	mild cognitive impairment
mEC	medial entorhinal cortex
MEG	magnetoencephalography
MRI	magnetic resonance imaging
MTL	medial temporal lobe
MWMT	Morris Water-Maze task
PC	personal computer
PET	positron emission tomography
PMT	parieto-medial temporal pathway
PPA	parahippocampal place area
PPC	posterior parietal cortex
RSC	retrosplenial cortex
SZ	schizophrenia
VE	virtual environment
VR	virtual reality
VSST	virtual supermarket shopping task

allothetic cues	sensory cues originating externally, for example visual or auditory cues
desktop	in this context, the *desktop* term describes any machine used to administer a virtual environment on a monitor, most commonly with mouse and keyboard. Can designate PC, Mac, notebooks and other devices
desktop VE	designates the virtual environment itself administered on a desktop
idiothetic cues	sensory cues originating from within one's body, such as vestibular or proprioceptive
Navigator	unless specified, referring broadly to both animal and human subjects

1. Introduction

Since the early 2000s, the use of virtual environments (VEs) and virtual reality (VR) in neuropsychological research has become quite a prominent method in studies of memory, perception, attention, navigation and other aspects of cognitive processing. VEs have several major benefits for navigation research, as they allow scientists to observe navigating behaviour in subjects laying still in the magnetic resonance imaging (MRI) scanner or wearing an electroencephalography (EEG) cap, provide full control over the experimental conditions and allow precise behavioural recordings.

Although vision, the primary source of information in VEs, is potentially the strongest contributor to spatial cognition in humans, even people without sight are more than capable of getting around. Researchers have stressed the importance of proprioception and vestibular information in navigation, and some forms of navigation can work without any visual input. Although virtual simulations can mimic the real world to an immense visual detail, many sensory inputs are not easily accessible in the virtual world. Participants often move around using keyboards or gamepads and there is very little proprioceptive or vestibular stimulation involved.

The major benefit of virtual navigation then suddenly becomes an unexplored question. Are the navigation processes in VEs good representations of navigation in the real world? Does the navigation require proprioception or vestibular input to function properly? Do people use different strategies while navigating virtual worlds than they do navigating the real world? And if they do, does the quality of the acquired representation differ?

Given the number of studies on human navigation which use VEs is quite large, the assessment of comparability and transferability is necessary to address potential discrepancies between their results and those which could be observed in the real world.

The aim of my thesis is to investigate the benefits of using VEs to study human navigation, to address their limits and drawbacks and to assess the validity of using VEs as a tool to make conclusions about human navigation in the real world.

1.1 Navigation

Navigation is one of the most common forms of cognitive processing which can be found across the entire animal domain, as all animals need to navigate to find food, shelter or mates (Grieves and Jeffery, 2017). This offers scientists a unique target of investigation which promises some level of transferability of results between species.

Navigation allows both self localization and being able to follow already traversed routes, but also to travel novel routes, to explore the environment or to correct for any new obstacles on already learned paths. Many animals are able to successfully navigate unknown areas in search for home or food (Jeffery, 2003). Complex navigating behavior, which cannot be explained by mere stimulus response learning, has been observed in bats (Yartsev and Ulanovsky, 2013), pythons (Pittman et al., 2014), rats (Jeffery, 2003), birds (Lucas and Simmons, 2005), spiders (Casto et al., 2020) and many other species.

Navigation constitutes a high level process which is dependent on analyzing and integrating multiple sensory streams - in humans this is mainly vision and vestibular information, but auditory signals, proprioception (Chen et al., 2013) and olfaction (Jacobs, 2012) can also serve as orienting cues. This is beneficial for scientists, as although sensory modalities will vary greatly across species, e.g small foraging animals might rely on smell much more than bipedal creatures, we can assume that the final spatial representation might have similar properties across species.

Because I am reporting on studies from both the human and animal domain, in case of general navigation I will use the term *navigator* throughout the thesis to designate either human or animal subjects.

1.1.1 Navigation strategies

Navigation, simply put, is the process of getting from one place to another. It requires both correct self localization (*here*) and knowledge of the final destination (*there*). *Here* and *there* needs to be either connected by a well-remembered route, for example traveling through a series of paths and crossroads in a car, or a knowledge of geometrical relationship between *here* and *there* while traveling through unexplored or complex environment, similar to traveling through a desert with a compass. As such, navigating to places can take many forms and we understand multiple navigation strategies on which I will expand in this section.

Our knowledge of an environment depends on collecting and processing both external and internal cues.

Idiothetic cues are *internal* sensory cues which originate within the navigator's body. These are mainly vestibular cues to determine rotations and accelerated movement through the environment, and proprioceptive cues, which can serve as information about general body movements, such as assessing speed from muscle exertion, traveled distance from the number of steps or the number of wing flaps in flies (Fry et al., 2008).

Allothetic cues, on the other hand, are cues which originate *externally.* These are mainly visual perceptions defining surrounding spatial features, such as environmental geometry or landmarks, but in many species can also stem from olfactory (Jacobs, 2012), auditive, or haptic signals. In some species, senses such as magnetosensation (Holland et al., 2006) or echolocation (Yartsev and Ulanovsky, 2013) have also been found to be important drivers of navigation signals.

Navigation strategies can use both types of cues and their exact interaction and relative importance for effective wayfinding is one of the ongoing questions in the field.

Beaconing. The arguably simplest form of navigation is called beaconing (Geva-Sagiv et al., 2015). Beaconing describes navigating towards a single allothetic cue, for example flying towards a sound or walking towards a smell. This form of navigation is very simple and the manifested behavior can be understood in a simple stimulus-response paradigm, rather than proper navigation, and I will not discuss this strategy further.

Path integration. Path integration, also called “dead reckoning”, is a basic, yet dominant form of navigation. Path integration is prominent in many animal species (Etienne and Jeffery, 2004). Path integration is a computational process allowing the navigator to update the so-called homing vector, i.e. the relationship between current position and origin. This is done primarily with idiothetic cues (Klatzky et al., 1998; Grieves and Jeffery, 2017).

No allothetic cues are used in true path integration, but vision can provide optic flow information (Loomis and Beall, 1998; Chrastil et al., 2015). In the absence of visual cues, navigators can profit from vestibular and proprioceptive input which provide necessary information to keep track of rotation and movement (Chen et al., 2013, 2018). This is especially important for navigation in open fields, such as tundra, desert or sea, where vision might not provide useful information. But spatial updating can also be achieved using only occasional idiothetic input and then adding together the time and speed information. Therefore, it is not necessary to constantly keep track of idiothetic cues, if one is moving steadily in a constant direction.

The major disadvantage of path integration is that it suffers from large cumulative error which increases over longer distances (Etienne et al., 1998; Etienne and Jeffery, 2004). The farther the navigator travels, the more likely they are to fail to return just on path integration basis. There are two potential errors the navigator can make - either choose an incorrect return heading (rotational/angular error) or return an improper distance (translational/distance error). These errors can rise from various sources, such as biases in velocity, memory decay, accumulating noise and others (Stangl et al., 2020). In case of missing idiothetic cues, rotational error is arguably more affected than distance error (Waller and Greenauer, 2007).

Path integration in humans is often investigated using triangle completion tasks (Loomis et al., 1993; Klatzky et al., 1998) or more complex path completion tasks (Stangl et al., 2020). In these tasks, participants walk from an origin point through a defined set of turns and at the end are asked to designate their heading in respect to the starting point. To assess the importance of various external or internal cues on path integration error, these tasks can be done in varying conditions: blindfolded while walking, sitting on a wheelchair (Waller and Greenauer, 2007), on treadmills providing proprioceptive cues (Harootonian et al., 2020), while watching videos, or during imagined movement (Klatzky et al., 1998).

Reference frames. Before moving forward to navigation strategies which rely on allothetic cues, I would like to briefly address the topic of reference frames.

Position can never be represented as an absolute value and always needs to be in reference to something and there is an infinite number of such reference points (Bennett, 1996). The path integration strategy keeps the position relative to the origin point and is sometimes referred to as an idiothetic or inertial reference frame (Moser et al., 2017). But this is not always sufficient for successful navigation, mainly in case the navigator is moved passively. In such cases, the navigator’s new location must be inferred in relation to external, allothetic cues.

Reference frame then serves as such a relative positioning framework. In the majority of the literature, we encounter the egocentric and allocentric reference frames (Klatzky, 1998; Moraresku and Vlcek, 2020). The egocentric reference frame has the navigator as its reference center, and represents all the landmarks and points of interest relative to the navigator's position. The allocentric reference frame, on the other hand, represents space through relations of external landmarks with the navigator being only a part of the representation.

Although the outcome of both of these representations is mathematically equivalent, the two reference frames seem to have functional differences and are represented in different brain regions (Snyder et al., 1998). Our understanding of location representation in place cells in the hippocampus (see later section 1.2.2) points to their directional independence which suggests that the space is represented in the medial temporal lobe (MTL) in the allocentric reference frame. On the contrary, the egocentric reference frame has been mostly seen to be represented in the parietal cortex (Snyder et al., 1998; Wilber et al., 2014), probably due to inputs from somatosensory and visual cortices (see section 1.2.2).

Although the allocentric reference frame is often understood as relying on external landmarks, it has been demonstrated that the place cell and grid cell coding, which is arguably allocentric in nature, is affected by path integration processes using idiothetic cues (see section 1.2.1).

Response strategies/Route following. Where path navigation serves as the most basic form of self updating and recognizing navigator's position through idiothetic cues and can be considered true navigation, response strategies have their roots in memory processes. Response strategies, such as view-dependent navigation or route following, work simply based on stimulus response or associative learning. Based on the stimulus the navigator experiences, for example a particular landmark, they chose a given response, for example "turn left at this church".

The response strategies correspond well to the ideology of behaviorism and formed the pivotal hypotheses in our understanding of how navigation works. Research of navigation in the first half of the 20th century used complex mazes and understood navigation simply as a list of decisions the animal has to make based on prior learning (Tolman, 1948).

A little more advanced are theories suggesting view-based or view-dependent navigation. These postulate that the navigator uses retinal image and its deformation to calculate position and rotation in respect to the learned view (Geva-Sagiv et al., 2015; Cartwright and Collett, 1983). Given the relative abundance of visual information in any scene, even in absence of significant landmarks, this form of navigation can provide useful information.

But researchers understood that navigation must be more complex than simply a series of choices, as path integration itself is not response-based. The potential source of this confusion was with the tasks themselves, as complex mazes and even boxes with geometrical features allow animals to implement response-based navigation as a solution, although they might adopt a different navigational strategy in their natural environment.

The decoupling of navigation and memory have been a tricky endeavor, as the original maze tasks could have all been solved by simple stimulus response strategies. This was eventually solved by replacing the standard maze structures with the Morris Water-Maze task (MWMT) (Morris, 1984). MWMT is purely spatial and cannot be, in some forms of its administration, solved by response strategies and memory alone.

Cognitive maps. In 1946, Tolman observed that rats are able to make navigational decisions and correctly select paths with the correct heading although they never directly experienced them (Tolman et al., 1946). This was in contradiction to the prevailing response-based strategies, which dictated the animal should prefer paths reinforced during learning, regardless of their inferiority or incorrect headings. He concluded there needed to be some high level representation of the environment which had not been encoded through direct experience, but was inferred based on other information. This led him to form the influential idea of a cognitive map (Tolman, 1948).

Cognitive maps differ from response-based strategies as they assume complex associations between the landmarks and other spatial features, such as environment borders, routes or obstacles. These features are not employed in navigation merely as decision points, but allow creation of a representation where they share geometric relationships defining the spatial layout and allow inference about the environment even without direct experience (O'Keefe and Nadel, 1978).

The idea was revolutionary at the time, due to still strong behavioristic approach to both animal and human learning (Grieves and Jeffery, 2017), and it did not go without its share of controversy. Tolman's results failed to replicate in a study conducted shortly after his original findings (Gentry et al., 1948, 1947) and were criticised for a potential methodological flaw: the place of the final reward was clearly marked by a ceiling light, a potential landmark for a simple response-based strategy. This flaw was investigated recently with human subjects in virtual environments (VEs) (Wilson and Wilson, 2018) and researchers again failed to replicate Tolman's results when the distal cue above the goal was missing.

Other discussions around cognitive maps stem from the fact that simpler solutions than cognitive maps exist to many of the observed behaviors. Many navigation tasks used to demonstrate the existence of cognitive maps could have been solved by simpler and less assuming strategies, such as path integration or beaconing (Bennett, 1996). For these reasons, some researchers (Gallistel, 1994) define the cognitive map as any spatial representation, not necessarily with map-like properties, which allows animals to navigate. This, although addressing the terminology discrepancies, unfortunately defines a cognitive map in a way in which is untestable and incomparable between species.

The idea of a cognitive map generally suggests an infallible system which builds a perfect euclidean representation of space. But even from our experience, we know that to be false. Both people and animals can make mistakes, prefer longer routes, and cannot make shortcuts in all situations. The euclidean understanding of cognitive maps has few benefits, primarily allowing to conceptualize expected results in a fairly straightforward mathematical explanation (Bennett, 1996), but there is substantial evidence that cognitive maps might not be representative, at least on the behavioral level, of the real navigation strategies.

Other researchers therefore propose the spatial representations are stored as view-graphs (Gillner and Mallot, 1998) or labelled graphs (Chrastil and Warren, 2015, 2013). Few studies by Elizabeth Chrastil and William Warren investigated graph theories and they postulated that labeled graphs explain human navigation behaviour better than euclidean theories (Chrastil and Warren, 2015; Warren et al., 2017; Chrastil and Warren, 2013; Ericson and Warren, 2020). The labelled graph theory states that landmarks (nodes) are connected by paths (edges) of varying weight, depending on the distance between their nodes. The relative positioning of the landmarks in respect to each other is then coded locally at each landmark. This separates labeled graphs from euclidian maps in which the relative positioning of landmarks is a property of the entire system.

Regardless of the ongoing debate, the cognitive map theory sounded plausible and was instrumental to the conceptualization of neural findings in the 1970s, which demonstrated that some level of spatial representation does exist on neural level and it has euclidean properties (see section 1.2.1).

Conclusion. In conclusion, there are many navigation strategies which can be used at any point and there does not seem to be a single dominant one. Both humans and animals can switch between different strategies as the situation requires (Geva-Sagiv et al., 2015). For example, it is not necessary to use cognitive maps if the entire trip can be made along the river, or using beaconing towards a particular smell or a visual cue. It might be impossible to use visual cues in the dark or unnecessary over short distances and so the navigator will rely on path integration. On the contrary, when allothetic cues are available, navigation using cognitive maps or cognitive graphs is arguably the most reliable and offers solutions, such as shortcutting or solving for obstacles, which other strategies lack.

1.2 Biology of navigation

In this section, I will focus on the neural underpinnings of spatial navigation. I will describe some of the discovered spatially selective cells and then provide an overview of neural systems supporting navigation in animals and humans.

1.2.1 Cellular level

Neurons modulating activity based on various spatial features have been discovered in both animal and human central nervous systems. These cells can fire action potentials in reaction to navigators being in a particular place, moving in a particular speed or facing in a certain direction. This section offers an overview of the most important cells with these properties.

Place cells. Although the behavioural studies demonstrated that animals have a high capacity of representing space in a manner which could not have been explained by response strategies, it took until the 1970s before the first observations of spatially tuned cells were discovered. In a key study in 1971, Johnatan Dostrovsky and John O'Keefe reported an existence of cells in the rat's hippocampus which fired when the animal was in a particular position in the studied environment, the place cell's place field (O'Keefe and Dostrovsky, 1971; O'Keefe, 1976). Combining the behavioral studies conducted since 1940, John O'Keefe and Lynn

Nadel summarised what science knew at that time about spatial navigation and how these novel hippocampal cells can form the basis of Tolman's cognitive maps (O'Keefe and Nadel, 1978).

Place cells have several interesting properties. Firstly, their location in the hippocampus is not relevant to the location of their place field in the environment. In other words, place cells close to each other can represent very different locations (O'Keefe, 1976). This is in contrast to other brain regions organization, for example retinotopic organization of visual cortex.

Secondly, place cells undergo change in their firing rate following environment change during a process called remapping. This leads to observations where the same place cell signals completely different locations in two different environments (O'Keefe and Conway, 1978). This remapping can be driven by geometry change or rotational and translational shifts in the environment (Muller and Kubie, 1987; Yoganarasimha and Knierim, 2005).

Thirdly, place cell activity seems to be driven by a variety of sensory inputs. They can be modulated by visual cues, with the visual cue rotation also causing the place field rotation and removing it leading to place cell field unpredictable rotational shift (Muller and Kubie, 1987), but they also can also remain stable when the cues are removed (O'Keefe and Speakman, 1987). Place fields can be formed in darkness and remain stable despite turning the lights on (Quirk et al., 1990), can be modulated by whisking behavior or olfactory cues (Save et al., 2000). Place cell activity seems to be also driven by environmental boundaries, with elongating the geometry of the environment also elongating the corresponding place fields (O'Keefe and Burgess, 1996).

As previously discussed, idiothetic input can also drive place cell activity (Chen et al., 2013). Rat recordings show that place cells have relatively stable place fields even in darkness or in case the rats are blind, documenting that vision is not necessary for place cell activity (Save et al., 1998). Other authors obtained similar results, observing that vestibular cues seem to be necessary to properly tune the place cell activity (Ravassard et al., 2013) and that potential competition between different cues leads to reduction in place field accuracy.

Place cells seem to represent a high memory structure, the final path in a complex cognitive process which combines multiple sensory cues (Jeffery, 2007).

Due to the nature of the recording technology, most place cell research has been done in rats, but direct recordings of neuronal activity in epileptic patients has demonstrated their existence in the human hippocampus as well (Ekstrom et al., 2003).

Grid cells. Place cells seem like the final step of a fairly complex process. Although undoubtedly present and studied for over 30 years, in the early 2000s it was still unclear what process leads to their spatial tuning.

Hippocampus does receive some vestibular and visual sensory input, but probably not to the extent which would warrant the place fields to be formed based on this input alone. Also, the operation of integrating multiple sensory streams into what was later observed to be the place cell code seemed like a multistep process. In 2004, a Norweigan group led by May-Britt and Edvard Mosers published their findings demonstrating the presence of other place sensitive cells in the entorhinal cortex (EC). Given the properties of these cells, they called them grid cells (Fyhn et al., 2004; Hafting et al., 2005).

Unlike place cells, which have a single firing field in a given environment, firing fields of grid cells form a hexagonal grid, with different grid cells' fields overlapping each other. This final mesh then covers the entirety of the environment (Hafting et al., 2005). The grid cells can shift their firing fields with external cues rotation in a similar fashion that place cells do (Fyhn et al., 2007; Hafting et al., 2005), so their activity is also dependent on allothetic and not solely idiothetic cues, although the idiothetic ones are important as well since darkness does not abolish grid code (Hafting et al., 2005).

Because of the grid regularity and their dependence on animal movement, researchers proposed these to be the core of metric calculations and path integration (McNaughton et al., 2006).

Investigation of grid cells in human subjects is a little more complicated, but Jacobs et al. (2013) were eventually able to observe the grid cells using intracranial recordings in epileptic patients. A slightly different approach can also be used to study the hexagonal tuning of the EC's activity. Because of the hexagonal arrangement of grid cells' firing fields, the same grid cell network should have a similar firing pattern in periodic intervals of 60 degrees (sixfold rotational symmetry), which was observed in the functional MRI (fMRI) signal (Doeller et al., 2010).

Head direction cells. One of the interesting features of place cells and grid cells is their non directional tuning. While place cells in narrow corridors exhibit a sort of directional properties, firing stronger or only when the animal passes in a given direction (McNaughton et al., 1983; Muller et al., 1994), most place cells in open spaces seem to fire regardless of animal orientation (O'Keefe and Conway, 1978). But naturally, proper spatial positioning requires rotational components, otherwise spatial strategies, such as path integration, would not work.

First reports of cells tuned to spatial direction came in the 1980s (Ranck, 1984) and were soon expanded by Jeffrey Taube's team (Taube et al., 1990; Valerio and Taube, 2016). Head direction cells (HD cells) are found primarily in the postsubiculum, although they have been also found in retrosplenial cortex, and other adjoining areas. HD cells have been found in rats (Taube et al., 1990), bats (Rubin et al., 2014), birds (Ben-Yishay et al., 2020), and recently in fish (Vinepinsky et al., 2020).

Taube concluded that HD cells do not have any "preferred" direction (Taube et al., 1990) and they cover the entirety of 360 degrees of plenary angles. HD cells in mice are also thought to be reliant on vestibular input, as its absence abolishes the signal (Valerio and Taube, 2016).

The HD cells are tuned to a particular head orientation in the environment, respective to external cues. Some have argued that this actually leads to their uneven firing rates around borders, therefore makes them responsive to environmental geometry (Peyrache et al., 2017). HD cells use not only idiothetic cues, but are also tuned by allothetic cues in a similar fashion to place cells and they can effectively code for crude spatial information (Yoganarasimha and Knierim, 2005; Peyrache et al., 2017).

Other cells involved in spatial processing. Border cells are cells found in the medial entorhinal cortex (mEC) and parasubiculum and they fire when the animal is close to one of the environmental borders or obstacles (Solstad et al., 2008). These cells could also be considered as conjunctive HD cells, because of limited tuning that HD cells can have around the borders (Peyrache et al., 2017). Environmental borders have also been shown to modulate spatial grid code (Keinath et al., 2020), and grid cells remap in respect to environment geometry changes (Fyhn et al., 2007), potentially suggesting a much larger role that geometries and borders play in spatial knowledge.

In mEC, we can also find speed cells, which are neurons modulating their firing rates by animal speed (Kropff et al., 2015).

Conjunctive cells are cells reacting to more than a single spatial or navigational feature, e.g. head direction and speed. These cells are to be expected, as simply connecting to the same postsynaptic targets can create such conjunctive signals, and they can fulfil unique tasks in navigation. For example, the same cell can code navigator's location and target location, representing both egocentric and allocentric reference frames and effectively coding for a goal vector (Wilber et al., 2014). Conjunctive grid cells have also been observed in the mEC to code for combinations of grid and direction (Sargolini et al., 2006), and place fields of place cells found in human recordings were often remapped depending on goal position (Ekstrom et al., 2003). Recent findings suggest that even pure grid cells might be modulated by head orientation to a certain degree (Gerlei et al., 2020).

1.2.2 Neural systems supporting navigation

In the previous section, I outlined the cellular coding of spatial information, from head orientation and speed to location specificity. In this section, I would like to focus on larger neural systems supporting navigation.

Hippocampus Hippocampus is a structure in the medial temporal lobe (MTL) documented to be essential in memory processes and navigation. Knowledge of hippocampal function originated from case studies demonstrating memory impairment after hippocampal damage or targeted resection or lesioning. The most prominent was the case of Henry Gustav Molaison (HM), whose MTL structures were surgically removed in order to treat his severe epilepsy (Corkin, 2002). After the operation, HM started to suffer from a severe anterograde amnesia. Although retaining most of his preoperative memories, HM was unable to form new long term memories, scoring very low on the Wechler memory scale in language, stories and association subtests (Scoville and Milner, 1957).

HM was administered a multitude of tests to assess his cognitive skills and address what the MTL might be responsible for. Besides the mentioned impairment of episodic memory, HM was also affected in his navigational skills (Milner, 1965; Corkin, 2002). At first thought to be a byproduct of memory impairment, the discovery of place cells in cornu ammonis (CA) in hippocampus shifted the view of hippocampal function from memory to navigation (O'Keefe, 1976) and studies using MWMT also conclusively demonstrated that hippocampal lesioning impacts spatial skills (Morris et al., 1982).

Before the discovery of grid cells, the hippocampus was thought to be the originator of path integration, as the place cell signal was observed to be preserved even in the absence of external cues, therefore clearly originating from within (McNaughton et al., 1996). The current understanding of hippocampal place signal is more in line with an integrative functionality, which can work based on either allothetic or idiothetic signals depending on their availability.

Focusing on human studies, the importance of hippocampus is documented in structural MRI studies by Eleanor A. Maguire (Maguire et al., 2000; Woollett and Maguire, 2011; Maguire et al., 2006). She and her team at UCL noted that there are hippocampal structural changes in London Taxi drivers, which can be related to their obligatory, 4 year long, extensive training of London's traffic infrastructure called "the Knowledge". Posterior hippocampal gray matter was observed to be increased in taxi drivers in comparison to controls (Maguire et al., 2000), in comparison to bus drivers who also drive the London's traffic but only on predetermined roads (Maguire et al., 2006) and even within subject longitudinal study pre and post "the Knowledge" (Woollett and Maguire, 2011). Hippocampal activation in fMRI during navigation has been observed as well (Spiers and Maguire, 2006; Huffman and Ekstrom, 2019).

The exact role of the hippocampus for spatial navigation is still an ongoing question. We know from animal studies that the hippocampus hosts spatial sensitive cells. In humans, it manifests clear spatial properties in both direct (Ekstrom et al., 2003, 2005; Jacobs et al., 2013) and indirect recordings (Chrastil et al., 2015; Spiers and Maguire, 2006).

The hippocampal involvement has been argued to have more to do with object/landmark recognition or memory (Eichenbaum, 2017), rather than spatial navigation on its own. Hippocampal cells in primates (Rolls, 1999) as well as in direct recordings in humans (Ekstrom et al., 2003) have been observed to also react to spatial views.

Entorhinal cortex. Entorhinal cortex (EC) is commonly separated in literature to its functionally distinct lateral and medial (mEC) parts. Especially mEC has has high importance for navigation systems due to the presence of grid cells (Hafting et al., 2005; Fyhn et al., 2004, 2007) and high connectivity of its layers to hippocampal CA1 and CA3 areas, which are the primary locations of place cells.

Although the inner workings of navigation systems are still investigated, the EC is thought to be the originator of path integration and metric information (McNaughton et al., 2006; Chen et al., 2013).

As I discussed in the section 1.1.1, path integration can be also solved by using information about heading and speed, rather than continuously checking incoming proprioceptive information. Given the importance of other mEC cells for updating self position, speed cells in mEC are thought to add this important information to path integration systems (Carvalho et al., 2020). mEC also contains multitude of conjunctive cells. We can find cells coding for grid code and directionality at the same time (Sargolini et al., 2006).

Other brain regions important for navigation. Posterior parietal cortex (PPC) is a recipient of various allothetic and idiothetic cues from auditory, visual and somatosensory cortices and is thought to serve as a translational system between egocentric and allocentric reference frames (Snyder et al., 1998). Lesions of PPC lead to egocentric disorientation (Aguirre and D'Esposito, 1999). Cells found in PPC in rats have been observed to exhibit conjunctive egocentric-allocentric properties in respect to the navigation target (Wilber et al., 2014). The PPC neurons have also been found to represent space in the eye-centered reference frame (Cohen and Andersen, 2000), probably due to the PPC role in representing eye movements (Tanabe et al., 2002). For a review of PPC in navigation see Calton and Taube (2009).

Retrosplenial cortex (RSC) serves as a connection between PPC and the MTL. RSC has been suggested to be keeping track of homing vectors and involved in path integration (Chrastil et al., 2015), and generally managing egocentric to allocentric translation (Epstein, 2008; Vann et al., 2009). Patients with RSC lesions have trouble coordinating allocentric and egocentric representations after heading changes (Hashimoto et al., 2010). For an overview of RSC anatomy and function see Vann et al. (2009).

Another spatial sensitive area is the parahippocampal place area (PPA) located in the MTL. PPA responds to visual scenes, both outdoor and indoor and irrespective of the number of objects (Epstein and Kanwisher, 1998) and activates in landmark retrieval (Rosenbaum et al., 2004).

Brain circuits supporting navigation. All these studies demonstrate that navigation is a very complex process involving brain areas responsible for anything from gaze following to body sensation and locomotion. There are several important circuits which connect the relevant brain structures and which can cause spatial processing impairments when damaged.

Parieto-medial temporal pathway (PMT) connects the caudal portion of the inferior parietal lobule and passes through the posterior cingulate cortex, RSC and connects to the MTL (Kravitz et al., 2011). RSC is known to project to the postsubiculum, which is populated with head direction cells (see section 1.2.1). This suggests that there is some translation happening between the ego-centered reference frames represented in the RSC (Hashimoto et al., 2010) and object centered in the caudal portion of the inferior parietal lobule (Chafee et al., 2007) and HD cell signal represented in the postsubiculum, which has been found to be independent of animal position and orientation (Taube et al., 1990).

Most of the studies stipulate that the posterior parietal region seems to represent spatial representations in their egocentric coordinates, due to close relationship to both somatosensory body centered input and visual input through occipito parietal pathway. The hippocampal formation and other parts of the MTL are then thought to be representing space in allocentric coordinates, as grid cells in mEC, place cells in the hippocampus and HD cells in the pre- and parasubiculum, are demonstrating body-independent firing patterns. The translation between egocentric and allocentric reference frames is then happening somewhere along the PMT pathway, likely in the RSC.

Oscillations in navigation processes. One of the more unique features of the neural systems supporting navigation are the permeating neural rhythms which can be observed during navigator's movement through space. Majority of the studies presented in previous sections focused predominantly on single units and local field potential (LFP) recordings, but the primary source of neurological data in human studies are brain oscillations (Kahana, 2006). Since the early 2000s, the neuroscientific field has expanded with the help of intracranial electroencephalography (iEEG) studies involving subjects undergoing invasive monitoring to localize the epileptic focus. Although this technique is not new, its use in conjunction with controlled cognitive experiments came only recently (Kahana, 2006).

Brain oscillations are rhythmic patterns of neural activity generated both spontaneously and in response to external stimuli. Oscillations in humans can be easily measured with scalp EEG, but it can reliably focus only on surface cortical areas, while research of oscillations in navigating animals focuses heavily on hippocampus (Jacobs et al., 2007). Using invasive methods, oscillations can be observed by pooling individual neuronal spiking or through LFP recordings. LFPs are summative recordings of extracellular signals which result from ion movement across the neural membranes.

The brain oscillations can be separated into frequency bands of functional importance. These are delta (1-4Hz), theta (4-8Hz), alpha (8-12Hz), beta (13-40Hz), low gamma (40-80Hz) and high gamma (80-150Hz).

Oscillations can be the answer to a few neuroscientific questions dealing with spike timing. Synchronous oscillations can potentially explain the necessary separation of memory encoding vs retrieval (Hasselmo et al., 2002). Also, episodic memory as well as memory for routes need the exact sequence to be consistent across retrievals. Synchronizing the neuronal spiking using oscillations might be necessary. The observed oscillatory activity is then the result of a sequence retrieval (Buzsáki, 2005). Oscillations play a significant role in many cognitive processes, such as attention (Fries et al., 2001), memory (Jensen and Tesche, 2002), or spatial navigation (Aghajan et al., 2017; Chen et al., 2018; Jacobs et al., 2013).

The frequency band important for navigation is the theta band (4-8Hz). Rats travelling through the environment demonstrate increased theta power in the hippocampus during movement (O'Keefe and Recce, 1993). The similar observations of theta band oscillation increases during navigation and have been observed in human subjects as well (Ekstrom et al., 2005; Aghajan et al., 2017; Watrous et al., 2011; Vass et al., 2016).

1.3 Importance of navigation

Before moving forward, it is necessary to address the core question of why it is important to study navigation in humans. Beyond the mere scientific curiosity, there are a few strong reasons which make navigation research a very desirable field for neuroscientists, psychologists and psychiatrists.

1.3.1 Transferability of results between animal and human research

Navigation is a complex cognitive process, which is largely independent of sensory input and is natural to all animals. The core task in allowing transferability of results between animal and human studies is to conduct the study with comparable protocols.

Unlike studies in memory or perception, paradigms of navigation studies seem to be transferable between different species. The beauty of navigation tasks is their relative independence on sensory modalities (Jeffery, 2007), as place cell fields can arise from visual, olfactory, proprioceptive cues as well as echolocation etc. (see section 1.2.1). Navigation is also an everyday requirement for any living creature, animals can be observed and studied in their foraging activity, navigation to safe spaces (Morris, 1984), or travelling between multiple food sources (Cartwright and Collett, 1983). Navigation (and hippocampal involvement) is also considered by some to be part of declarative memory (Eichenbaum, 2017) and therefore can serve as a bridging topic between memory research in humans and animals.

Navigation tasks can provide comparable behavioral outcomes, although the solutions can be based on different sensory and cognitive processes in different species. In other terms, although rats and humans might perceive the environment differently and even use different sensory cues to encode the world, the observed behaviours and even brain circuitry involved can be largely the same.

Although requiring animals to navigate at the human level might be challenging, adopting animal tasks to humans is proving to be useful in neuroscientific knowledge transferability. The dominant navigation task used in animal studies is the MWMT, which has been used in many navigation studies in humans in VEs (Fajnerová et al., 2014; Horner et al., 2016) and demonstrate that hippocampal damage affects performance comparably to what has been observed in animals (Astur et al., 2002). The MWMT can be also built in the real world, allowing precise comparison between animal and human behaviour and investigating navigational strategies requiring idiothetic input (Hort et al., 2007; Kalová et al., 2005; Mokrisova et al., 2016).

The relative transferability of navigational results from animals to humans can be useful during the process of drug development or testing animal models of mental disorders, such as schizophrenia or obsessive-compulsive disorder (Stuchlik et al., 2014; Pratt et al., 2012). Testing spatial impairments, which could indicate deficits in declarative memory or cognitive control due to localization of these functions in the MTL, can therefore provide useful insights into drug efficiency or its side effects.

1.3.2 Navigation impairment as a marker of pathological aging, neurological and mental disorders

Another major reason to study navigation is that it seems to be a very early marker of multiple neurological diseases or pathological aging. Navigation tasks can also be used as a metric of determining patients' state and easily track their progress over time.

Aging. Navigation is one of the processes affected by the aging process. It has been demonstrated that elderly participants are imparied in their route strategies (Hilton et al., 2020a), path integration skills (Stangl et al., 2020), or loss of ability to encode scenes (object-location binding) (Muffato et al., 2019).

The source of the navigational impairment can be due to the decline in the hippocampal volume, but various studies marked the difference in navigation strategies in the elderly population (Schuck et al., 2015). Elderly population seems to be less reliant on hippocampal activation in relation to boundary processing and more on landmark based navigation. This suggests that elderly population has impairment in their allocentric processing, and relies on simpler navigational strategies, such as beaconing.

Other researchers also propose that elderly population shifts towards more conservative strategies and encodes spatial locations using room geometry rather than in allocentric object relations (Segen et al., 2020). This is corresponding to the findings that elderly population tends to scan the spatial scene more but keep scanning already viewed regions of interest more than young people (Hilton et al., 2020b) and observe landmarks less (Grzeschik et al., 2019). These behaviours, although not directly tied to navigational efficiency, help us understand the deficit in elderly population spatial skills.

Our understanding of why this impairment occurs can help us in designing better navigational aids or markers for nursing homes or hospitals, but it can also help in diagnosing and assessing patients with pathological aging.

Navigation impairments in neurological disorders. Navigation impairments have been observed in multiple neurological diseases, probably due to their impact on the MTL areas, such as hippocampus or EC. Such impairment has been indicated in Parkinson's disease (Schneider et al., 2017), epilepsy (Amlerova et al., 2013) or multiple sclerosis (Němá et al., 2020). But the most documented is the impairment of spatial skills in Alzheimer's disease.

Alzheimer's disease (AD) is a prevalent neurodegenerative disease with progressive neuronal loss particularly affecting elderly population. The progression of AD is marked by mild cognitive impairment (MCI) in the beginning, which slowly develops into dementia. The early stages of AD are marked by neurofibrillary tangles in the EC and parts of hippocampus, advanced stages then spread to the hippocampus and other MTL areas and the final stage also affects the cortical areas (Braak and Braak, 1991; Braak et al., 2011).

Given what we know about the EC and hippocampus, we should expect particular deficits to manifest with the increasing AD progression. The EC (see section 1.2.2) is primarily thought to be the path integration center. It is therefore not surprising that path integration is affected in early AD (Mokrisova et al., 2016). This can allow doctors to uncover the disease's onset much earlier than the memory manifestation occurs (Bierbrauer et al., 2020). AD patients have been also found to fail in allocentric navigation (Hort et al., 2007; Gazova et al., 2012; Kalová et al., 2005).

The observations that AD affects memory of connected pieces of information or related events (e.g. location and its name) more than singular information (e.g. list of locations) led researchers to investigate the particularities of associative memory (also called memory binding) deficits (Parra et al., 2009). Patients suffering from AD can still hold unbound information but have trouble with creating new associations. Patients carrying the allele for APOE-4, which is known to be the genetic risk factor for AD, have been shown to have reduced CA and dentate gyrus activity and compensatory increase of cortical regions in associative tasks (Suthana et al., 2010). These deficits in sequential binding can be also observed in spatial tasks as AD patients fail to remember the order of presented locations (Kalová et al., 2005) or learning routes in virtual tasks (Pengas et al., 2010), although some researchers have found no route learning deficits (Allison et al., 2016). Some have suggested a deficit in scene recognition (Sheardova et al., 2014), but the impact seems modest in comparison to other navigational or memory impairments.

AD has no cure at the time of this writing, but early diagnosis and subsequent therapy can contribute to slowing of the disease progression. Correct assessment of a patient's state has an important value for science, as it allows better understanding the disease's progression as well as targeting the correct population for experimental therapy. For more general review of spatial impairments in AD see Hort et al. (2007) or Vlček and Laczó (2014).

Navigation impairments in mental disorders. Virtual environments in psychiatry have a long history (Rothbaum et al., 1995, 1999; Rizzo et al., 2004; Wiederhold et al., 2002). They have been successfully implemented and used in anxiety disorders, namely phobia treatment (Maples-Keller et al., 2017), post traumatic stress disorder (Rizzo and Shilling, 2017) or study and treatment of addictions (Bouchard et al., 2017; Saladin et al., 2006). These examples used VEs to simulate and track participants' symptomatology or provide safe environments to train desired behaviour, but have not addressed the spatial impairments.

Spatial impairment as a potential symptom of mental disorder has been observed in schizophrenia (Hanlon et al., 2006; Fajnerová et al., 2014) or depression (Cornwell et al., 2010).

Schizophrenia (SZ) is a debilitating chronic illness with positive and negative symptomatology. SZ patients suffer from abulia, apathy and cognitive deficits, such as memory and processing speed. Studies in animal models of schizophrenia have demonstrated a decrease in the MWMT performance (Stuchlik et al., 2004) and performance deficits were also observed in SZ patients using the virtual analogs of the same task (Fajnerová et al., 2014; Hanlon et al., 2006).

The neurological reasons for the performance decrease could be linked to functional and structural changes affecting MTL structures in SZ patients (Antonova et al., 2004), but other explanations, such as changes in functional connectivity, also serve as possible explanations. Frontotemporal connectivity, related to memory, was observed to be disrupted in SZ (Ragland et al., 2004), and can lead to failure to recruit hippocampus during spatial tasks. Hippocampal inactivity during MWMT was indeed observed in SZ patients and related to their spatial impairment (Folley et al., 2010).

Navigational tests could be good markers of a patient's condition, provide a comparable testing platform between animal models and human behaviour and can provide an insight into the disease progression. Their other benefit is the potential streamlining of the diagnostic process with the use of automated administration in VEs. If such tests can supplement other testing procedures, they might earn their place in neuropsychiatric test batteries.

1.4 Virtual environments

Virtual environments (VEs) are a tool used in psychology and neurosciences since the 1990s. VEs are 3D simulations of space, usually with some level of interactivity, which let users freely explore while being still. VEs have been used even in studies with animals, including rats (Aghajan et al., 2015), but also fish (Jouary et al., 2016) or bees (Rusch et al., 2017). Most of the key findings of these studies have been elaborated on in the previous chapters.

VE describes the software part independent of the presentation hardware. VEs can therefore be presented on a flat screen monitor with a desktop PC (sometimes referred to as desktop VR or non immersive VR, in this thesis referred to as desktop VE), but these environments can also be explored in virtual reality (VR) using Head Mounted Displays (HMD). In recent years, a new VE presentation came to existence labelled augmented reality (AR), which presents the environment as an overlay over the real world using see through displays or cameras.

Throughout this thesis, I am using the term virtual environment regardless of the administration method, although most research in VEs has been done on desktop PCs. The following chapters and their content are concerned primarily with human centered research.

Desktop virtual environments. In this thesis, I am using the term desktop VE to describe a VE administered on a monitor, usually with a keyboard and a mouse as controls. They are the most common and the majority of research in human navigation has been done in desktop VEs. They have the major advantage of being widely accessible and therefore promoting reproducibility and ease of deployment. As they are also more available to consumers as well, so participants might be more used to using the desktop VEs, rather than the newer VR systems.

There are three major disadvantages of the desktop VEs. Firstly, the VE is presented on a flat monitor and participants are relying solely on monocular cues for depth and distance, which might impair spatial learning. Secondly, the controls are usually not representative of captured behaviour, e.g. walking by pressing a key instead of physical movement. Participants in VE studies use a combination of keyboards, mice, buttons or dedicated controllers to move around in the environments. Thirdly, there is rarely any stimulation of the proprioceptive, nor vestibular systems, which might impair spatial learning as well (see section 1.5.1).

Virtual reality. Virtual reality (VR) was conceptualized and used since the 1960s, but it saw a boom in recent years. VR uses binocular cues to present the VE, and usually is accompanied by body- and head-tracking capabilities, which gives users much more natural control over the in-game avatar.

VR can use much more natural controls, allowing participants to simply walk around in the real world and while moving within the VE as well. This should, based on the importance of idiothetic cues, be beneficial to any spatial learning. Recent VR headsets even come with built-in hand tracking allowing users to grab things with their hands, which can reduce cognitive load and increase ecological validity. This is different from desktop VEs, where participants usually press keys to do a certain action. Secondly, VR uses binocular cues for depth, which provide higher sense of immersion and arguably better depth perception, which might be important for any navigation research.

However, VR also has a few specific drawbacks. One of them is arguably more challenging development, as the VE needs to be tailored to the specific HMD and its particularities - type of tracking, type of controllers etc. This might be fine for one time projects, but can increase costs and reduce transferability from one project to another. It also limits reproducibility and sharing between different groups, as each group would need to have the same VR setup. Desktop administered VEs can usually be simple to share and administer on any PC or laptop.

The second drawback is the higher financial investment. The price of entry includes not only the cost of the HMD, but also the cost of a hardware system which can run the VE simulation in VR. Unlike desktop VE, which is presented on a single display, VR needs to present two images, one for each eye, at higher refresh rate to address cybersickness (see chapter 1.4.3). This can drive to cost to be several times higher than for desktop VEs.

Finally, although participants are free to walk in VR, they are limited by the physical space as well as VR tracking hardware, usually to about around 10x10 meters in most consumer VR solutions. Administering experiments exploring larger spaces requires some modification of the movement paradigm, such as using in-game teleportation (Vass et al., 2016), controllers (Huffman and Ekstrom, 2019), large scale moving platforms or stationary omnidirectional treadmills (see Figure 1.1) (Liang et al., 2018; Harootonian et al., 2020), which in turn can invalidate the ecological validity and transferability of the results to the real world.

1.4.1 Presence and immersion

Presence describes the sense of being in the environment (Witmer and Singer, 1998). It is assumed that high presence leads to higher ecological validity, as the participants behave in the similar way they would have behaved if the same things happened in the real world (Rizzo and Shilling, 2017).

Immersion, on the other hand, is the capability of given hardware to achieve presence. In other terms, high immersion devices allow users to hypothetically achieve higher presence. Virtual reality is considered to be highly immersive, while watching a navigation happen in front of a screen less so. Some researchers refer to desktop VEs as non immersive VR, but this is not fully correct, as both desktop simulations and VR are immersive, only to a different degree.

It has been demonstrated that better VR HMDs can lead to higher presence in comparison to 3D TVs or low cost solutions (Chessa et al., 2019). This is observed in increased reported presence, but also with better congruence between expected and manifested physiological responses to presented stimuli, such as feelings of vertigo while being on a top of a skyscraper, increased heart rate on a virtual roller coaster etc. Arguably higher presence should lead to higher ecological validity.

Presence can be measured using questionnaires, for example Presence Questionnaire (Witmer and Singer, 1998) or SUS questionnaire (Slater et al., 1994; Usoh et al., 2000).

Figure 1.1: Cyberith Virtualizer. The omnidirectional treadmill used in study 1 and study 4 allows participants to freely move in the environment while strapped in. The ring and harness support the participant so they do not fall in case of slipping.

1.4.2 Five benefits of virtual environments

VEs provide five major benefits to neuroscientific studies of navigation (summarized in Table 1.1).

Economic benefit. The economic benefit addresses both money and time constraints of real world research. Many navigation studies in VEs could be technically done in the real world. This includes studies involving radial mazes to compare human navigation to animal navigation (Wilson and Wilson, 2018), which could be done if the maze was constructed. Studies involving human analogues of MWMT could be administered in real world analogues, and some have been (Fajnerová et al., 2014; Mokrisova et al., 2016), but these devices are costly and usually non warranted for a single time use. A more extreme example of potential research topics could be navigation in absence of gravity using for example using astronauts as subjects. Conducting similar research in VE is relatively easy with the added possibility of obtaining neural recordings at the same time (Kim and Maguire, 2019).

Other examples, such as studying participants during car navigation or exploring how they experience a novel town for the first time, could be technically done in the real world. But VE allows simulating an infinite number of environ-

Name	Problem	VE solution
Economic benefit	Studies face problems of being too expensive or time consuming	VEs allow to run the experiments more cost- or time-efficiently
Full control	Studies face the issue of external factors confounding the results	VEs allow to run experiments which would be challenging to run in a controlled manner in the real world
Navigating without movement	Studies are limited by the constraints of the machinery which requires participants to be completely still	VEs allow to run navigation experiments while using imaging techniques, such as EEG, MRI, MEG etc.
Making the impossible possible	Studies are limited by the constraints of the physical world and subjects' physiological limits	VEs allow to model situations which would not be possible in the real world
Precise recordings	Studies in the real world might struggle with obtaining the precise experimental record	VEs allow almost perfect tracking of all behaviours within the environment

Table 1.1: The five major benefits of navigation experiments in the VEs

ments of desired geometries and test all participants within a single room. Any study in the real world also needs to be carefully administered and tracked by an experimenter. This leads to increased demands on researchers' time. Research done in VE can be done in either fully automated way or can be at least partially automated.

Lastly, there is also the convenience of remote administration, which can, to a certain degree, address the participant scarcity. This dramatically increases the potential of collecting thousands of participants by simply delivering the experiment to them (Coughlan et al., 2019; Coutrot et al., 2019). Although such self-selected voluntary samples need to be analysed cautiously, their potential use allows for ease of standardization and exploring potential cultural aspects of navigation behaviour and performance (Coutrot et al., 2020).

VEs have been implemented in psychiatry since the 1990s for similar reasons (Rothbaum et al., 1995), demonstrating that their use in treatment of acrophobia, claustrophobia, agoraphobia offered dramatic reduction of costs - flying on a virtual plane vs renting a real plane. The other promising benefit of VEs in psychiatry is the mentioned automation of use, when the therapist can administer the scenario to multiple patients at once. For a review of VR/VE use in psychiatry see van Bennekom et al. (2017) or Hejtmánek and Fajnerová (2019).

Full control over experimental conditions. Most research in psychology and neurosciences is done in laboratories, to precisely control the entire experimental procedure. This is unfortunately not possible with navigation research done in the real world. The real world experiments can suffer from unexpected circumstances hindering the procedure or affecting the results in unexpected ways.

Researchers usually solve this by having participants navigate indoor environments (Richardson et al., 1999; Ruddle and Lessels, 2006; Stangl et al., 2020;

Aghajan et al., 2017). While navigation within buildings provides, to a certain extent, controllable environments, the space limitations do not allow for addressing potential performance decline with increased trajectories and the surrounding walls are ever present landmarks preventing investigation of path integration with vision or true cognitive map strategies. As participants have continuous access to the environmental boundaries, pointing tasks within the building can be solved using path integration and navigation accuracy by response-based strategies.

Similar problem afflicts animal research. There is an interesting disparity between real world navigation, which can span areas of hundreds of meters to thousands of kilometers, and our knowledge of navigation originating in limited boxes of laboratories (Geva-Sagiv et al., 2015).

Another difficulty with real world navigation studies is the inability to monitor participants' attention and limit the surrounding features. Despite assuming that the participant might orient in the world in respect to the landmarks and or street layouts, it might be well possible that the participant will encode the environment by seemingly irrelevant features, such as recycling bins or "the corner where I saw a lady walking a dog", or they merely use path integration.

Study by Gramann et al. (2017) demonstrated that personally relevant directions have a different impact on the final spatial representation. Allowing the participant to form their own representation while not being able to control and limit the amount and quality of the environmental features poses a fairly significant problem and can lead to much higher variability of participant performance then in more controlled environments.

Navigating without movement. The benefit of testing spatial behaviours while the participant is completely still is one of the most obvious benefits of using VEs. Many imaging techniques in both humans and animals require perfect stationarity for noise free recording. These include the dominant imaging techniques used in human neurosciences, such as MRI, magnetoencephalography (MEG), EEG and iEEG, but also techniques such as eye tracking (see Figure 1.2). Although this is usually not a problem for most cognitive research, it is an insurmountable obstacle for navigation research.

VEs can overcome this problem by allowing participants to actively navigate during the imaging technique. This allowed researchers to observe hippocampal activations in fMRI during VE guided navigation in Spiers and Maguire (2006), pinpoint and find activity in CA1 related to spatial knowledge acquisition (Suthana et al., 2009), compare behaviours and their EEG data in gamers vs non gamers during spatial tasks (West et al., 2015) or compare navigation strategies between genders using eye tracking (Andersen et al., 2012).

VEs have become useful in animal studies as well. Although single cell recordings in animals can be obtained relatively noise free even during animal's movement, other methods require the animal's head to be fixed. For example, researchers were able to monitor cellular activity using fluorescence imaging in awake mice while they navigated a VE on a styrofoam ball treadmill (Dombeck et al., 2007).

Recently, some novel solutions to the problem have become available. Klaus Gramman's group at University of Berlin is experimenting with mobile EEG (Wunderlich and Gramann, 2020) and research involving subjects on virtual

Figure 1.2: Example of a desktop VE setup with eye tracker SR 1000

treadmills with scalp EEG has been successful in uncovering some of the properties of oscillation during navigation tasks (Liang et al., 2018), although properly denoising the EEG signal without signal loss is still quite challenging. Research including free moving subjects with intracranial recordings has also been conducted (Bohbot et al., 2017; Aghajan et al., 2017), but due to the ethical constraints remain relatively scarce. However, novel methods and opportunities are still being developed and the field looks promising (Topalovic et al., 2020).

Making the impossible possible. One of the most exciting aspects of VEs is that they allow researchers to change anything in the environment, even break the laws of physics to uncover hidden patterns of behavioral and neural activity. This can include things like moving distant mountains to change the landscape and see how it affects encoding of local space. It can involve teleporting people with or without them knowing it or changing where each door leads from one session to another. One can also argue that the mere idea of moving through the world while being completely stationary can be considered unreal.

Gillner and Mallot (1998) implemented a paradigm in which building landmarks were dynamically modified, made visible in some instances and invisible in others, or the number of landmarks on the same path varied from trial to trial. Such manipulations of allothetic cues would be certainly impossible without the VEs. Similar manipulations of external landmarks have also been used in a recent study monitoring navigational strategies in the elderly (Grzeschik et al., 2020).

The general idea about our spatial representation is that it is being computed in euclidean space. But this can also be an assumption which is solely based on the fact that we only test animals and humans in euclidean spaces, as it is physically impossible to do otherwise. VE on the other hand allows us to model any type of space, which breaks the laws of physics and can offer us unique insight into navigational behavior and its neural coding.

A very interesting study conducted by Warren et al. (2017) created an environment with non-euclidean properties and teleportation wormholes. Using such VE they were able to decouple the allothetic and idiothetic information and address the cognitive graphs vs cognitive maps debate discussed in section 1.1.1.

Although unnatural movement, such as movement with a joystick or a keyboard, can be considered problematic due to its difference from the real movement, it can also uncover some of the intricacies of how the spatial cognition works. Experiment by Lindsay Vass explored the separation of visual and imagined navigation in humans using a virtual environment with programmed teleporting (Vass et al., 2016). This research was able to look at navigation using intracranial recordings and found increased theta band oscillations, commonly visible during active navigation, even during the teleportation. This suggests that neural activity comparable to that of active navigation can be created solely based on imagined self updating.

Precise recordings. The last benefit of VEs, which needs to be mentioned, is the ability to precisely record subjects' behaviors with relative ease and continuously throughout the experiment, not only relying on summative final scores. This promises much more precise analysis of navigational behaviour. Good recordings also promote reproducible sciences, and allow potential retroactive analysis of behaviours in case the paradigms change.

The only limitation of the recording is the limitation the experimenters program into the VE in terms of the simulated behaviors. In other words, researchers can record only what they allow participants to do - if participants are limited to fixed traversing speed or have limited freedom in rotation and or movement, then they are losing that information. While there is no limitation to human movement or behaviors in the real world, the VE always asks researchers to make choices prior to the experiment to model only some behaviours without the option to reconstruct it later.

Solutions to this problem can be the more and more available motion tracking devices used with VR hardware, which allow to collect data not only on participants' position within the environment, but tracking all individual limbs as well. Such recordings allow researchers to reconstruct the entire experimental procedure ex-post without the fear of missing some essential behavioral markers. This approach is very promising, and recently published studies from UCLA (Aghajan et al., 2017; Topalovic et al., 2020) used it to investigate indoor navigation with the additions of intracranial recordings and eye tracking as well.

1.4.3 Limitations of VEs

The benefits of virtual environments for navigation research are aplenty. But before going further, I need to also discuss a few key drawbacks that these technologies have. I will not discuss the difficulties and challenges that are tied to the development of the VEs themselves, as these are arguably as challenging as developing a standardised paper tests or specialized hardware and merely require a different set of skills.

Experience with video games

Prior video game experience is often a confounding variable in any research involving VEs. Having played video games not only makes participants either more accustomed to the controls, it can also affect the way they encode information, their level of cybersickness (see sections 1.4.3) or overall performance. Properly assessing and removing this effect is therefore important for any analysis.

Cognitive load and trouble with controls. One of the major drawbacks of VEs is the potential trouble subjects might have with its controls. While using a mouse and a keyboard on a computer can be considered a skill that the majority of participants will manage, navigating 3D VEs can pose a challenge for participants not used to first-person video games (Walkowiak et al., 2015).

Having trouble with the controls then increases cognitive load on some participants and can create unwanted stress. Increase in working memory cognitive loads has been linked to change of navigational strategy to a more heuristic based one (Brunyé et al., 2018). This can be problematic as this change in participant's behaviour might not be immediately obvious, but it creates a bias in the final dataset. Similar switch in strategy from configural to route based has been linked to a time pressure (Brunyé et al., 2017) and increased cognitive load has been shown to increase existing biases in spatial decision making (Bartlett et al., 2020). Participants having trouble with the controls might therefore use different strategies or perform qualitatively differently than others. On the contrary, habitual gamers were shown to use more response-based strategies than non gamers (West et al., 2015).

Another problematic impact of the increased cognitive load is that it might affect different experimental metrics unequally. Let us consider an experiment in which participants learn a virtual town and are asked to point from few landmarks to other landmarks (typical pointing task - see Weisberg and Newcombe (2018) or Starrett and Ekstrom (2018)). If a participant has formed a flawless spatial representation of the environment, but is still unfamiliar with the controls, their accuracy in the task can be perfect, but their reaction times will be slower. It is therefore paramount to provide sufficient training opportunities to each participant and potentially try to pinpoint participants having trouble and analyse their data separately.

Another solution can be to use different control mechanisms which participants might be more comfortable with. This could include joysticks or controllers, or using immersive HMD VR with more naturalistic controls. Needless to say, it is also necessary to keep the experimental paradigm similar between the subjects, so testing half the participants with a keyboard and half with a controller might introduce unwanted variability into the data.

Game differences. Studies often assess participant video game experience based on their current behaviour, e.g. "How many times in a month do you play video games?" But this approach might not be ideal. It is comparable to considering people who have never driven a car to drive the same way as those who only drive a little. Secondly, there are large differences between different types of video games (Sobczyk et al., 2015). Questions such as "Do you play videogames?" are not necessarily useful in assessing gaming experience for navigation research as playing logic or puzzle games on a mobile phone might affect performance differently then playing first-person shooters or role-playing games (Unsworth et al., 2015).

Recommendations. Video game experience is a confounding variable which should be addressed in any navigation research using VEs. Researchers should make sure that particiaptns do not differ greatly in their ability to control the simulation and should provide sufficient training to those who struggle.

More complex questionnaires, such as Covert Video Game Experience Questionnaire (Sobczyk et al., 2015), which address not only frequency of video game engagement but also separate between different video game types and inquire about life long experiences are recommended.

Cybersickness

One of the major disadvantages of VEs, and especially immersive VR, is the cybersickness. Cybersickness manifests itself by nausea, dizziness, disorientation and if not addressed, it can cause tiredness and headaches (Rebenitsch and Owen, 2016; Bohil et al., 2011).

Although the precise cause of cybersickness is unknown, it is thought to be caused by sensory mismatch (motion sickness) or postural instability (sea sickness) (Rebenitsch and Owen, 2016). Motion sickness is caused by the scenery changing while the vestibular system signals stillness. Cybersickness can be caused by the same mismatch on desktop PCs, or the opposite mismatch in VR (participant moves, but the scenery in HMD does not). The postural instability theory states that the sickness arises from the posture oscillations which try to make the visual world aligned with gravity, e.g. swaying on a boat. This constant tilting there and back makes people feel nauseated (Villard et al., 2008). The postural instability theory can also explain potential sex differences in perceived motion sickness (Koslucher et al., 2016).

Cybersickness tends to happen more in simulations involving translation and rotation, and it has been found to increase with increased speed and over time (So et al., 2001; Dużmańska et al., 2018). Sessions for newcomers not yet habituated to the VR are therefore recommended to be kept below 20-30 minutes, although more extreme VR simulations, such as rollercoasters, might elicit cybersickness sooner (Nesbitt et al., 2017).

Luckily, similarly to motion sickness, which tends to disappear with repeated experiences, cybersickness seems to degrade with habituation as well (Howarth and Hodder, 2008). This can be slightly problematic for the selection bias (see section 1.4.3), but it gives hope of reducing the cybersickness related VR dropout in the future studies due to people getting more and more accustomed to the VR content.

Cybersickness caused by the head movement and visual mismatch can be alleviated by investing in better hardware and software optimization to decrease the lag between the user actions and visual updates (Rebenitsch and Owen, 2016). The goal is to arrive at a minimum of 90 frames per second (FPS) in the VR and 60 FPS on a monitor, which should provide smooth experience. The rendering PC needs to be fast enough to process participants' input (keyboard and mouse input for VE and head movement, controller movement and inputs in VR) and display the resulting visual changes within the target 10-20 ms timeframe. Investing in HMDs and PCs which can render the VE at a high resolution and at these target refresh rates is paramount to participants' comfort.

For these reasons, cybersickness was a major issue with older VR setups, which suffered from low resolution, lags and usually were not capable of head and body tracking. One of the troubling state of affairs about cybersickness research is that a lot of prominent studies are based on VR hardware released between 1995 and 2015. The VR scene has changed dramatically in the last five years, so it is necessary to wait if the new hardware and software changes and high public adaption change things for the better.

For a review of device specific cybersickness see Geršak et al. (2020).

Assessing cybersickness. Cybersickness can be assessed by the Simulator Sickness Questionnaire (Kennedy et al., 1993) or VR specific Virtual reality Sickness Questionnaire (Kim et al., 2018). Heart rate and palpitations monitors are also useful tools used previously in studies assessing the presence and comfortability of various setups (Chessa et al., 2019; Geršak et al., 2020). These seem to be good indicators of increased stress levels, but their implementation in regular administrations can be challenging and only a few studies report their use (Saredakis et al., 2020).

The postural instability theory states that the sickness is caused by constant swaying, and automated algorithms which estimate participant's nausea from HMD movement are currently being developed by the lead HMD manufacturers and VR developers.

Ethical considerations. Cybersickness is not only a safety issue, but an ethical one as well. It can cause temporary health issues and unless spotted early, causes unnecessary, graduating discomfort. As such, it should be addressed in the ethical review of any proposed experiment. The risks for participants should be lowered to the minimal degree and participants should be reminded that they can stop the experiment at any point. While automated ways to assess the discomfort with the potential markers from HMD itself are still being developed, until such time arrives, it is necessary to keep constantly checking with the participant.

Selection bias. The major issue with cybersickness is not necessarily the increased dropout of participants, but the potential bias in such dropout. For example, a study using VR HMDs as well as Desktop VEs by Plechatá et al. (2019) found that while 17 percent of elderly participants felt nauseated, no young participants in the study were affected by VR. This can create uneven group representations and also lead to uneven skills between the experimental groups as well.

As cybersickness decreases with habituation, it makes the dropout not random and the final sample potentially biased. Different groups can be suffering from cybersickness to a different extent, with some studies suggesting female participants are more likely to suffer from cybersickness (Lawson et al., 2004; Levine and Stern, 2002; Flanagan et al., 2005), while others suggest that more cautious interpretation and analysis of potential confounds, such as gaming experience or age, is needed. Another problem can appear if participants do not drop out but their performance suffers. This can be adding unwanted noise into the data.

For all these reasons, careful study of the dropout rates and search for a potential bias in obtained results is recommended and experiments should be planned and conducted in a way which does not discriminate or prefer certain groups (Vasser and Aru, 2020).

General recommendations. There are few simple recommendations for any research dealing with VEs and especially VR. Firstly, the participants should not be tired and should arrive well rested, as tiredness increases the cybersickness risks. Participants should not be hungry, but should refrain from eating 30-45 minutes before the experiment. The experimenter should constantly check with the participant about their feelings and offer breaks from the experiment in case the participant is not feeling well. In case of repeated feelings of unease or increasing dizziness, the experiment should be terminated prematurely. The exposures should be kept short, with cybersickness symptoms starting to appear after 20-30 minutes.

1.5 Is navigation in virtual environments real navigation?

In the first section, I introduced the strategies and neural correlates of navigation in animals and humans. In the second section, I outlined the definitions and benefits and drawbacks of VEs in neurocognitive research. In this last section, I would like to merge the two and address some of the questions and problems of using VEs to study navigation.

While using monitors, speakers and other devices to administer experiments dealing with episodic memory, attention, language processing and other cognitive processes poses some problems for the ecological validity and transferability of results, these seem fairly minor. Although there might be some emotional or social disparity between hearing somebody's voice through a speaker and hearing them live, or observing an image of a building rather than seeing the real building, there are not many sensory cues which are missing from these experiences.

Navigation in VEs on the other hand is more problematic. I have noted the multisensory nature of navigation in both animal research and human research. Navigation can rely on vision, olfactory cues, auditory cues, haptic cues and more. This means that while researchers focusing for example on face recognition can be certain that people use vision, in real world navigation research we are never sure. VEs allow perfect control of the simulation, which unfortunately also means that researchers need to painstakingly select all cues to be presented. Omitting certain cues, for example not including sources of auditory information in the environment or simulating lighting conditions in an unreal fashion, can have an unexpected impact on participant's behaviour.

Moreover, there is the importance of idiothetic cues. Research has proven that self motion cues are one of the main driving forces of navigation (Chen et al., 2018) while most navigation research in humans uses VE implementations without idiothetic cues.

1.5.1 Behavioral view

Some restraints from using VEs in navigation research, can be caused by their limited visual fidelity. If the vision is the primary source of information of spatial knowledge, the lack of visual features in the scenery can change how people navigate.

Needless to say, a lot of navigational research done in the early 2000s necessarily suffered from the limited graphical capabilities. An influential manuscript demonstrating comparable learning performances between VEs, maps and real acquisition in 1999 (Richardson et al., 1999) used graphics requiring less computational power than is now available on mobile phones. Case studies observing navigational behaviours in VE also found clear effects of spatial impairment even in graphically simple environments (Spiers et al., 2001) and fMRI research papers also used now quite dated graphical engines and were able to observe meaningful responses (Spiers and Maguire, 2006).

The virtual environments used in animal research are also very crude, usually projecting low contrast images of low resolution landmarks (Aghajan et al., 2015). Regardless, animals do exhibit spatial sensitive cells in these low fidelity environments even in absence of idiothetic cues, although their spatial accuracy is lower (Chen et al., 2018).

Ruddle and Lessels investigated the topic of visual richness using the real world, low-fidelity and high-fidelity VE (Lessels and Ruddle, 2005). Their results suggest that although photorealistic environments offered some benefit over the impoverished visualisations, the largest performance increase has been found in participants who were able to actively roam the environment, rather than move with a joystick. Needless to say, they observed benefits of high-fidelity scenery on trial times and performance in their subsequent study (Ruddle and Lessels, 2006), but noted that these benefits were observed only in introductory trials and were lost as the experiment progressed.

But even with high fidelity visual rendering, there still seem to be some elements missing, as learning in any form of VE usually leads to slightly worse spatial knowledge acquisitions than real world learning.

The most troubling aspect of VE implementations in navigation studies are the missing idiothetic cues. The trouble with the potential vestibular mismatch is not only the increased risk of cybersickness outlined in the previous section (see 1.4.3), but also removing the potential of path integration from the spatial knowledge acquisition. It has been demonstrated that in case of discrepancies between idiothetic and allothetic information, e.g. slowing or speeding up the visual gain of a rat's physical movement, the place cell code is influenced predominantly by idiothetic cues (Chen et al., 2013). Studies in humans involving path integration or spatial estimates suggest that idiothetic cues are essential for good spatial performance (Holmes et al., 2018; Burgess, 2006) and previously discussed studies pointed towards importance of idiothetic cues over visual accuracy of the environment (Ruddle and Lessels, 2006).

Roberta Katzky and others (Klatzky et al., 1998) demonstrated that idiothetic information was necessary to force subjects to adapt their heading through the triangle completion task. In other terms, subjects who merely watched or imagined the task correctly calculated the translation along the path, but did not update their final heading. Similar results were observed in studying spatial inferences made from multiple viewpoints, depending on how these were presented, with participants actively moving while experiencing the views showing to be the most precise in their spatial judgements (Holmes et al., 2018).

Other researchers also noted the importance and overall benefits for full bodily movements for successful navigation (Ruddle and Lessels, 2006; Chance et al., 1998), but others argue that physical rotations are significantly more important and translations can be safely done using joystick without significant impairment (Riecke et al., 2010). Waller et al. (1998) also observed that VR with free head turning led to better learning then desktop VE.

But vision is still a strong driving force of place cell activity, both in rats and primates. Some studies observing hippocampal structures did not even observe any true place cells, but rather only view-dependent cells (Rolls, 1999) and Gillner and Mallot (1998) demonstrated that learning of spatial information is possible even from only experiencing sequences of views and movement decisions.

Despite the participants' spatial performance differs between the real and virtual worlds, they still perform quite well in VEs (Waller and Greenauer, 2007) and can even efficiently transfer spatial information from the VE to the real world (Witmer et al., 1996; Waller et al., 1998).

The difference between the animal studies and human studies might be attributed to the fact that humans rely on vision arguably more, as we travel much larger distances and we often use modes of transport which do not correlate to proper idiothetic cues - cars, boats, horses etc. Because the path integration error accumulates over time, the reliance on this mode of navigation over large environments might be suboptimal.

As I outlined in section 1.2 navigation is a very sensory multifaceted and cognitively complex process, which seems to be using a variety of sensory inputs to achieve its goals. Although the exact comparability of neural responses in virtual and real navigation has not been assessed yet.

1.5.2 Neural correlates of VE navigation

It has been observed in animal research that although the place cells spike in both real world and two dimensional VE, the visual cues only are not enough to create a reliant code for spatial selectivity (Aghajan et al., 2015) and fewer robust place cells are observed in VE in comparison to the real world. The power or theta oscillations is also observed to be diminished in VEs (Ravassard et al., 2013), but phase precession seems to be consistent across VE and the real world (Aghajan et al., 2015; Ravassard et al., 2013).

But the situation is slightly different in human studies. Researchers observed fMRI activity to increase in navigation implied areas during VE navigation (Spiers and Maguire, 2006; Doeller et al., 2010) and hippocampal changes and damage affect navigation in the VEs as well ((Woollett and Maguire, 2011; Spiers et al., 2001). The theta band oscillations observed to increase in animals during movement, increase in human navigation solely based on visual input generated by VEs

(Watrous et al., 2011; Ekstrom et al., 2005) and this happens even in case of imagined translation without any visual input (Vass et al., 2016; Horner et al., 2016). Researchers also investigated if the functional connectivity observed in fMRI differs during recollection of environments which have been learned through variable means - VR and omnidirectional treadmill, VR and controller and desktop VE with a controller. They could not observe any differences in functional connectivity response between conditions, with hippocampus, RSC and parahippocampal cortex being all activated in a condition independent way (Huffman and Ekstrom, 2019).

But there are also some differences between the results obtained from animals and those from human iEEG studies, which question the comparability of real world and virtual navigation.

One of the challenges in studying spatial navigation in humans is the inability to obtain direct intracranial recordings of cellular activity, like the scientists have done in animals since the 1970s. Many studies addressed this problem using patients with epilepsy, who are undergoing a presurgical intracranial monitoring (Ekstrom et al., 2005; Jacobs et al., 2007; Aghajan et al., 2017). But as the movement of patients is restricted, direct recordings of moving people are challenging to obtain and the majority of these studies have been done in VEs.

One of the most perplexing differences between human iEEG results and results from animal studies has been the difference in observed power of theta oscillations during navigation (see section 1.2.2). In animals, the hippocampal theta increases power in the 4-10Hz band (O'Keefe and Recce, 1993), whereas in humans this increase in power has been observed predominantly in the 1-7Hz band (Jacobs, 2014).

Are these observations just interspecies differences, or some particularities of epilepsy? Or are they caused by the navigational modality itself. Recent studies were able to compare the theta power differences in moving and virtually moving patients and demonstrated that the real world movement has potentially the similar properties as in animals (Bohbot et al., 2017; Aghajan et al., 2017), although more research into this topic is needed.

2. Aims and hypotheses

This thesis aims to investigate the benefits and drawbacks of using virtual environments (VEs) to study processes of human navigation and to offer demonstrations of such use. It also aims to assess whether navigation in VEs is representative of real world navigation and if idiothetic cues are necessary or vision is sufficient for successful spatial learning.

There were three main hypotheses:

1. Navigation in VEs leads to comparable behavior and performances as navigation in the real world
    a. People can acquire accurate spatial knowledge in VEs and apply this knowledge in the real world
    b. Navigation in the VE is comparable to navigation in the real world
2. VEs can overcome problems of real world navigation studies (such as economical feasibility) and provide more controlled experimental conditions
3. Studying navigation impairment in VEs can provide useful markers of mental disorders.

Study 1. This study demonstrates the comparability of VE vs real world navigation and offers some insights into potential complications of VE use and limitations of VE to real world spatial knowledge transfer.

Study 2. This study does not use VE directly, but uses iEEG recordings in human subjects to demonstrate that only vision is necessary to drive neural responses to spatial scenes.

Study 3 and study 4. These studies demonstrate the usefulness of VE in addressing some of the problems outlined in the section 1.4.2, which navigation research in the real world faces. Namely, they show how VE can solve the problems of economical feasibility, experimental control and machinery requiring stillness.

Study 5. This study uses VE to investigate the memory and navigation impairment accompanying mental disorders and documents this impairment in a group of schizophrenia patients.

3. Studies

Reported impact factors are 3 year average IF at the time of the manuscript submission taken from Web of Science InCites Journal Citation Reports.

3.1 Study 1

Hejtmanek, L., Starrett, M., Ferrer, E., & Ekstrom, A. D. (2020). How Much of What We Learn in Virtual Reality Transfers to Real-World Navigation? *Multisensory Research*, 1–25. Impact factor: 1.829

Aim

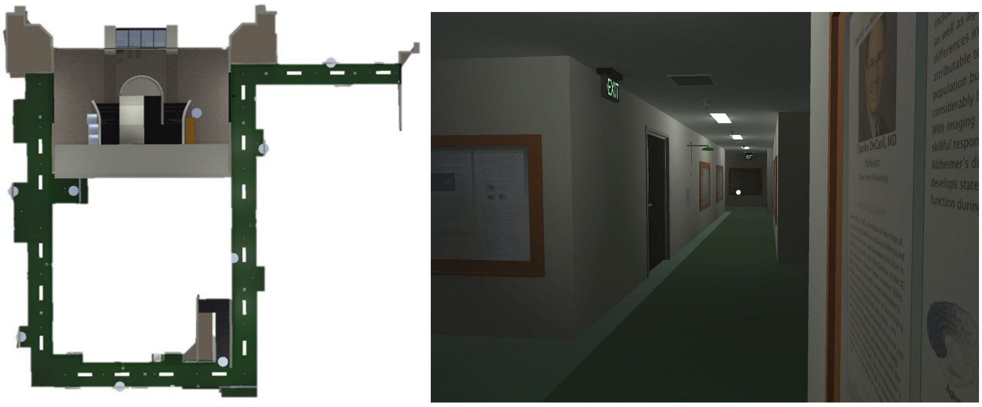
The aim of the study was to investigate the processes of spatial knowledge acquisitions in various modalities. Specifically, how well can people acquire spatial knowledge in VEs of variable immersion and to what extent is this knowledge transferable to the real world. Previous research suggested that idiothetic cues are necessary for creating proper metric representation of the environment. We wanted to test this idea by having participants learn the same building layout in conditions with varying levels of idiothetic cues.

Methods

The experiment took place in the real and virtual version of UC Davis Center for Neuroscience. Participants were asked to learn the positions of 6 offices out of 32 by free exploration in one of the three learning modalities - desktop VE, immersive VR with an omnidirectional treadmill (see Figure 1.1), real world, and then transferred to one transfer modality - immersive VR with an omnidirectional treadmill, real world. In each trial, participants were asked to find and approach a particular office in the building. They kept checking doors until arriving at the correct one, after which they were told their next goal. After 18 trials (each office visited 3 times), participants were asked to point to all 6 offices from two separate pointing locations (12 pointing trials), and then transferred to one of the transfer modalities. Participants completed a total of 36 visiting trials and 24 pointing trials. Participants' position and behaviour in the real world were tracked using a custom iOS application, providing us with trial times and trajectories. To assess the transfer from one modality to another, participants' normalized paths,visitation errors (checking incorrect door) and pointing accuracy were analysed. Total of 152 participants were tested, 47 did not finish the experiment due to cybersickness. Screenshot of the building and the building layout are in Figure 3.1. The building can be experienced online at http://hejtmy.com/CFNS-task/

Results

All modalities were comparable during the first 6 trials (each office visited once). By the end of the learning phase (18 trials), the effect of learning modality was apparent. Participants learning in the real world performed better than those in



(a) Top view (b) First-person view

Figure 3.1: Top view of the UC Davis Center for Neuroscience (a) and a first-person view from inside the VE (b)

desktop VE or immersive VR in normalized path, number of visitation errors or pointing accuracy. We observed no significant differences between desktop VE and immersive VR. Immediately after transferring to the real world, we observed a significant increase in performance in all learning 3 modalities with immersive VR slightly outperforming desktop VE in benefits gained, suggesting that immersive VR offers some benefit for the real world transfer. This benefit was slowly negated and all conditions eventually achieved almost indistinguishable performance by the last trial. Investigating participants' performances over the entire course of the experiment, we observed significant effects of learning modality on both visitation errors and normalized paths, with normalized paths not differing significantly between groups. Investigating groups which transferred to the immersive VR, we observed participants learning in the real world achieving better performances faster, but all participants equalizing by the end. All these results suggest that while some aspects of navigation are still not captured by the VE, VEs lead to successful spatial learning which can be applied in the real world.

Manuscript contributions

I programmed the experimental paradigm and VR and omnidirectional treadmill implementation. To track participants' behaviour in the real world, I created an iOS application able to triangulate position based on Bluetooth iBeacon signal strength. At the beginning of data collection, I personally administered the experiment to about half the participants and later oversaw the administration to the rest. With the exception of hierarchical models provided by prof. Emilio Ferrer, PhD, I was responsible for data analysis and interpretation. I co-wrote the manuscript with prof. Arne D. Ekstrom, PhD, with prof. Emilio Ferrer, PhD and Mike Starrett providing useful feedback and comments.

3.2 Study 2

Vlcek, K. , Fajnerova, I., Nekovarova, T., **Hejtmanek, L.,** Janca, R., Jezdik, P., Kalina, A., Tomasek, M., Krsek, P., Hammer, J., Marusic, P. (2020). Mapping the scene and object processing networks by intracranial EEG. *Frontiers in Human Neuroscience*, Accepted September 2020, in press, Impact factor: 2.673

Aim

Several scene processing areas have been identified using direct recordings in animals or indirect recordings in humans with fMRI. As fMRI research can suffer from temporal inaccuracy, which can miss subsecond processing of visual stimuli, clear definition and characterization of many of these areas in humans is still lacking. This study aimed to localize and characterize brain networks and areas underpinning scene and object processing using direct recordings of local field potentials from patients with epilepsy.

Methods

We collected iEEG data from 27 epileptic patients undergoing medical screening to localize the epileptic foci. Participants viewed a set of 650 images with spatial scenes, objects, faces and fruits/vegetables. Participants were asked to press a key when fruit/vegetable appeared to keep their attention. Responses to faces were not analysed in this study. We focused on changes in broadband gamma activity (50-150Hz, BGA), as these have been shown to correlate with both fMRI response as well as local neuronal firing. Bipolar referencing was used to remove the signal from distant areas. We transformed the iEEG data to the time-frequency domain using Hilbert envelope and normalized the resulting power. We then searched for channels responding to objects and scenes using non parametric tests comparing their BGA power post and pre-stimulus. These channels were then mapped onto their corresponding anatomical regions of interest. We also used K-means clustering on channel MNI coordinates to find anatomically close clusters of responsive channels and matched centroids of these clusters to both documented and newly identified functional areas responsible for scene and object processing.

Results

A total 2707 bipolar channels were analyzed. We observed 252 channels which increased their BGA in response to the scene presentation. Out of these, 177 channels were responsive to both objects or scenes and 75 to scenes only. We found the scene-selective channels in the parahippocampal, lingual (and fusiform) gyrus (30% of channels), retrosplenial cortex (24% of channels), occipital cortex (11% of channels), anterior temporal cortex (11% of channels), and hippocampus (11% of channels). Using the K-means clustering we have determined seven scene-selective clusters. Some of these clusters overlapped already defined scene-selective functional areas, such as the parahippocampal place area, medial place area or occipital place area, some were localized to areas not previously observed to be scene-selective, such as the hippocampus or posterior precuneus.

Manuscript contributions

I helped with administering the experiment to patients, co-created a device allowing synchronization of behavioral data and iEEG recordings and programmed parts of the Matlab package used in the data analysis. I participated in the article writing process.

3.3 Study 3

Hejtmánek, L., Oravcová, I., Motýl, J., Horáček, J., & Fajnerová, I. (2018). Spatial knowledge impairment after GPS guided navigation: Eye-tracking study in a virtual town. *International Journal of Human-Computer Studies*, *116*, 15–24. Impact Factor: 2.300

Aim

With the increased use of navigational aids, such as GPS, it is important to assess the effects they have on our ability to form and encode spatial representations. We aimed to investigate how the navigational aids impact spatial knowledge acquisition and how the level of attention affects spatial learning.

Methods

Participants completed a total of 42 there-and-back tasks accompanied by pointing in a large virtual town. The task consisted of participants following a predetermined route from a starting position to a goal position displayed on a GPS-like map on a monitor (learning phase) and then returning back to the starting point with the map available, but without the route displayed (recall phase). Participants also completed two pointing tasks in each trial (from goal to start and then from start to goal). Participants' eye movements were recorded using SR 1000 eye tracker throughout the experiment to track attention given to the GPS-like map and other parts of the screen. Participants also completed a battery of psychological tests assessing their general cognitive abilities, and a blank map tests to check how well they learned the environment. The city overview and participants' first-person view can be seen in Figure 3.2. The experimental setup of the desktop VE and the eye tracker can be seen in Figure 1.2.

(a) Top view

(b) First person view

Figure 3.2: View city layout from a top view (a) and participant's view (b) during the experiment

Results

As expected, participants on average observed the provided GPS-like aid significantly more during the learning phase, on average almost as much as the central portion of the screen. We found a significant effect of participant's attention on the GPS-like aid during learning on their navigation efficiency and pointing accuracy. The increased GPS-like aid use also negatively affected participants' blank map scores in both location placement and naming. One of the interesting findings was that the participants' attention on the map correlated with their subjectively assessed spatial skills, so people less confident in their skills relied on it more in both learning and recall phases. We found no gender effects in navigation performance, although men had a tendency to finish the tasks faster.

Manuscript contributions

I contributed to the virtual city design and modelling, programmed the core of the experimental framework and data logging as well as the eye tracking implementation. I administered the experiment to all participants. I preprocessed and analysed the behavioral and eye tracking data and co-wrote the manuscript with Mgr. et Mgr. Iveta Fajnerová, PhD.

3.4 Study 4

Harootonian, S. K., Wilson, R. C., **Hejtmánek, L.**, Ziskin, E. M., & Ekstrom, A. D. (2020). Path integration in large-scale space and with novel geometries: Comparing vector addition and encoding-error models. *PLoS Computational Biology*, *16*(5), e1007489. Impact Factor: 4.700

Aim

This research had participants do triangle completion tasks on an omnidirectional treadmill with participants relying on haptic and proprioceptive input. Aim of the study was to investigate path integration performance in varying triangle types and sizes and evaluate several models potentially explaining the path integration errors and to show how using VEs enables studies of navigation with or without sight in a safe environment and over long distances.

Methods

The study consisted of two experiments. In the Experiment 1, participants integrated path over triangles of similar sizes, but different types (isosceles, equilateral, etc.). The homing vector distance was kept constant across all triangle types. The Experiment 2 used only a single triangle shape, but varied its scale. Participants used an omnidirectional treadmill (see Figure 1.1) for movement and to investigate participants' navigation without vision, controllers with haptic feedback provided them with directions.

Results

Participants underestimated homing vector distances in both experiments, and overestimated homing vector angles in Experiment 1. A subset of trials in Experiment 1 exploring navigation with visual beacons demonstrated smaller errors in both distance and angle estimation. Angle estimations were not significantly affected by triangle type, but distance estimations were, with participants in equilateral triangles having the lowest distance error. No correlation between angle and distance errors were found. Experiment 2 showed better distance estimations for small triangles and increase of variance of distance with increasing triangle perimeter. Computational models revealed an effect of underweighting both triangle sides and effect of past trials on path integration error. Vector Addition models performed better than Error Encoding models in estimating participants' errors.

Manuscript contributions

I designed and programmed the experimental framework used in the study and helped with the paradigm implementation in the Unity3D, as well as implementation of the omnidirectional treadmill and controller haptic feedback. I also wrote the pipelines to load and preprocess the behavioral data.

3.5 Study 5

Plechatá, A., **Hejtmánek, L.,** Fajnerová, I. Virtual Supermarket Shopping Task for cognitive assessment and rehabilitation of psychiatric patients: Validation in chronic schizophrenia. *Československá psychologie*, accepted September 2020, in press. Impact Factor: 0.373 (taken from Scimago: https://www.scimagojr.com/)

Aim

As navigation skills are among the impaired abilities in patients with mental disorders, we developed a novel task which addressed both memory and executive deficits in schizophrenia (SZ), but also the navigation and planning deficits. This article aimed to assess the validity of the tool and investigate the specifics of SZ impairment.

Methods

We developed a Virtual Supermarket Shopping Task (VSST) which simulates an activity of daily living (ADL), specifically shopping experience. Participants firstly familiarize themselves with the supermarket VE and then are asked to remember lists of items and then collect them as fast as possible and in the shortest distance. VSST was designed to address patient's short term memory, spatial memory as well as planning and execution skills. Twenty patients and twenty healthy controls were tested with VSST and a battery of neuropsychological tests. Each participant completed VSST at difficulty of 3, 5, 7 and 9 shopping items. Battery of tests consisted of: Rey Auditory Verbal Learning Test, Logical Memory, Trail Making Test, PEBL Continuous performance task, Positive and Negative Syndrome Scale, Beck's depression and anxiety inventory and Global Assessment of Functioning. We assessed VSST convergent and divergent validity with the existing neuropsychological measures. We also explored the relationship of VSST performance to participant's condition and demographics. Supermarket layout and participant's view can be seen in Figure 3.3.

(a) Top view (b) First-person view

Figure 3.3: Top view (a) and a first-person view (b) of the VSST

Results

VSST performance was severely impaired in SZ patients in higher difficulties (7 or 9 items). Only negligible or no significant differences were found in both groups' performances in lower difficulties. Investigating navigation impairment in SZ patients, we observed they tend to take longer time per distance travelled, suggesting longer planning or orientation pauses. VSST task performance correlated with neuropsychological scales, suggesting the task targets similar executive and memory processes as the current methods. We found some effects of gender on performance and age on trial distance and time, but no effect of gaming experience in VSST performance. We suggest that VSST can offer few benefits such as increased ecological validity, similarity to ADL, automated administration, possibility of remote administration, and addressing navigation performance not commonly present in neuropsychological assessment.

Manuscript contributions

I contributed to the development of the VSST by programming the core of the experimental framework powering VSST and data logging. I programmed data loading and preprocessing pipelines, preprocessed and analysed the data and cowrote the article with the first author Mgr. Adéla Plechatá.

4. Discussion

4.1 Study 1

In this study, we investigated transfer of spatial knowledge to the real world from either an immersive VR controlled with an omnidirectional treadmill, desktop VE controlled with a keyboard and mouse, or a real world modality with tracking participants using a custom app. Previous studies marked the importance of proprioceptive and vestibular cues to acquire proper spatial representation of the environment (Klatzky et al., 1998; Waller et al., 1998; Holmes et al., 2018). The omnidirectional treadmill served to substitute some of these cues, although arguably not to the full extent.

When participants encountered the environment and had to search for each office for the first time, they demonstrated comparable trial distances and visitation errors (checking incorrect doors) in all modalities. This suggests the free exploration was approached in a similar way and no modality presented unnatural complications. Also, all modalities clearly manifested spatial learning, slowly improving from one trial to the next. The learning speed differed between modalities, with participants learning in the real world acquiring the environmental knowledge the fastest. Participants also demonstrated similar performances in the last trials, suggesting that all modalities can eventually achieve comparable spatial knowledge.

The results demonstrate that the immersive virtual reality allows participants to acquire the same spatial knowledge as the real world learning, but the learning process is slightly slower. This is corresponding to research suggesting learning modality independence on formed spatial representation and neural activity (Huffman and Ekstrom, 2019), but in contrast to previous studies, which demonstrated that VE learning is qualitatively different and participants fail to achieve comparable levels of proficiency (Ruddle and Lessels, 2006). We suggest that this discrepancy might be a byproduct of learning rate and had the participants in the other studies been given more time, they might have performed better.

Prior to the transfer to the real world, participants in both the immersive VR and desktop VE had comparable performance in visitation errors, distance traveled and pointing performance. This is somewhat similar to results of Waller and Greenauer (2007), who investigated what effect various modalities (real world, video recording and watching a video recording while being driven on a wheelchair) have on the formed spatial representation. They observed that participant's performance, although quite comparable in all conditions, did not differ between the wheelchair and visual-only conditions, but the walking condition led to better pointing performance. Our results, on the contrary, demonstrated that proprioceptive input was not enough to match the performance improvements of participants learning in the real world.

Needless to say, Waller and Greenauer (2007) found an effect of proprioceptive input on distance estimation accuracy, although this was not significant due to large intersubject variability. It is possible that while vestibular information might be the core sensory input necessary for path integration angular accuracy (Klatzky et al., 1998; Riecke et al., 2010), the proprioceptive input can be predominantly used in distance estimations. Unfortunately, we have not asked the participants to estimate distances, an omission to be corrected in future research.

Limitations. One of the experimental battles was the large participant dropout due to cybersickness (47 participants, 31%). Dropout was larger in the “VR to real world” group, than in the “real world to VR”. This is probably due to much longer time requirements of the learning phase. While learning the environment in the first 18 trials took approximately 40 to 60 minutes, the second half of the experiment took only 15 to 30 minutes. Therefore, participants in the “VR to real world” group had to spend about twice as long in the VR. As the time was also dependent on participant’s performance, with more skilled navigators taking less time to learn the environment and therefore spending less time in the VR, it is possible that the dropout rates were not evenly distributed along the navigational abilities and created a bias in our sample. This would need to be investigated in the future.

When comparing participants’ performances at the end of the experiment, we observed that participants in the real world still made significantly fewer visitation errors (checking incorrect doors) than participants in the immersive VR, although the groups were comparable in their measured distances and pointing. Had the visitation errors differences been the outcome of spatial learning, we would expect the pointing performance to suffer as well. But in fact, VR groups pointed significantly better, albeit the effect was not strong (average pointing error was 18° in VR, 22° in the real world). This suggests that the difference in the visitation errors might have originated with the condition itself, not on the level of spatial learning.

One explanation could be that while VEs allow participants to acquire spatial knowledge in terms of configurational or layout information, their visual fidelity is unsuficient and can lead to failures to recognize correct doors. Arguably, all the doors in the VE looked exactly the same, but the doors in the real world can have visual tells making them easier to tell apart. However, research studying impacts of visual detail suggests that it is not important for spatial search tasks (Ruddle and Lessels, 2006).

A different explanation can be found in the way participants were given feedback. In the real world, participants were being told ”correct” or ”incorrect” by the experimenter, while in the VR and the desktop VE they received automated auditory feedback. During the initial trials, participants had to constantly keep checking each door (32 doors in total) to learn the correct one, which made them visit the incorrect doors more than hundred times. For this reason, we chose the negative feedback not to be overly obnoxious. Nevertheless, one can argue that the real world feedback and the VE feedback had different emotional valence for the participants. The mere presence of the experimenter during the real world testing could also motivate the participant to simply perform better.

Thirdly, not checking a door and then being forced to return while on the omnidirectional treadmill could potentially be more punishing, then not checking it in the real world. This is due to the increasing cybersickness participants had felt as the experiment progressed. This could have motivated them to simply check all doors they passed as a precaution, as there was no direct penalty.

Although our experiment demonstrated that the spatial representation can be obtained from both the real world and the VE regardless of the level of immersiveness, the question remains about the quality and the neural representation of the spatial knowledge. It could be possible that all participants navigated the environment in a similar manner, but the neural representation qualitatively differed, although previous studies claim otherwise (Huffman and Ekstrom, 2019).

Conclusion. This study demonstrated differences and similarities of spatial learning in modalities with variable idiothetic cues. While the initial exploration of the environments was similar between the conditions and participants in all modalities achieved the same spatial knowledge by the end of the experiment, real world navigation led to fastest spatial acquisition suggesting some differences between real world and virtual navigation still remain. Learning in the desktop VE and in the immersive VR with an omnidirectional treadmill had comparable effects on spatial acquisition, although immersive VR seemed to have been a better platform for VE to real world spatial transfer.

4.2 Study 2

One of the key issues with studying navigation in VEs is the problem of relying almost exclusively on visual cues. This study aimed to explore the neural signal captured by iEEG in relation to visual processing of objects and scenes. As scene processing is happening in a separate neural pathway and is more important for navigation, I will only discuss the scene processing results.

We have observed channels which increased their broadband gamma activity (BGA, 50-150Hz) after scene presentation. This approach revealed 252 bipolar channels. Some of these channels were located in areas previously linked to scene and landscape processing, such as parahippocampal place area (Aguirre et al., 1998), medial place area in retrosplenial-medial parietal region (O'Craven and Kanwisher, 2000) and occipital place area in the transverse occipital sulcus (Nakamura et al., 2000). We have also observed scene-selective channels in areas not previously documented, such as anterior temporal cortex and hippocampus.

One of the troubles with iEEG recording is the relatively crude spatial sensitivity of the LFP signal in relation to the functional size of the brain area. The signal at each channel can be influenced by travelling brain oscillations or modulated from afar (Zhang and Jacobs, 2015). To address this, we used bipolar referencing, which calculates new neural signals to be the difference between two neighbouring channels on a single electrode. This is a common approach, but can reduce spatial precision of the computed channel, as well as position it potentially outside of the original functional area. To address this and to avoid any prior assumption about anatomical localization, we implemented the K-means clustering algorithm, which uses the bipolar channels' MNI coordinates and creates clusters of anatomically near channels.

This approach was able to identify 7 scene-selective clusters, with one partially overlapping the occipital place area, one the parahippocampal place area and one the medial place area, all demonstrated to have spatial sensitive properties in previous studies (Aguirre et al., 1998; O'Craven and Kanwisher, 2000).

We have also found scene-selective cells in areas not previously reported. Namely, most hippocampal channels in our sample were identified to be scene-selective (7 scene only, 20 in total). Hippocampus was not previously identified in humans to be scene-responding, although it has been demonstrated to contain view-dependent cells in primates (Rolls, 1999) and humans as well (Ekstrom et al., 2003), suggesting potentially larger visual modulation of hippocampal activity than observed in rats and mice.

Limitations. It is necessary to ask, what exactly are the implicated areas processing and if the neural signal is really coding spatial information, or if it is merely processing image complexity. Although the images were grayscaled and corrected for luminance differences, other features (such as differences in shading or edges) can also play a role during visual processing. Nevertheless, previous research indicated that spatially selective areas, such as PPA, react uniquely to scenes, rather than multitude of objects (Epstein, 2008). Another reason to believe that the signal represents spatial processing is the fact that many of these channels were found in already established scene-selective areas. These areas also have direct connections to RSC, EC and hippocampus, which are established to be dominant in spatial processing.

Needless to say, there was a lack of control over the exact nature of the processing involved, as participants were only asked to react to fruits or vegetables. Hippocampal activation can be observed during memory retrieval, which could be stronger in scenes than objects. And while 7 hippocampal channels were found to be specifically responding to scenes, 15 were found to be responding to both objects and scenes. Previous studies also implied hippocampus to be involved in recognition of familiar places in rats (Klement et al., 2005). Potentially, separating scenes into familiar vs non familiar might have clarified the memory vs scene processing answer.

Lastly, although almost all described functional areas related to scene processing contained channels from multiple patients, the parietal cortex and the frontal cortex had channels coming from a single patient. This unfortunately constitutes a problem with many iEEG studies (Qasim and Jacobs, 2016). Combined with potential inaccuracies in channel localization, any general statements about functional areas have to be made cautiously.

Conclusion. Although this study was not using the VEs in establishing the neural responses related to spatial processing, it was able to demonstrate that even static visual input is sufficient for driving spatial-related neural responses from areas implicated in navigation.

4.3 Study 3

In this study, participants navigated through a virtual city in a desktop VE, while their eye movements were being tracked. This allowed us to monitor how much attention participants dedicated to the GPS-like navigational aid, and how it affected their spatial learning.

This task tried to solve few issues not addressed by previous studies. The first one was the inability to monitor participant's attention during navigation. Studies investigating the effect of navigational aids in real world environments

(Ishikawa et al., 2008; Münzer et al., 2012) simply removed the aid during testing procedures, but this created a division between the conditions making them harder to compare.

Some authors have argued that the modality of spatial cues during encoding affects the quality of final representation (Münzer et al., 2012; Zhang et al., 2014). Therefore, taking away the aid during testing forces participants to suddenly use a strategy they did not use during learning. We solved this by leaving the GPS-like map present throughout the entire experiment while monitoring how much the participants had used it. This allowed us to demonstrate that the duration spent with the aid was related to participant's performance. It also allowed us to directly tie participant's subjective assessment of their spatial skills to the amount of attention they dedicated to the GPS-like aid.

The second problem with the real world experiments is the environment's size. Real world studies have been investigating relatively smaller environments, for example local zoos (Münzer et al., 2006) or few streets on campus (Patai et al., 2019; Münzer et al., 2012). Other researchers used large environments, but traversed in cars (Ishikawa and Montello, 2006), which is not ideal due to different neural and behavioral aspects of route-based navigation (see section 1.1.1).

Using real world environments can also lead to landmark ambiguity (too many potential landmarks), intervening environmental variables, such as changes in weather, or road construction. To control for the intervening environmental variables, researchers often choose to conduct the study inside a building (Richardson et al., 1999; Witmer et al., 1996), similarly to what we did in the Study 1. This removes some external cues as well as environmental distractors, but it also limits the environment's size. Using VE allowed us to examine participants' behaviour in a relatively large space with perfect control over the intervening variables.

The other problem which we had faced at the time of the study conception, was that mobile eye tracking devices were costly and somewhat unreliable. Studies involving eye tracking were usually confined to the laboratory spaces and sitting position. The situation has changed in recent years and mobile eye trackers seem to be comparable in their accuracy to their stationary counterparts (Ehinger et al., 2019). Recently, an eye tracking contact lens was constructed (Khaldi et al., 2020) and eye tracking using a mobile phone camera (Valliappan et al., 2020) was demonstrated, offering directions for future research and testing the study's validity in the real world.

Limitations. One of the potential limitations is that looking at the GPS-like aid does not necessarily mean it is being actively used. Some people might glance towards it only to support their already made decision, similarly to musicians needing the notes in front of them despite knowing the composition by heart.

The use of VE could have also affected the results in an unexpected way. For example, some participants might have not been trying to learn the city as best as they could, as failure to navigate poorly did not have any real consequences, whereas learning in a real city might offer better incentives. We also refrained from giving participants immediate feedback, as we had no prior standards of what constituted good and bad performance. Similarly to the study 1, where participants seemed to perform better in the experimenter's presence, absence of external motivators could potentially inhibit spatial learning in the VE.

Conclusion. In conclusion, we observed that participants' spatial performance was negatively correlated with the time they spent engaged with the navigational aid. We found their attention was related to participant's subjective assessment of spatial skills, something that the future studies might consider when conducting similar research. VE in this case proved to be a useful tool, allowing us to investigate spatial navigation skills in a large controlled space, while constantly monitoring participants' attention.

4.4 Study 4

The fourth study investigated the path integration with triangle completion tasks. We used the VEs to overcome some of the problematic aspects of real world studies (external boundaries and intervening variables) as well as path integration studies done in VEs on monitors (missing idiothetic cues).

Studying path integration in a desktop VE allows precise positional recordings and infinitely large spaces, but removes idiothetic cues. These are paramount for euclidean knowledge acquisition (Chen et al., 2013), as well as decreasing path integration angular error (Waller and Greenauer, 2007; Klatzky et al., 1998; Holmes et al., 2018). VR combined with an omnidirectional treadmill allows participants to cover infinitely large spaces, which would otherwise be challenging or impossible to do in a controlled way. It also provides free head movement and access to proprioceptive information, such as muscle tension, number of steps and, to a limited degree, level of forward lean. Lastly, it makes studying sight-guided path integration, having participants navigate towards a series of visible beacons, possible.

To prevent any dangers and intervening cues, path integration studies have been conducted in indoor sports fields (Stangl et al., 2020) or hallways (Waller and Greenauer, 2007), but these locations are naturally limited in their size (Loomis et al., 1993; Klatzky et al., 1998). Path integration over short distances can be relatively easy, and it is not clear how effective it can be over distances as large as half a kilometer. In the real world, there are environmental hazards as well as uncontrollable allothetic cues, such as auditory or olfactory markers. This is problematic, since any external boundaries or landmarks could allow participants to solve the task by a different strategy, e.g. cognitive map or view matching.

Using a VR with an omnidirectional treadmill, we were able to explore triangle completion task in triangles of hundreds of meters long. We observed that the size of the triangle does not necessarily affect the path integration's angular error, while it does increase the distance errors logarithmically.

Usual path integration tasks have the experimenter guiding the participant by actively leading them, or pulling them behind on a rod or a rope, while the participant is blindfolded (Stangl et al., 2020; Loomis et al., 1993). This can potentially create a stressful situation affecting the results. The active path completion also poses potential dangers. When a participant walks to the original destination without sight, they might be afraid of hitting an obstacle or a wall, feeling anxious that the experimenter might not stop them soon enough and therefore choosing a more cautious strategy. By using a VE with the treadmill, it is possible to remove these limitations while keeping the necessary idiothetic information intact.

Nevertheless, although accounting for all these potential drawbacks of traditional triangle completion tasks, our results were similar to previous studies, such as homing distance underestimation and angle overestimation (Fujita et al., 1993; Loomis et al., 1993).

Interestingly, we found no correlation between participant's angular and distance errors. This could be caused by the independence and different importance of rotational and translational idiothetic cues. The rotational input has been demonstrated to be more important for successful spatial updating than translation cues (Riecke et al., 2010; Waller et al., 1998), although other researchers argue that both are necessary (Chance et al., 1998). While the rotational cues were unhindered and participants had complete freedom of head and body movement, they could not really move forward, only lean forward and walk in place. Secondly, this result also suggests that participants did not solve the triangle completion task using triangle templates, as doing so would arguably manifest in some relationship between estimated distances and angles.

Limitations. A potential limitation could be that the haptic feedback from the controller was confusing for some participants and provided insufficient directions. Comparing performance between these haptic driven trials, and a subset of trials which used visual beacons, we observed no differences in participants' precision during the guided portion of the triangle. This suggests the observed better performance in visual trials was not because of insufficient feedback from the controller.

One of the main limitations is that the omnidirectional treadmill has limited vestibular input and somewhat unnatural walking. Participants could have had trouble with estimating how long the virtual steps were and could have led to increased variability of distance errors. The results demonstrated the distances' standard deviations grew with the triangle size. Participants also underestimated the homing distance more in longer trials. The computational models suggested that this could be due to the walked distance regressing to the mean over the length of the experiment, but the possibility of it being a byproduct of the treadmill remains open.

Conclusion. Using VEs in this case allowed us to investigate path integration over large spaces with idiothetic cues largely intact, and have precise recordings of participants' trajectories. In triangle completion tasks, participants are usually guided by the experimenter while blindfolded, while the VE allowed us to remove the experimental intervention and potentially create a safer space. We were also able to investigate triangle completion tasks with visual beaconing, which would be practically impossible to do over longer distances in the real world.

4.5 Study 5

We have created a virtual supermarket shopping task (VSST) to bring a new method for potential rehabilitation and assessment of cognitive deficits in psychiatric patients.

Schizophrenia (SZ) patients performed significantly worse in the task than healthy controls in all difficulties except the easiest. The observed performance in VSST correlated with existing metrics of memory, suggesting that the task addresses similar deficits as standardized cognitive tests. While we have observed a general impairment of VSST performance in SZ patients, surprisingly, we have not been able to link it directly to SZ symptomatology. Patients' results were not significantly correlated with PANSS scores, which is contradictory to findings from other studies linking negative symptomatology to worse cognitive performance in standardized tests (Bezdicek et al., 2020) and spatial tasks (Folley et al., 2010). But given that the correlations with negative and positive symptomatology were moderate (r = -0.41 and r = 0.42, respectively) and the many reported correlations were lower (Ventura et al., 2009), we estimate that this might be only due to our relatively small sample (20 patients).

VSST allows precise recordings of participants' behaviours and tracking metrics not addressed by standard neuropsychological batteries. These include route planning, or spatial deficits. In this study, we focused primarily on trial distances. Although the distance measure is a very simple metric, not capturing behaviours such as repetitive route following or other heuristics potentially indicative of the disorder, it could mark navigational deficits.

One of the interesting observations was that SZ patients needed longer to travel the same distance. This behavior can be explained in several ways. First, the task requires participants to memorize the items, remember the supermarket layout, plan the trip to minimize the time and distance, and then execute this plan. It is possible that although the spatial skills were unaffected, the demonstrated slower performance was due to slower processing speed and executive functions, reported to be impaired in SZ (Fioravanti et al., 2012).

Although the core VSST performance was not affected by age, we observed an impact of age on navigation times (increasing with age) and marginal impact on distances (decreasing with age). In other words, older participants took longer, walked shorter distances, while their memory for objects was not impaired. We have not observed any effects of video game experience on trial times, as we did in Study 3.

The trial time increase in older groups could be representative of one of the VE drawbacks of unnecessarily and unevenly increasing cognitive load to different populations. Older participants might simply perform worse in certain VE tasks due to the unfamiliarity with the controls or the task.

Limitations. It is difficult to disentangle the source of observed differences between the SZ patients and the healthy controls in such a multifaceted task. Besides memory impairment, which we controlled for by using standardized memory tests, the performance differences could arise from motivational deficits, as the negative symptomatology of the illness' progress. We have observed that the SZ patients consistently collected three items on average, regardless of the trial demands (three to nine items to be collected). This could mean that they were simply giving up on the task early. However, we observed no significant differences in trial times between the groups (healthy: 190s per trial, SZ patients: 172s per trial), suggesting that both SZ patients and healthy controls spent approximately the same amount of time in each trial. Needless to say, we had tested voluntary participants, so some level of internal motivation was to be expected.

There could also be some confounding factors caused by the VE. For example, the navigational strategies can be different in the VE in comparison to the real world, as failures to plan a good route are arguably less punishing. When executing a planned path through a shop, anything we forget forces us to walk back and costs us time. Although similar in the VSST, walking back in the VE is not as demanding as it would be in the real world. We observed an increase of walked distances with increasing difficulties. Although this sounds logical, as picking up 7 objects instead of 3 might require more distance to be covered, this is not necessarily true. Considering the limited supermarket layout, the minimal distance necessary to pick 5 items should be relatively similar to 9 items distance, as all items are effectively on the same route. One could, for example, pick up carrots while going to collect yoghurts, had they planned the trip accordingly. Increase in the distances with progressing difficulties therefore suggests more unnecessary trips were being taken.

Lastly, comparison of VSST performance with daily functioning in SZ patients is necessary to address the task ecological validity and comparability of the VE implementation to the real world functioning.

Conclusion. Although similar tasks could be technically conducted in real environments, their cost and time requirements would probably far surpass the potential benefits. Use of VE allowed us to precisely record participants' behaviours and control for extraneous variables, while simulating a sufficient representation of ADL with clear behavioral correlates to patients' condition. Closer investigation of mnemonic and navigational strategies and identifying individual differences could lead to a promising diagnostic application.

4.6 General discussion

The first hypothesis of this thesis was that the navigation in VEs leads to comparable behavior and performance as navigation in the real world and this knowledge is transferable. Results from the study 1 demonstrated that navigation behaviour manifested during the first encounter with the environment is comparable between the VE and the real world. Moreover, navigation in both virtual modalities, desktop VE and immersive VR, led to spatial learning which was transferable to the real world, strongly suggesting that the formed spatial knowledge is modality-independent. Needless to say, participants learning in the real world environment acquired the spatial knowledge the fastest. Study 2 then explored the processing of spatial scenes using intracranial recordings from epileptic patients. The results demonstrated that even spatial scenes presented on a screen can elicit responses from areas implied in navigation and spatial processing, such as the parahippocampal place area, supporting the view that vision-based tasks could be sufficient for navigation studies in humans.

Second aim of the thesis was to investigate how VEs can overcome some of the problems of real world navigation studies. In section 1.4.2, I presented five areas how VEs can help neuroscientific research in investigating spatial navigation. These were the economical benefit, allowing full control over experimental conditions, studying navigation without movement to make neural recordings possible, modelling impossible environments or allowing easy environmental manipulations, and providing precise recordings. Studies 3 and 4 demonstrated these features of navigation studies in VE. In study 3, we used VE to collect precise recordings of eye movements during navigation in a large city environment. In study 4, using VE with an omnidirectional treadmill, we were able to observe path integration both with and without vision over long distances.

Last aim was to demonstrate that navigation impairment studied in VEs can provide useful markers of mental disorders. In study 5, we used VE to document memory and spatial impairment in schizophrenia patients. This use of VE allowed us to create a safe learning and assessment space and with the precise recordings of participants' decisions uncovered some of the specific cognitive deficits which accompany the illness.

The presented studies showed that VEs offer a suitable and ecologically valid alternative in situations where experiments in the real world are not possible.

Limitations of VEs

Besides these demonstrated benefits of VEs in navigation research, there are some limitations which can affect their universal adoption.

There are some potential differences in navigation behaviour between the real world and VE. We observed some of these in study 1, with participants in the real world learning faster than in VR. But study 4 demonstrated similar performance in path integration tasks in VE as was reported in real world studies (Klatzky et al., 1998), and other studies argue for modality independent learning of spatial representations (Huffman and Ekstrom, 2019). So the difference between the conditions, although possibly attributable to the missing vestibular cues on the treadmill, could also arise from other sources. Some researchers argue that visual fidelity is not important for spatial tasks (Ruddle and Lessels, 2006) and others have found somewhat comparable spatial performances between various modalities (Waller and Greenauer, 2007; Witmer et al., 1996), so it might be possible that the differences between VE and real world spatial performance arise from other than navigation processes.

A potential explanation can be in participants' different approaches to the navigation tasks in VEs. Participants might simply not take them seriously, or adopt a different approach based on prior experience with games (West et al., 2015). A majority of VE studies rely on participants' inner motivations, although gamifying aspects are being sometimes used (Coughlan et al., 2019). The reliance on inner motivation is not necessarily problematic in the real world experiments either, as researchers can expect that participants who show up want to perform well. But there can be some differences in how participants approach tasks done with the experimenter by their side and how they perform in fully automated, impersonal tasks. In study 1 we observed participants made more errors in the VR condition than in the real world, despite other spatial metrics being comparable. This can be either attributed to feedback in the real world being delivered personally, or participants simply checking all doors in the VR, as there was no real reason not to. In the supermarket VE in study 5, failures to pick necessary items are not as punishing as the same forgetfulness in the real world, so participants can simply adopt a different, more erratic approach to the task.

Changes in administration which might provide a more motivating environment, manipulating the way feedback is provided and observing differences in spatial learning in the VEs could answer some of these questions.

The other potential issue is that different participants have different experiences with video games. Effects of gaming and increased cognitive load due to unfamiliarity of the task has been observed to modify performance or change navigation strategies (West et al., 2015; Brunyé et al., 2018). Although we have not observed any direct benefits of gaming experience on the primary performance metrics in any of our studies, we have observed the effect it had on trial times in study 3. This is not an uncommon problem, and most studies control for confounding skills by administering standardized tests. Some of the recommendations of what can be done in respect to video gaming experiences can be found in section 1.4.3.

And lastly, use of VEs in research brings the complication of cybersickness which can lead to increased participant dropout. Although we have not experienced problems in studies 3 and 5, suggesting that desktop VEs do not cause excessive cybersickness, we observed thirty one percent dropout in study 1. This could have been caused by overly long experimental protocol, with some participants spending more than an hour in the VR despite it being their first time. It could also be attributed to the constricted spaces of our VE, as it was built from a series of narrow and barren hallways. The possibility of the dropout begin caused by the exertion from walking on the omnidirectional treadmill is contradicted by the results from study 4, where people walked very long distances and did not feel nauseated. Therefore, the increased levels of cybersickness in the study 1 were probably due to a combination of long exposure, exertion and optic to vestibular mismatch, all of which have been connected to increased risks (Saredakis et al., 2020; Dużmańska et al., 2018).

5. Conclusion

Virtual environments (VEs) are an incredibly useful tool in neuroscientific research of navigation. They allow navigators to remain stable while moving through the world and therefore providing researchers an opportunity to collect neural and physiological recordings. Thanks to VEs, researchers can precisely record the entire experimental procedures and freely modify and control the environments, which would be economically impossible or challenging to do in the real world. Importantly, the behavioral and neural responses induced by real and virtual navigation seem to be, at least in humans, quite comparable.

In this thesis, I presented examples of research of human navigation in real and virtual worlds, demonstrating that while some differences exist in the quality or speed of spatial learning, the acquired spatial knowledge is comparable and transferable between both modalities. I also offered examples of experiments which would be complicated to carry out without VEs, such as letting participants navigate large towns while monitoring their attention using eye tracking, testing path integration over distances of hundreds of meters or testing cognitive deficits of psychiatric patients in a safe environment, while controlling for all surrounding allothetic cues.

While the VEs, and the associated hardware, are still not perfect, navigation in a VE can cause nausea and introduce confounding factors to collected data, these systems are rapidly improving. New generations of head mounted devices offer better head and body tracking, new levels of interactivity and enhance the felt presence. They also have the potential to reduce cybersickness, and improvements in graphical hardware and software can achieve almost photorealistic environments. Overall, VEs seem to be indispensable for navigation research, enabling experiments that would be not possible without them.

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