ROUTE NAVIGATION AND DRIVING

ROUTE NAVIGATION AND DRIVING: ROLE OF VISUAL CUES, VESTIBULAR CUES, VISUAL SPATIAL ABILITIES, AGE AND MOOD DISORDERS

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For my mother, Azadeh.

Lay Abstract

This thesis focuses on enhancing our understanding of wayfinding while driving in young and older adults. Using a driving simulator, we ran various virtual reality experiments to examine the underlying mechanisms of navigation while driving and ways to improve wayfinding of drivers. We identified useful cues for route learning in different environments where there were no navigation aid systems. We examined correlations between various spatial skills and performance that may improve drivers' wayfinding in unfamiliar environments. Furthermore, we assessed age-related effects on route learning and potential interventions to improve navigation in older drivers. The findings from the experiments reported in this thesis introduce the principle of route learning while driving in terms of how various internal and external factors can affect it. Drivers can incorporate these findings into their navigation tasks to overcome the wayfinding challenges that they encounter when driving in unfamiliar environments.

Abstract

The studies reported in this thesis aim to provide insights on the process of navigation while driving. Driving requires processing and monitoring multiple tasks and sources of information. Navigation while driving increases the cognitive load of the driving task. Offloading the task of navigation to navigation aid systems such as GPS has potential disadvantages for our spatial memory skills. In this thesis, we introduce useful cues and skills to improve the performance of drivers in a variety of situations where they must navigate without the help of GPS. We used a motion simulator with six degrees of freedom to simulate various virtual reality driving scenarios that combine both visual and vestibular cues. In the following chapters, we report the effects of landmark cues, vestibular cues, self-reported mood disorders (e.g., depression, anxiety, and stress), individual differences at the visual spatial level (e.g., working memory span and mental rotation skills), age, and self-reported navigation skills on drivers' route learning. We showed that successful navigation in various navigational situations depends on the type of landmarks available in the environment and the specific visual-spatial skills of drivers. We showed that vestibular self-motion cues improve egocentric route learning. Depression, anxiety, and stress affected drivers' route learning ability and dependency on GPS. We observed no deficit in age-related navigation performance when older drivers were able to use an egocentric frame of reference, however there was less optimal navigation performance of older drivers when wayfinding required an allocentric frame of reference. Overall, the application of the findings of this thesis may lead to an increase in efficacy and success in navigation performance and wayfinding while driving.

Acknowledgments

First and foremost, I want to express my deepest gratitude and respect to my supervisor, Professor Judith Shedden, for her phenomenal support and tremendous supply of wisdom over the years of my education at McMaster University. I would like to thank her for her remarkable kindness. She generously and patiently taught me the steps of becoming an independent researcher, and her advice will undoubtedly be an ongoing support throughout my future research career. I grew up in her lab, where I learned a huge amount about science and humanity and had a chance to experience Canada. I will never forget that the person who I am now, is mainly because of her support and encouragement. I would also like to express my appreciation to my supervisory committee members: Professor Martin Von Mohrenschildt, Professor Joe Kim, and Professor Hongjin Sun. Professor Mohrenschildt has been a great co-supervisor, whose beneficial feedback has always been significantly helpful for my research. He gave me the confidence to work with a massive motion simulator, patiently supported me, and was there for me whenever I encountered an issue with the simulator. He helped me expand my knowledge of data analysis, and his advice on programming and computation has been of great benefit to my psychological experiments.

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My collaborator, Darren Kenney, who made a great contribution to my work, deserves special recognition. Since he joined our research lab, we have started a productive team. When you read his name as co-author throughout my thesis, recall my sincere appreciation of his contribution to these works. I also can't forget the many undergraduate students, Hannah Song, Emily C. Cheung, Michelle Chau, Sidney Sharp, Ahmed Kamhawy, Prerna Sharma, Kristen Arnold, Safwan Sarkar, and Michelle Sharma, who have been extremely helpful in bringing my studies to completion, particularly with respect to participant testing.

Last but not least, I want to express my true appreciation for the tremendous support of my mother, father, and aunt Khadijeh. They patiently supported me through ups and downs and never stopped encouraging me. My father's and mother's first concern has always been to comfort me and provide me with a suitable environment to study in. We moved to Canada so that I could have a better education and future. They sacrificed a lot for me, and words cannot help me thank them enough. I should thank my friends who made the tough graduate school days easy and manageable. This challenging period of my life turned into one of the best with the support of all the amazing people I've named.

Up until this part of the acknowledgement section, I had written it months ago, when my life was busy with work and school. However, everything changed in my life on October 26th. My mom, my source of calmness, courage, and love, passed away. We lived in Canada together and went through lots of ups and downs, but she never stopped believing in me and did anything she could to make my life comfortable. I already miss her so much. The thought of her not being in my life anymore tears my heart into pieces. I know she is in God's hands in a great place now. I hope I can make her happy at the end of November by defending this thesis and becoming her Dr. Yasi. I would like to greatly thank my supervisor, Dr. Shedden, who didn't leave me alone during the difficult times that I have been going through. Knowing that I have her support made me feel safe and was very heartwarming. My father, who has always been a tough man but with a soft and kind heart inside, is going through a lot himself, but he has been patiently trying to be both my mother and father these days. I appreciate him a lot. I would like to thank Dr. Margaret McKinnon, my job supervisor, who believed in me by hiring me last year in her lab. She greatly supported me during this difficult time and didn't let me feel alone. I am greatly thankful to my friends, Mona, Iman, Farah, Dena, and many others, who supported me like family and never left my side.

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Declaration of Academic Achievement

Five published or to-be submitted papers addressing the effects of environmental visual cues, vestibular cues, visual-spatial skills, age-related changes in navigational point of view, and self-reported mood disorders and type of GPS instructions on wayfinding are included in this thesis. Below you can find a list of these papers and my specified contributions to each.

Chapter 1:

Author: Yasaman Jabbari

Chapter 2:

Jabbari, Y., Kenney, D. M., von Mohrenschildt, M., & Shedden, J. M. (2022). Testing landmark-specific effects on route navigation in an ecologically valid setting: a simulated driving study. *Cognitive Research: Principles and Implications*, *7*(1), 1-12. https://doi.org/10.1186/s41235-022-00374-w

Comments:

I designed the project with the insight and help of my supervisors, Dr. Shedden and Dr. Mohrenschildt. I collected the data and performed the statistical analysis. Darren Kenney provided insights on data analysis and helped with writing the manuscript.

Chapter 3:

Jabbari, Y., Kenney, D. M., von Mohrenschildt, M., & Shedden, J. M. (2021). Vestibular cues improve landmark-based route navigation: A simulated driving study. *Memory & Cognition*, *49* (8), 1633-1644.

Comments:

This project was designed as a follow-up to the previous study by adding vestibular cues to the visual cues. I collected the data with the help of a thesis student, Michelle Sharma, and performed the primary data analysis. Darren Kenney and I collaborated on further data analysis and writing.

Chapter 4:

Manuscript:

Jabbari, Y.; von Mohrenschildt, M.; Shedden, M. J. (to-be submitted). Navigation in a Simulated Driving Task: Visual Spatial Abilities and Self-Reported Navigation Skills. *Canadian Journal of Experimental Psychology.*

Comments:

This project was designed as a follow-up to the first study by looking at the effect of visual-spatial abilities on wayfinding. I collected the data, performed statistical analysis, and wrote the paper. Some undergraduate students, Hannah Song, Emily C. Cheung, Michelle Chau, Sidney Sharp, Ahmed Kamhawy, and Prerna Sharma helped with literature review.

Chapter 5:

Manuscript:

Jabbari, Y.; Kenney, M. D., von Mohrenschildt, M.; Shedden, M. J. (to-be submitted). Egocentric Spatial Encoding of Drivers is Preserved with Age: a Simulated Driving Study. *Memory & Cognition*.

Comments:

I collaboratively designed the experiment with Darren Kenney and my supervisors Dr. Shedden and Dr. Mohrenschildt. This study was part of a series of studies running in our lab on older adults. Data was collected with the help of a research assistant Hannah Song, and honors thesis students, Vincent Li and Ryan Lee. I performed the statistical analysis and wrote the paper.

Chapter 6:

Jabbari, Y.; Arnold, K.; Kamhawy, A.; Sharma, P.; Sarkar, S; Shedden, M. J. (to-be submitted). Individual Differences in Navigation and GPS Use: Mental Health, Working Memory, and Spatial Skills. *Journal of Environmental Psychology.*

Comments:

This chapter represents the data and results of an online study that I collaboratively designed with the help of Dr. Shedden and 2 undergrad thesis students: Ahmed Kamhawey, Prerna Sharma, and 2 4QQ students (independent study course): Kristen Arnold and Safwan Sarkar. Data was collected online with the help of the named undergraduate students. I performed the data analysis and wrote the paper. The named undergraduate students helped in literature review and writing as well.

Chapter 7:

Author: Yasaman Jabbari

Preface

A sandwich format has been used for the preparation of this thesis. Chapter 1 provides a general overview of spatial navigation and factors affecting our wayfinding ability. Chapters 2 and 3 are published articles, and chapters 4, 5 and 6 are to be-submitted manuscripts to academic journals. These chapters are presented independently of one another, with no prior knowledge assumed, and are verbatim reproductions of published or to-be submitted manuscripts. Finally, chapter 7 is the discussion of all the findings and the application of the results.

Chapters 2, 3, 4, 5 and 6 each contain a detailed introduction and discussion specific to the studied project. As a result, the introduction chapter, chapter 1, provides more general information, which facilitates the comprehension of other chapters. In order to facilitate the reading process and simplify the flow of the information, cited references in chapters 1 and 7 are provided at the end of the corresponding chapter.

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CHAPTER 1: An Introduction to Spatial Navigation and the Importance of Internal and External Factors on Wayfinding Skills

1.1 Navigation, route, and survey knowledge

Spatial cognition is a branch of cognitive science that embraces various mental processes like attention, perception, memory, and executive functions. Our spatial cognition is defined by the information we obtain through perceiving and interacting with spatial characteristics of our environment, such as relations, distances, and orientations, among other cues (Stack & Mallot, 2000; O'Keefe & Nadel, 1978; Dalton et al., 2019; Ruddle & Lessels, 2006; Poucet & Save, 2009). Studying spatial cognition helps us understand how spatial perception can assist us in overcoming navigational challenges. All humans and non-human animals develop mechanisms of spatial navigation to overcome fundamental challenges such as orienting in space, locating resources, finding escape paths, and developing homing strategies. Our knowledge of human spatial cognition is built on decades of research on animal spatial cognition. The review in this section of the introduction will touch on both animal and human research.

Navigation is a complex behavior that involves a combination of physical and cognitive factors. When we navigate, we physically orient in space while using various mental faculties, including sensory processing and decision-making (Meneghetti et al., 2016; Waller & Nadel, 2013). Our sensory system processes auditory, somatosensory, vestibular, and visual cues to acquire knowledge about our surroundings and this information is integrated in the brain to provide perceptions of where we are and how we are moving through space (Warren & Kurtz, 1992; Foo et al., 2005; Ruddle & Lessels, 2006; Ekstrom, 2015).

Navigation plays a crucial role in our successful everyday functioning. We use our navigation skills in an extensive range of activities, from searching for a box of pills in a kitchen cabinet to traveling by car toward a faraway destination. This thesis examines navigation akin to finding one's way through a large-scale environment, such as searching for a destination while driving in an unfamiliar town.

Three of the most commonly studied navigation strategies for human and non-human animals involve the use of route knowledge, survey knowledge, and path integration. Navigation by route knowledge, also known as landmark-based navigation, involves using landmarks to determine the travel direction. Navigation by survey knowledge, also known as cognitive mapping, involves using bird's eye view mental representations of an environment for wayfinding (Kelly & McNamara, 2008; Mou et al, 2004; Waller & Lippa, 2007; O'Keefe & Nadel, 1978; De Condappa, 2016). Path integration, also known as dead reckoning, involves using velocity and acceleration for self-locating (e.g., Wallace & Whishaw, 2003; Poucet & Save, 2009).

Most important to this thesis is the work on the two fundamental navigational frameworks of survey knowledge (allocentric, environment-referenced frame) and route knowledge (egocentric, self-referenced frame), and the effect of internal and external cues on these two frameworks. Trowbridge (1913) first suggested that insects, birds, and mammals are able to make an "imaginary map" of their environment. Later, Tolman (1948) expanded this idea, theorizing that rodents' representation of their surroundings is not limited to egocentric route knowledge, but in fact they can learn the spatial layout of their environment by forming a "cognitive map" of their surroundings. Since then, in most species, application of the two comprehensive reference frames of route and survey knowledge for wayfinding has been well accepted. These two navigation strategies will be addressed in detail in the following paragraphs and chapters.

Route knowledge is a primary form of navigation, and is viewpoint-dependent, meaning it is based on egocentric encoding of the environment. Route knowledge is acquired when we make a spatial form of our environment by remembering sequences of routes and landmarks relative to our position in space (e.g., I turned right at the gas station), or by remembering our body movements in temporal order in a landmark-free environment to orient in space (e.g., I turned right, straight, and then left). External references such as landmarks and internal references such as body-based cues can enhance route knowledge by providing useful orientational and navigational information. Route knowledge mainly requires an understanding of the relationship between self and reference cues (Kelly & McNamara, 2008; Wolbers & Wiener, 2014; Igloi, et al., 2010; Mou et al, 2004; Waller & Lippa, 2007; O'Keefe & Nadel, 1978).

Navigation by survey knowledge, also known as cognitive mapping, is viewpoint-independent and based on the allocentric encoding of the environment. Survey knowledge is acquired when we make a spatial form of our environment by remembering the relative location of landmarks or target destinations with respect to other landmarks (e.g., the parking lot is between the coffee shop and gas station). Survey knowledge allows more flexibility in navigation compared to route knowledge. Application of survey knowledge enables navigators to discover new routes between known areas, such as shortcuts (O'Keefe & Nadel, 1978; Tolman, 1948; Waller & Lippa, 2007; Brunyé, et al., 2017; Siegel & White, 1975; Wolbers & Wiener, 2014; Igloi, et al., 2010). Route-based navigation strategies are less cognitively demanding and emerge faster (Brunyé et al., 2017; Hartley et al., 2003; Poldrack et al., 2001). In contrast, survey-based navigation strategies require generating mental representations of an environment through visualization and mental rotation. Therefore, they are considered to be more cognitively demanding (Brunyé et al., 2017; Brunyé & Taylor, 2008; Gagnon et al., 2014; Thorndyke & Hayes-Roth, 1982).

The Landmark, Route, Survey (LRS) theory by Siegel and White (1975) suggested that individuals' representation of their environment is learned through a hierarchy of knowledge such that navigators first acquire route knowledge by using landmarks and, with experience, gain survey knowledge of an environment. The developmental literature indirectly supports this idea, in that use of route vs. survey knowledge is age dependent. In children the ability to use landmark knowledge develops first, followed by route knowledge and then survey knowledge (e.g., Hermer & Spelke, 1994; Schmelter, Jansen-Osmann, & Heil, 2009; Tonucci & Rissotto, 2001). However, more recent research suggests that the development of survey knowledge can happen earlier or in parallel with route knowledge (Kim & Bock, 2021; Montello, 1998; Ishikawa & Montello, 2006; Marchette et al., 2011; Iglói et al., 2010). Kim & Bock (2021) in a virtual wayfinding task examined the development of spatial knowledge in young adults. They observed a simultaneous gradual increase in landmark, route, and survey knowledge across the order of trials, which is completely against the LRS hierarchical development idea.

Individual differences such as age and visuo-spatial skills can affect survey and route knowledge learning of navigators (Wolbers & Hegarty, 2010). In a visual navigation study conducted by Ishikawa and Montello (2006), some navigators were able to acquire a correct survey knowledge of their surroundings after only one exposure to the environment, while others did so after ten, and some others required more time and gradually attained it over time. Their findings not only highlighted the importance of individual differences, but also showed that the development of survey knowledge can occur at the very beginning of route learning and does not adhere to the LRS staged learning theory. The experiment presented in chapter 2 of this thesis evaluates the development of survey and route knowledge in drivers. Furthermore, individual differences and the role they play in the navigation performance of drivers will be discussed in detail in sections 1.4 and 1.5 of the introduction and in Chapters 4 and 5.

1.1.1 Spatial Navigation in Animals

Spatial navigation is a fundamental activity for animals to survive, migrate, and locate nests or food sources. Application of the appropriate wayfinding strategies in animals is mainly associated with their nervous systems and the available resources in the environment. Path integration is a common wayfinding strategy in animals which benefits from resources like optic flow, proprioceptive, and vestibular cues (Collett & Collett, 2000; Thorup & Holland, 2009; Wehner et al. 2014). Another important source of navigational information for animals is geomagnetic cues. Some species, like migratory birds, lobsters, and sea turtles, detect the magnetic field of the earth and use it during migration and self-localization (Lohmann et al., 2007). Celestial cues like the sun, moon, polarized light, and stars can also assist animals to orient in space (Dacke et al., 2013). Certain species of birds, ants, and honeybees that have internal clocks can also benefit from celestial cues (Lohmann et al., 2007; Wiltschko & Wiltschko, 2003). Geometric cues like the shape of the environment are another useful source of navigational information for both humans and rodents (Hermer & Spelke, 1996). Furthermore, creating a survey knowledge of their surroundings by integrating simple cognitive maps is a sophisticated navigation skill seen in mammals, and some species of insects like ants and honeybees (Menzle, 2012; Cheesman et al, 2014).

The spatial ability of rodents has been mainly assessed using the Morris Water Maze (MWM), in which the location of a hidden platform (below the surface of the water) is signaled by two distal landmarks. Similar to the performance of humans in MWM (e.g., Moffat & Resnick, 2002; Driscoll et al., 2005) rodents by using self-motion cues, can develop an egocentric strategy to find the platform. Using the location of the distal landmarks, they are also able to develop an allocentric cognitive map of the area and orient themselves towards the platform (Gerlai et al., 2002; Moghaddam & Bures, 1996).

1.1.2 Neural basis of route and survey knowledge

Both humans and rodents mainly rely on the hippocampus for navigation by allocentric strategies (aka survey knowledge or cognitive maps), and on the caudate nucleus of the striatum for egocentric navigational strategies (aka route knowledge or landmarks) (Baumann et al., 2010; Hartley et al., 2003; Doeller et al., 2008; Iglói et al., 2010; Chang & Gold, 2003; McDonald & White, 1994; 2002).

Striatum is located in the basal ganglia in the forebrain and receives information from the cerebral cortex. The striatum includes the caudate nucleus, which is important for learning, memory, and executive functions. It has been shown that damage to the dorsal striatum in rats results in an inability to egocentrically perform a task (McDonald & White, 1994). The hippocampus is located in the temporal lobe and has direct connections with the prefrontal cortex. The hippocampal system is essential for episodic and spatial memory (Addis et al., 2011; Kim et al., 2015). Place cells of the hippocampus provide support for “map-like” representations of environments (O’Keefe and Nadel, 1978; Ekstrom et al., 2003). The para-hippocampal area is another crucial region for survey knowledge-based navigation, and studies have shown that this area is sensitive to landmark-based navigation as well (Epstein & Vass, 2014).

A fMRI study done by Igloi and colleagues (2010) on lateralizing hippocampal regions indicated that the left hippocampal region is correlated with allocentric spatial coding and survey knowledge, while the right hippocampal region is correlated with egocentric spatial coding and route knowledge. Studies on London taxi drivers have shown that the right hippocampal region of taxi drivers has enlarged over years of gaining spatial knowledge of a large-scale environment including landmarks, street names, and routes (Maguire et al., 2006). Later, other studies showed that the hippocampus can support retrieval of a highly familiar route (e.g., Brown et al., 2016). Retrieval of a route, specifically if it is dependent on contextual behavior, can involve episodic memory. In this case, it can be suggested that navigating sequences of a route can be controlled by the hippocampus. Overall, fMRI studies indicated a tendency of the hippocampus toward engaging in map-based over route-based navigation (Hartley et al., 2003; Iaria et al., 2003; Doeller et al., 2008).

Research has shown concurrent activities in parietal, striatal, and limbic regions of the brain during the application of the route and survey-based navigation strategies (Latini-Corazzini et al., 2010; Burgess et al., 2002; Poldrack and Packard, 2003). Concurrent activation of these areas indicates a cooperation between route and survey-based encoding strategies by the navigators. The neural correlates of landmark, route, and survey knowledge cannot be strictly assigned to specific brain regions. While some of the subcomponents involved in landmark, route, and survey knowledge have distinct neural correlates, each type of spatial knowledge, as itself, is not concentrated in a single brain region. Therefore, it is not surprising that multiple networks of brain regions could be active when a navigator executes a wayfinding task (Chrastil, 2012; Schinazi & Epstein, 2010; Mellet et al., 2010; Doeller et al., 2008; Hartley et al., 2003; Weniger et al., 2010).

For instance, Huntington's patients with specific caudate nucleus injury do not exhibit poor performance in a route-based wayfinding task, as they are able to compensate for it by having more activity in the hippocampus (Voermans et al., 2004). Navigators' familiarity with the environment may alter the neural correlates supporting route knowledge. A virtual wayfinding study done by Hartley et al. (2003) showed that traveling unfamiliar routes increases neural activity in the caudate nucleus, posterior parietal cortex, and parahippocampal cortex, whereas traveling the same route repeatedly increases the response only in the caudate nucleus. Accordingly, it is not possible to solely assign a specific brain region to the neural correlates involved in landmark, route, or survey knowledge. In the rest of the introduction, you will find a detailed description of the important internal and external factors that affect the wayfinding of drivers. Furthermore, in the following chapters, we delve deeper into each described factor through a scientific experiment.

1.2 Visual Cues and Navigation

Visual cues, such as landmarks, are critical and dominant cues for navigators, and can be defined from different points of view. Lynch (1960) referred to them as points of reference that are external, like buildings, mountains, or signs. Sigele and White (1975) later added that landmarks are a source of helpful information for route and survey knowledge-based navigation. In general, landmarks are salient features that are visual, auditory, or olfactory in nature, which can reinforce our mental representations of the spatial environment by enabling us to encode, recall, and describe our surroundings effectively (Montello 2017; Caduff & Timpf 2008; Lynch, 1960; Stack & Mallot, 2000).

The effectiveness of a landmark as a navigational cue depends on various features including visibility, familiarity, distinctive characteristics, stability, and the location of the landmarks (Gillner, et al, 2008; Steck & Mallot, 2000). Visibility from a distance, closeness to the road or intersection, and having visually distinctive features have been repeatedly found as relevant factors in studies that determine useful landmarks (e.g., Burnett, et al., 2001). For instance, landmarks located at decision points are more helpful to navigators in recalling routes than landmarks at non-decision points (Janzen, 2006). Virtual reality research has shown that familiar everyday landmarks can enhance navigation in contrast to abstract landmarks (e.g., a 3-D model of an everyday object like a car, clock, or mug vs. an abstract painting) (Ruddle et al., 1997).

Other research has focused on the role of the stability of landmarks, which is important for maintaining a reliable spatial representation. Not surprisingly, when landmarks at decision points are obscured, switched, or removed, the accuracy of navigators in route-based decision making decreases (Hurlebaus, et al., 2008; Iaria, et al., 2003; Mallot & Gillner 2000; Waller & Lippa 2007).

1.2.1 Types of Landmarks

The contribution of landmarks to different navigation strategies depends on the kind of landmark and the type of information they provide to navigators (O'Keefe & Nadel, 1978; Stack & Mallot, 2000; Lynch 1960). Visual, auditory, semantic, and olfactory landmarks can all be comparably suitable for enhancing spatial orientation. However, spatial cognition researchers put more weight on visual cues than others (Hamburger & Roser, 2014; Roser et al., 2011).

In terms of visibility, landmarks can be classified into two categories: proximal and distal. Distal (global) landmarks are visible from considerable distances and most often provide orientation information. Since their absolute positions do not change relative to the navigator's position in their local environment, they can provide stable relative positional information to the navigators (e.g., the North Star or the moon). Distal landmarks can also potentially provide local positional information when navigators are in close proximity to the landmarks (e.g., a water tower can be distal or proximal relative to the navigator's position) (Steck & Mallot, 2000; lynch, 1960; Buckley et al., 2015). In a virtual laboratory setting, the walls or periphery of a bounded navigation area can be used as a distal cue to provide directional information. Cylindrical walls of a test environment have been found to control thalamic head-direction cells in rats, which are usually active when distal landmarks are being used (Zugaro, et al., 2001).

In contrast, proximal (local) landmarks can only be seen from a short distance (e.g., a gas station) and most often provide precise local positional and route-based information to navigators (Buckley et al., 2015; lynch 1960; Steck & Mallot, 2000). While distal landmarks enhance the learning of the compass direction of a path, proximal landmarks enhance the learning of specific directions (Hurlebaus et al., 2008). Ruddle (2011) showed that the presence of proximal landmarks reduced the number of errors participants made when tracking and back-tracking a learned route. When we travel through an environment with proximal landmarks, our spatial view can differ largely even with small lateral and turning movements. As a result, in contrast to distal landmarks, proximal landmarks are more difficult to use to estimate distance and form a cognitive map of the environment (O'Keefe & Nadel, 1978; Save & Poucet, 2000). This has been observed by the failure of proximal landmarks, in contrast to distal landmarks, to trigger the firing of place cells in the hippocampus that are responsible for cognitive mapping (Cressant, et al., 1997).

Landmarks, especially proximal landmarks, can serve as associative cues to the turning directions that need to be taken by the navigator (Waller & Lippa, 2007; Chan, et al., 2012). A proximal landmark (e.g., gas station) located at a decision point can be considered an associative cue indicating a direction to take at the decision point (e.g., turning left at the gas station). Proximal landmarks can also be considered as beacon landmarks if they indicate accurate and reliable positional information for a single goal location (e.g., parking lot of a gas station: parking lot is the goal and the gas station is the landmark); Waller & Lippa, 2007). Research has shown that beacon-based navigation can develop in the early stages of navigation learning as it is a simplified goal localization strategy (Lee et al., 2006). Beacon-based navigation emerges fast as it requires less cognitive effort compared to other strategies. However, it results in transient spatial information and less accurate directional information (Waller & Lippa, 2007). Reliance of navigators on beacon-based navigation can overshadow the learning of the association between other cues and can result in a failure in the application of other navigational strategies like survey-based navigation (e.g., Chan, et al, 2012; Segula, 2017).

1.2.2 Benefits of Using Landmarks

When we navigate in a landmark-rich visual environment, we can use a landmark-based navigation strategy to accurately orient in space. In particular, landmarks are beneficial to recognize places, guide navigation, and provide spatial reference frames (Chan et al., 2012; Waller & Lippa, 2007; Hamburger & Roser, 2014). Research has shown that landmarks can enhance the learning process of finding the shortest path between two areas (Jansen-Osmann & Fuchs, 2006). Compared to an environment with no landmarks, the presence of either type of landmark (proximal or distal) improves navigational accuracy. Waller and Lippa (2007) observed that learning a route without landmarks was associated with poor route knowledge after five decision points when compared to learning a route in a landmark-rich environment. They found that without the support of landmarks, memorization of 5 or 6 route-based actions at the decision points (e.g., turning left or right) was possible for the navigators. However, the rest of the actions on the following decision points were based on guesses.

In navigation studies, proximal and distal landmarks appeared to have differential effects on the development of spatial representations of survey and route knowledge. Research has shown that proximal landmarks assist navigators in segmenting routes into a series of intermediate goals that eventually lead to a destination (Steck & Mallott, 2000; Ruddle et al., 2011; Hurlebaus et al., 2008). Proximal landmarks can enhance encoding of a traveled route and consequently reduce navigation errors when re-traveling the learned route (e.g., Ruddle et al., 2011; Jabbari et al., 2021). In contrast, the effective use of distal landmarks allows flexibility in navigational decisions. For example, if one understands their position in terms of compass headings like North and South, it is possible to navigate to a destination even when the learned route is not available. This suggests that distal landmarks are beneficial for building survey-based representations of an environment (Ruddle et al., 2011; Chan et al., 2012; Steck & Mallot, 2000; Jabbari et al., 2022).

1.2.3 Benefits of landmarks for Drivers

Landmarks play an important role in the wayfinding of drivers. Drivers' navigation strategies have been shown to be affected by the presence and type of landmarks (May et al., 2003; Burns, 1999). Landmarks can help drivers to focus on the road and increase their confidence and efficiency at wayfinding and decision-making (Tom & Denis, 2003; Burnett, 2000). Driver's wayfinding would be enhanced when good landmarks, in contrast to poor landmarks, are used to inform an upcoming action like a turn. Visibility, stability, distinctiveness, and location (closeness to a road or intersection) are characteristics of good landmarks (Green, et al, 1995; May & Ross, 2006). Taken together, these findings suggest that the use of landmarks facilitates spatial navigation and that the type of landmark determines our navigation strategy. In chapter 2, we assess the effect of different types of environmental landmarks on route and survey-based navigation of drivers. The effect of landmarks on navigation has been well studied, however, knowing how and to what extent these cues can enhance route memory while simultaneously driving still requires a systematic investigation.

1.2.4 Age Groups and the Use of Landmarks

Different age groups tend to use landmarks differently, as abilities related to assessment and encoding of environmental cues change throughout a person’s lifespan (Schuck et al., 2015; Driscoll et al., 2005). Navigation studies on children showed a predominant use of proximal cues at the expense of distal cues. Children at the age of 4 have difficulty locating a goal if it is signaled by spatial information from multiple visually indistinct landmarks; however, goal finding performance is improved if the goal is signaled by a unique local landmark (Lee et al., 2006). The tendency toward using distal landmarks develops approximately around the age of 5 (Laurance et al, 2003). The opposite trend is observed when people reach 60 years old and above, such that older people start to use proximal landmarks over distal (Moffat & Resnick, 2002; Driscoll et al., 2005).

Studies done using the Virtual Morris Water Task (VMWT), where a hidden platform's location is signaled by two distal landmarks, showed that learning of the spatial connection between the distal landmarks and the platform location was significantly hindered in older adults (60 years of age and over) than in young adults (aged 20–39) and middle-aged adults (age 40–59) (Driscoll et al., 2005; Moffat & Resnick, 2002). Accordingly, navigation by survey knowledge and tasks that require cognitive mapping are quite challenging for older adults. In chapter 5, we assess the application of route-based and survey-based navigation strategies in young and older adults in a driving task.

1.3 Self-Motion Cues and Navigation

Navigational success is influenced by spatial information we acquire from internal cues such as self-motion cues as well as external cues like environmental landmarks. It has been demonstrated that motion-related idiomatic cues, optic flow, and environmental cues improve the chances of successful and efficient navigation (Loomis et al., 1993; Gramann et al., 2005; Waller et al., 2004). Basically, there are various cues that contribute to the perception of motion. Self-motion cues comprise visual cues, such as optic flow, and idiothetic cues, such as vestibular cues, proprioceptive cues, and motor efference copies. Self-motion cues have multiple components to them, requiring the neural combination of visual, vestibular, and proprioceptive information, which are integrated to produce a single self-motion perception (Carriot et al., 2013).

Visual self-motion cues occur through optic flow, which produces a visual moving field as the retinal image changes while one moves through an environment. Optic flow provides a dynamic visual cue to humans through the perception of self-motion, which helps us to orient and find directions. Physical self-motion cues comprise idiothetic cues such as vestibular cues, proprioceptive cues, and motor efference copies that are mainly regulated by the vestibular and proprioceptive systems, which are responsible for representing one's self-motion and spatial orientation (Harris et al., 2000; Avraamides, et al., 2004).

Neurological studies have examined the important body and brain regions for motion, such as the otolith organs and semicircular canals in the inner ear, and how they impact navigation when they are damaged (Cullen, 2014). Prior animal studies have indicated that damage to the vestibular labyrinths, an important component of the vestibular system, results in a deficit in spatial memory tasks (Zheng et al., 2009). Similar findings have also been seen in human subjects. A study demonstrated that vestibular loss due to aging negatively impacted the ability of older adults to perform spatial navigation tasks (Xie et al., 2017).

In a study by Chance et al. (1998), navigators learned a virtual route using a head-mounted display in three testing conditions: a visual-only condition, a visual and vestibular condition involving translational and rotational body movements, and a visual and vestibular condition with only rotational body movement. The results showed that the group who learned the route by physically walking through the virtual route (translational & rotational movements) had the highest accuracy when asked later to point to the targets seen along the route. The group that received rotational movement at turns but translated through a joystick had the second highest level of accuracy, and the visual-only group had the lowest accuracy rate.

Vestibular organs and vestibular nucleus can also receive input from neck proprioceptors and motor-afferent signals (Medrea & Cullen 2013). Although it receives substantially less attention, the proprioceptive system is also thought to be essential for human spatial navigation. The proprioceptive system processes the body position in space and is preferentially activated during intentional muscle movements (Campos et al., 2014; Proske & Gandevia, 2012).

The proprioceptive system activates stretch receptors within joints and muscles during active bodily movement, potentially sending important signals to the navigation system. A study examined the ability to estimate the distance based on proprioceptive cues alone and when combined with visual input. Results indicated that individuals overestimated distance when they only had proprioceptive cues compared to visual-only, in which cases distance was underestimated. In contrast, the integrated condition had the highest accuracy (Campos et al., 2014). Research looking at proprioceptive cues is quite limited, and it is usually studied when combined with other cues.

In chapter 3, we assess the integration of external and internal cues during wayfinding. We discuss how vestibular cues might contribute to wayfinding by integrating with environmental cues like landmarks to enhance navigation. We assess whether the type of landmark influences this integration. Studying the integration of vestibular and visual cues in wayfinding while driving is a new contribution to the broad literature of spatial cognition and navigation.

1.4 Individual Differences & Navigation

Our spatial skills can be significantly affected by a range of individual factors like working memory capacity, mental rotation abilities, age, and gender (Lawton, 1994; Pazzaglia & De Beni, 2006). Individual differences play an important role in implementation of navigation strategies. It has been shown that there are systematic differences in navigation strategies of those with a higher spatial skill level (Garden et al., 2002). Studying these factors offers an insight into the nature of the cognitive processes and underlying mechanisms involved in spatial navigation.

Typically, higher skill navigators tend to apply survey-based navigation strategies like using cardinal directions and are flexible in switching from route-based to survey-based navigation when needed (Kato & Takeuchi, 2003). To build survey knowledge of an environment we require application of various cognitive and spatial skills. It is not surprising that individual differences contribute to performance when navigation requires multiple cognitive mechanisms like memory, perception, and multisensory processing. When navigational cues are limited, flexibility in implementing various strategies, as well as ability to use diverse types of navigational cues, would reduce the likelihood of getting lost in unfamiliar areas (Wolbers & Hegarty, 2010).

Our spatial abilities enable us to create, represent, and transform spatial information of objects or our surroundings. Individual differences in spatial abilities can be defined by the differences in object-based mental representations, and environment-based mental representations. Object-based mental representations involve mental rotation of objects with regards to the person or the environment. Environment-based mental representations involve mental manipulation of spatial reference frames with regards to the environment or features like landmarks (e.g., cognitive mapping) (Zacks et al., 2003).

Mental rotation test (MRT) is a typical spatial ability test that examines object-based mental representations and is broadly used to study individual differences in mental rotation skills. In this test, subjects are shown a 2D object on a paper or a screen and are asked to select a correct 3D rotated representation of the object from the provided options. MRT score can predict individual differences in navigation strategies (Malinowski, 2001). A lower MRT score is associated with more use of landmark and egocentric-based strategies, while a high MRT score is associated with higher use of allocentric-based strategies and better manipulation of spatial representations (Pazzaglia & Beni, 2006). A high MRT score is also related to fewer errors in the landmark pointing task (Castelli et al., 2008), and higher accuracy and confidence in deciding whether a route was the same or different to a previously learned route (Thoresen et. al., 2016).

One important underlying factor for individual differences in spatial skills is the role of working memory. Various spatial skills, like navigating in a new environment, demand the ability to hold and rehearse spatial information. Two important subcomponents of working memory are verbal working memory (VWM) and visual-spatial working memory (VSWM). Working memory processes, maintains, and manipulates verbal and numerical information (VWM) as well as images and spatial information (VSWM) (Baddeley, 2010).

VSWM comprises multiple cognitive components, and stores and rehearses visual and spatial aspects of an environment or a scene, including sequences of a navigated route. Spatial skills and VSWM are two closely related constructs. Individual differences in spatial skills can be dependent on how we store and process mental images in VSWM (Cornoldi & Vecchi, 2004). Neuroimaging studies have proposed similar brain activities for someone involved in a VSWM task and a spatial ability task such as the MRT discussed above (Levin et al., 2005).

In spite of the aforementioned references, there are inconsistent findings about the relationship between VWM and spatial abilities. Some studies claim that VWM does not play a significant role in spatial abilities either in environment-based spatial abilities like navigation (e.g., Gras et al., 2013) or object-based spatial abilities like mental rotation tests (Christie et al., 2013). However, some other studies indicate that VWM and VSWM can both predict mental rotation abilities (Pardo-Vazquez & Fernandez-Rey, 2012).

Our spatial skills can be significantly affected by our age and gender. Our navigation performance is at risk of declining with age, as there is an age-related tendency among older adults toward using route-based over survey-based navigation strategies. A route-based strategy is less cognitively demanding and does not require certain spatial skills like mental rotation. However, it is less flexible and does not allow navigators to have variations in their navigation (e.g., taking shortcuts) (e.g., Moffat & Resnick, 2002).

Gender plays an important role as an individual difference factor when it comes to navigation and spatial skills. In an fMRI study on gender differences and wayfinding in a virtual reality maze, Gron et al. (2000) found that the left side of the hippocampus, an area important for allocentric navigation and cognitive mapping, was activated mainly in men. In contrast, the right parietal and right prefrontal cortex, areas important for egocentric navigation and landmark based strategies, were activated mainly in women. Some studies show that men perform better in mental rotation tests than women (e.g., Hegarty et al., 2006; Levin et al., 2015). It has been observed that when performing mental rotation tasks, males show more activation in the left parahippocampal gyrus, right medial frontal gyrus, inferior parietal lobe, and inferior frontal gyrus. Wherase, females exclusively showed activation in the left parahippocampal gyrus. However, no sex differences were observed in performing VSWM tasks such as object location memory. Levin et al. (2015) found that both males and females activated common brain areas of the parahippocampal gyrus, middle temporal gyrus, inferior frontal gyrus, and medial frontal gyrus when performing the object location memory task.

Studying individual differences in spatial skills, especially in route learning, is of great importance not only for everyday navigation challenges that we face but also for occupations that demand wayfinding in high-risk situations like firefighters, military personnel, and paramedics (Baldwin & Reagan, 2009). In chapter 4, we discuss in detail various individual factors and spatial skills that can affect our navigation strategies while driving. The effect of individual factors on navigation skills has been studied by many researchers. However, how the combination of individual factors and spatial skills can affect a driver’s wayfinding skills still needs to be well investigated.

1.5 Aging and Navigation

Age-related deficiencies in various cognitive abilities like memory, attention span, spatial perception, and executive functions have been documented (Verhaeghe, et al., 2005; Iaria et al., 2009). Age-related changes differ among people, with some showing rapid loss of their mental capabilities while others only suffering from a minor reduction in their cognitive skills (Gazova et al., 2012). Spatial skills, like navigation, are similar to other cognitive processes in that they are susceptible to deterioration (Iaria et al., 2009). Age-related reduction in navigation skills has been documented in real and virtual environments (e.g., Newman & Kaszniak, 2000; Moffat & Resnick, 2002; Iaria et al., 2009) and both in normal and pathological aging, like Alzheimer's and MCI (e.g., Gazova et al., 2013; 2012; Iaria et al., 2009).

While some cognitive abilities dramatically decline with age, some function at their optimal capacity (Gazova et al., 2013). Research has shown that elderly adults consistently encounter impairments in survey-based navigation (allocentric) but not always in route-based navigation (egocentric) (Rodgers et al., 2012; Gazova et al., 201; Moffat & Resnick, 2002; Iaria et al., 2009). The two major navigation strategies, allocentric and egocentric, depend on particular brain structures (Iaria et al., 2003). Egocentric navigation is controlled by the parietal lobe, particularly the striatum (e.g., Rodgers et al., 2012). On the other hand, allocentric navigation is controlled by the medial temporal lobe structures, particularly the hippocampus and lateral prefrontal cortex (e.g., Moffat et al., 2006; Iaria et al., 2003). Neuroimaging studies showed an age-resistant increased level of gray matter activity in the caudate nucleus of the striatum when older adults perform an egocentric navigation task but revealed an age-related impaired performance of the hippocampus when older adults are engaged in an allocentric navigation task (Moffat et al., 2006; Antonova et al., 2009).

In a study by Harris and Wolbert (2014), young and old adults were trained on some paths to a target and then were asked to find shortcuts. They noticed that, in contrast to young adults, very few older adults transitioned from egocentric route finding to allocentric route finding to discover shortcuts. Schuck and colleagues (2013) asked young and older adults to discover an object's location within a spherical area where proximal landmarks were available. They noticed that while young adults used the spherical area's boundary to navigate, older adults used proximal landmarks to egocentrically find the location.

Other examples are about studies using a virtual Morris Water Maze task where young and older adults had to find a hidden platform in a virtual environment with the help of distal landmarks. Among the two age groups, older adults had difficulty in creating a cognitive map of the environment using the connectivity between the distal landmarks and the platform's location (Driscoll, et al, 2005). Compared to young adults, older adults faced some challenges in finding the hidden platform even on the first trial, where both age groups had no prior knowledge of the platform's location (Moffat & Resnick, 2002). Older adults traveled longer and more complicated routes to find the platform and made more errors in choosing a correct heading direction (Moffat & Resnick 2002; Driscoll et al., 2005; Daugherty et al., 2015).

Age-related impairments in the performance of the prefrontal cortex results in a reduction in executive functions of older adults which is associated with certain deficits in navigation performance like making slower reactions to stimuli in both virtual and real world navigation tasks (e.g., Driscoll et al., 2005; Zhong et al., 2017; Taillade et al., 2013a; 2013b). In Chapter 5, we compared the navigation skills of drivers of various age groups by evaluating their performance in using route and survey based strategies. Effect of age on spatial representation has been well studied using spatial memory tasks or virtual desktop mazes (e.g., Fernandez-Baizan et al., 2019; Ruggiero et al., 2016; Head & Isam, 2010; Moffat et al., 2001). However, this matter still needs to be tested in a more ecologically valid setting.

1.6 Navigation, Driving & Mood disorders

Driving is a common daily activity for many of us, and navigating is an integral component of driving. We usually drive with the intention of reaching one or multiple destinations along our way, and so proper navigation and situational awareness can decrease unsafe driving behavior like sudden turns (Dahmani & Bohbot, 2020). In recent years due to the advent of accessible GPS navigation systems in cars and smartphones, reliance on GPS systems for navigation in unfamiliar environments has increased. Undoubtedly, GPS has significant benefits for drivers. It provides us with traffic information, alternative route options, and can decrease the chance of getting lost. However, not everyone has access to car built-in GPS systems, and phones do not always have the proper signal to run GPS. More importantly, GPS provides us with impoverished navigational information about our surroundings, and long-term outsourcing of our spatial abilities to GPS systems has been shown to result in a decline in our wayfinding abilities (Modsching et al., 2006; Ishikawa et al., 2008; Fajnerova et al., 2018; Hejtmánek et al., 2018). Long-term GPS use has been associated with poor spatial skills, including deficient geospatial awareness and vigilance, decreased mental rotation and perspective-taking abilities in novel environments, and errors in distance estimation (Dahmani & Bohbot, 2020; Ruginski et al., 2019; Ishikawa et al., 2008).

An important question worth answering would be how much we pay attention to our surroundings when we drive down a route with the help of GPS. If we are going to drive that route again without GPS, would we be able to retrace the route accurately? Relying on GPS instructions, even though it facilitates navigation while driving, results in a poor spatial encoding of the environment because it makes us less attentive to the surrounding environmental cues (Gardony et al., 2015; Münzer et al., 2006; Dahmani & Bohbot, 2020). GPS instructions reinforce route based rather than survey based navigation. A driver who follows GPS instructions encodes only certain navigational responses, like turning left or right at a specific intersection, rather than allocentric relations between environmental cues (Dahmani & Bohbot, 2020; Münzer et al., 2006).

As mentioned earlier in this chapter, the hippocampus plays an important role in our spatial abilities. Mental health disorders can significantly impair the functionality of the hippocampus and, consequently, our spatial skills. Prior research has shown that depression is associated with a decrease in hippocampus volume (Hickie et al., 2005; MacMaster & Kusumakar, 2004; Videbech & Ravnkilde, 2004). In a study done by Cornwell et al. (2010), participants with major depression disorder underperformed non-depressed participants in navigating to the hidden platform of the virtual Morris Water Maze task. Less engaged right anterior hippocampus and parahippocampal cortices were observed among depressed participants during navigation relative to the non-depressed participants, which may indicate a non-optimized encoding of the hidden platform's location in the depressed individual.

Similarly, stress and anxiety are other important mental health disorders that can significantly affect our spatial abilities by disrupting the performance of the hippocampus (Brown et al., 2020). Mueller et al. (2009) showed that children with anxiety disorders had a lower accuracy rate and made more heading direction errors in the virtual Morris Water Maze task. Stress can significantly affect the encoding and retrieval processes of the information in memory. When we are under stress, we have a tendency to choose simple memory procedures that are usually caudate nucleus dependent (aka stimulus-response procedures) to guide our behavior (Schwabe et al., 2008; Schwabe & Wolf, 2013). Gardony et al. (2011) showed that during an induced arousal state, participants were less likely to use distal cues and configure the allocentric relationships between cues compared to proximal cues and configure simple stimulus-response strategies. The reason is the less engaged hippocampus in the retrieval of the high-demand memory procedures (e.g., allocentric relationships between the cues) due to the release of the stress hormones (Schwabe & Wolf, 2013; Oei et al., 2007).

To the best of our knowledge, there has been little to no research done on the effects of mental health disorders and GPS use on wayfinding skills (Dahmani & Bohobot, 2020). In Chapter 6, we provide results of an online survey investigating the relationship between mental health disorders, including depression, anxiety, and stress, on navigation skills, as well as GPS dependence and overreliance. This chapter also presents an online study on the effect of landmark-based GPS instructions on route and survey knowledge.

1.7 Summary

To summarize, the results of the studies presented in this thesis have important implications not only for the spatial cognition literature but also for the real-world challenges of wayfinding while driving a vehicle. Navigating and driving are both cognitively demanding tasks requiring the application of a variety of cognitive, visual, perceptual, attentional and physical processes (Foo et al., 2005; Ruddle & Lessels, 2006; Ekstrom, 2015). Using desktop virtual reality to assess navigation skills is less ecologically valid due to a lack of visual complexity and self-motion information. However, in the studies presented in chapters 2 to 5 (chapter 6 is an online study), participants experienced more ecologically valid situations by navigating in various virtual towns simulated in an immersive motion simulator which enabled them to drive and navigate while receiving self-motion information.

The major objective of this thesis is to evaluate both internal (e.g., self-motion cues and visual spatial skills) and external (e.g., landmark cues) factors that would impact drivers' spatial navigation. Identifying beneficial environmental resources for drivers, like landmark cues or useful spatial skills that could enhance the wayfinding of drivers, are some of the goals of this thesis.

In Chapter 2, we identify beneficial landmark cues for route learning and cognitive mapping of drivers. In Chapter 3, we examine whether physical self-motion cues (e.g. vestibular) are useful for route learning and whether they can be combined with landmark cues to improve drivers' route learning abilities. In Chapter 4, we assess individual factors at a visual-spatial level that can correlate with drivers' navigation strategies and the use of navigational cues. In Chapter 5, we study an important individual factor in more detail. We study the association of age with route learning and cognitive mapping in drivers. Finally, in Chapter 6, we present two online experiments. The first experiment is a survey study on the relationship of mental health factors (anxiety, depression, and stress) with wayfinding skills and GPS dependency. The second experiment assessed the same participants as the first experiment to examine the potential effect of incorporating landmarks into GPS instruction on route learning and cognitive mapping. The possible relationship between mental health factors and navigation performance of the participants was also assessed.

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CHAPTER 2: Testing Landmark-Specific Effects on Route Navigation in an Ecologically Valid Setting: a Simulated Driving Study

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Preface

Chapter 2 presents the results of an experiment in which the effect of environmental cues like landmarks on route learning of drivers was examined. In the experiment presented in this chapter, participants actively drove in a virtual town looking for a target destination. In the first step (Training phase), participants were guided through some routes that led to the destination in various conditions where different landmarks were present (proximal (local objects) &/or distal (distant objects)). Participants' memory for the routes was tested later in finding the target. In the second step (Transfer phase), participants navigated in the same environment through some different routes leading to the target, but without any landmarks, and their route memory was tested again. The training phase showed that, in contrast to distal landmarks, proximal landmarks were the most useful landmarks for drivers to learn the routes. While the transfer phase showed that learning routes using distal landmarks' navigational information was most helpful for drivers to find their way to the destination when there were no landmarks in the environment. The results of this experiment showed that drivers' navigation success is highly affected by the type of available environmental landmarks.

Abstract

We used a driving simulator to investigate landmark-based route navigation in young adults. Previous research has examined how proximal and distal landmarks influence route navigation; however, these effects have not been extensively tested in ecologically-relevant settings. We used a virtual town in which participants learned various routes while simultaneously driving. We first examined the effect of four different landmark conditions on navigation performance, such that each driver experienced one of four versions of the town with either proximal landmarks only, distal landmarks only, both proximal and distal landmarks, or no landmarks. Drivers were given real-time navigation directions along a route to a target destination and were then tested on their ability to navigate to the same destination without directions. We found that the presence of proximal landmarks significantly improved route navigation. We then examined the effect of prior exposure to proximal vs. distal landmarks by testing the same drivers in the same environment they previously encountered, but with the landmarks removed. In this case, we found that prior exposure to distal landmarks significantly improved route navigation. The present results are in line with existing research on route navigation and landmarks, suggesting that these findings can be extended to ecologically-relevant settings.

Significance Statement

During wayfinding and navigation, landmarks influence our spatial encoding and representation of the environment. Real world navigation is often paired with complex body coordination tasks such as walking or driving rather than simple keyboard or joystick movements. In this study, we assessed whether existing route-based navigation findings extend to ecologically-relevant settings by combining navigation and driving in an immersive driving simulator. Our results suggest that guided navigation while driving (e.g., GPS systems) may be facilitated differentially by proximal vs. distal landmarks. Route navigation was facilitated when the initial guided navigation was in the presence of proximal landmarks, suggesting proximal landmarks may be more specifically associated with navigation decisions. When tested in an environment without any landmarks, prior exposure to distal landmarks in that same environment improved navigation, suggesting that distal landmarks may facilitate orientation knowledge of the space. This work may be important for designing GPS navigation systems that improve navigation by taking advantage of spatial memory.

Introduction

As we move through a spatial environment, information about our relative position is updated. Humans are flexible navigators, actively changing navigation strategies depending on the available information such as external landmark cues in the environment (Caduff & Timpf, 2008; De Condappa, 2016; Foo et al., 2005; Siegel & White, 1975; for a review, see Montello, 2005). Landmarks can be categorized as either proximal or distal (Caduff & Timpf, 2008; Chan et al., 2012; Cohen & Schuepfer, 1980; Jansen-Osmann, 2002; Stankiewicz & Kalia, 2007; Steck & Mallot, 2000). Proximal landmarks are visible from a short distance and can provide local positional information (Chan et al., 2012; Steck & Mallot, 2000; Wilson & Alexander, 2008), whereas distal landmarks are visible from far distances (e.g., the moon or a city tower) and can facilitate acquisition of map-like orientation information (Hamilton et al., 2002; Jacobs et al., 1997; Steck & Mallot, 2000).

Landmarks are important for the generation and application of two qualitatively different types of spatial knowledge: survey and route knowledge (Evans et al., 1984; Jansen-Osmann & Fuchs, 2006; Montello, 2005; O'Laughlin & Brubaker, 1998; Waller & Lippa, 2007; Wiener et al., 2009). Survey knowledge is based on cognitive maps, which are mental representations of the environment that reflect the spatial configuration of landmarks relative to one another (O'Keefe & Nadel, 1978; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982; Tolman, 1948; Zimmer, 2004). Some work has shown that distal landmarks best support survey knowledge because they provide global orientation information about the environment (De Condappa, 2016; Hamilton et al., 2002; Jacobs et al., 1997; Livingstone-Lee et al., 2011; Mueller et al., 2008).

In contrast, route knowledge is a relatively basic navigation strategy that requires knowledge of a particular sequence of landmarks and turn decisions (Andersen et al., 2012; Daniel et al., 2003; Hartley et al., 2003; Klatzky, 1998; Siegel & White, 1975; Waller & Lippa, 2007). Proximal landmarks support route knowledge by providing intermediate goals along the route (Hurlebaus et al., 2008; Ruddle et al., 2011; Steck & Mallot, 2000). Successful navigation using route knowledge does not require survey knowledge, and tends to be less cognitively demanding but also less flexible than survey knowledge due to reliance on the *sequence* of decisions (e.g. Chan et al., 2012; De Condappa, 2016; Hartley et al., 2003; Knierim & Hamilton, 2011; Steck & Mallot, 2000; Wilson & Alexander, 2008). Moreover, the utility of proximal landmarks is limited to a local spatial area, and the view of that space changes with the viewpoint. Accordingly, using proximal landmarks to obtain allocentric information for locating a target is challenging (Benhamou & Poucet, 1998; Knierim & Hamilton, 2011; O'Keefe & Nadel, 1978; Save & Poucet, 2000).

Many navigation studies assessing route navigation used basic paradigms in which cognitive load was limited to the navigation task itself (Andersen et al., 2012; Bakdash et al., 2008; Carassa et al., 2002; Gardony et al., 2011; Hurlebaus et al., 2008; Janzen & Turennout, 2004; Knorr et al., 2014; Péruch et al., 1995; Stankiewicz & Kalia, 2007; Viaud-Delmon & Warusfel, 2014; Wallet et al., 2011). These studies were tightly controlled and provided internal validity, but we seek to extrapolate the findings to navigation in the real world. Studies that require active driving or walking while navigating in a real environment inevitably involve various confounding actions, but include sensory cues that are not available in a more limited environment, such as cues to production and detection of self-motion (Whishaw & Wallace, 2003; Poucet & Save, 2017; Lin et al., 2016; for a review see Chrastil & Warren, 2012). Moreover, actively driving and navigating associates actions with the relative spatial relations that link landmarks, routes, and allocentric directions (Appleyard, 1970; Chrastil & Warren, 2012; Duncan, 1984; Maguire et al., 2000, 2006). An immersive virtual environment can provide a more controlled and stable experimental design while bridging behaviour in the laboratory with behaviour in the real world (Appleyard, 1970; Chrastil & Warren, 2012; Farrell et al., 2003).

A more realistic driving scenario that incorporates simultaneous navigation and driving may present a more demanding situation for drivers, and this may interact with navigation strategies that are cognitively demanding, such as the use of distal landmarks for allocentric navigation (De Condappa, 2016; Waller & Lippa, 2007). Drivers may tend to be reliant on global positioning systems (GPS) for their navigation, and it has been recognized that outsourcing spatial cognition processing (Clark, 2017; Foglia, & Wilson, 2013; Gračanin, 2018; Hollan et al., 2000; Soler et al., 2017; Wilson, 2002) may result in significantly poorer spatial memory for locations (Hejtmánek et al., 2018; Ishikawa et al., 2008; Leshed et al., 2008; Münzer et al., 2006; Willis et al., 2009). Therefore, understanding how landmarks influence real-time route navigation in drivers is an important first step to understanding how the existing navigation literature extends to route navigation in the real world.

In the present study we used a driving simulator to simulate a realistic navigation environment. The first goal of our study was to examine the effect of proximal and distal landmarks on route navigation. The second goal was to examine the contribution of prior exposure to proximal and distal landmarks by assessing route navigation in that same environment without landmarks. Our hypotheses were that (1) route navigation would be sensitive to type of landmark, and that (2) route navigation in the absence of landmarks would be sensitive to prior experience with different types of landmarks in that same environment.

2. Method

2.1 Participants

We recruited 128 participants (55 females) between the ages of 18 to 31 years old (M = 19.21, SD = 2.48). These were graduate students who participated as volunteers and undergraduate students who participated for course credit. Participants were screened based on self-reports to have no vision or hearing problems and no sensitivity to cyber sickness or claustrophobia. Self-report questionnaires also estimated familiarity with computers and computerized and virtual games. Participants were randomly assigned to one of four groups (32 per group). Six participants were removed due to technical issues. Each group received a different type of landmark during the training block: combined (proximal and distal) (PD, $n = 30$), distal (D, $n = 31$), proximal (P, $n = 30$), or no landmarks (N, $n = 31$). The experiment was approved by the Hamilton Health Research Ethics Board and complied with the Canadian Tri-Council policy on ethics.

2.2 Experimental Setup

Visual stimuli were presented on three 42″ (diagonal) LCD panels, each with a resolution of 1920 × 1080 pixels, running at a 60 Hz refresh rate. The LCD panels were set up in an enclosed environment and aligned in an arc to provide a wide field of view (FOV) of 35° vertically and 120° horizontally (Figure 1). A wide FOV provides a higher viewer capacity that is more akin to driving in a real environment by increasing perception of the self-motion cues in the periphery as participants move through space and make head turn movements (e.g., Mizell et al., 2002; Narayan et al., 2005; Pausch et al., 1997;

Starkweather, 2003). Research has shown that using wide FOV displays is beneficial for navigation performance (e.g., Patrick et al., 2000; Tan et al., 2006; Tyndiuk et al., 2007).

Figure 1: Driving simulator from the participant's view as they completed the guided navigation phase of the combined landmark group (PD group). Participants controlled their vehicle with a steering wheel, gas, and brake pedals. The small screens on the left and right of the steering wheel were not used in this experiment. In this example, a tall radar tower at the edge of the town (distal landmark), and a colorful house at the upcoming intersection (proximal landmark) are visible to the driver. A white/green navigation arrow briefly presented at the bottom of the central screen indicates a left turn at the next intersection.

Participants sat in a bucket car seat positioned to maintain an approximate distance of 120 cm between the participants' eyes and the central LCD screen. The driving interface consisted of a Logitech steering wheel and gas and brake pedals (Logitech International S.A., Lausanne, Switzerland). There were two cameras inside the simulator pod for experimenter monitoring purposes; one provided a front view of the participant, and the other provided a bird's eye view of the interior. An intercom system allowed communication between the participant and the experimenter. Data from the steering wheel and pedals were continuously recorded at a sampling rate of 60 Hz.

2.3 Virtual Environment

The dynamic visual simulation of the town was coded in C++ using the Vega Prime (Presagis) library. The small virtual town consisted of a 3 × 3 grid of city blocks defined by a

4 × 4 grid of roads (Figure 2). The target destination was a dead-end at the center of the town. All conditions included visually-similar generic buildings throughout the town (see Figure 1), except for the landmarks which were distinctive. There were two types of landmarks: 4 proximal landmarks and 4 distal landmarks. Proximal landmarks were 3D renderings of a church, a store, a house, and a gas station. Proximal landmarks were located on corner lots at central intersections and were visually obstructed by the surrounding generic buildings so that they were only visible from nearby locations and could not be used as distal landmarks.

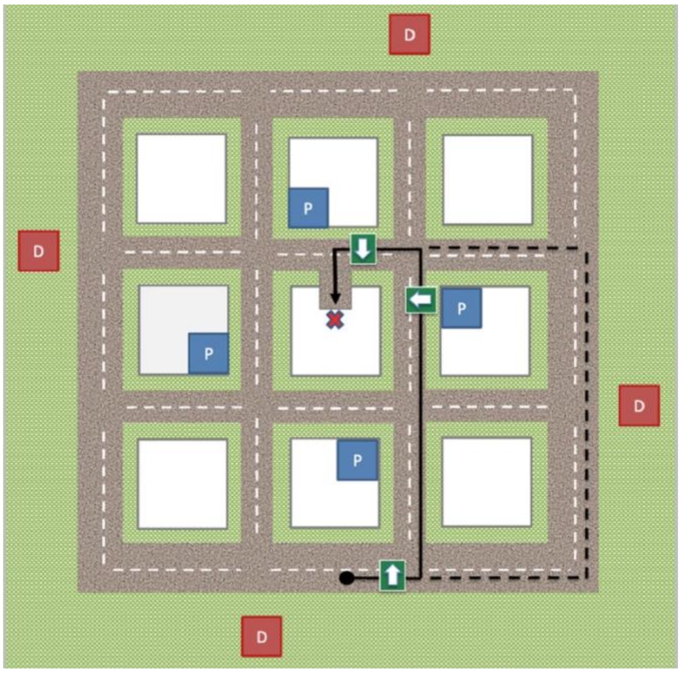

Figure 2 : Bird's eye view of the virtual town in the same condition (not shown to the participant). The red "D" squares indicate locations of distal landmarks, and the blue "P" squares indicate locations of proximal landmarks. An example training route is denoted with a black solid line from start position (black circle) to target location (red X). The arrows indicate the approximate point at which the white/green navigation arrows appear as the driver approaches the intersection during the guided navigation phase. The dashed black line is an example of an alternate route the driver might take during the testing phase if they failed to follow the trained route (learned in the guided navigation phase) but successfully reached the target location (e.g., partial route retracing)

Distal landmarks were 3D renderings of a radar tower, a control tower, a water tower, and a wind tower, located beyond the outer boundaries of the town and tall enough to be visible from most locations in the town when facing in the right direction. In experimental conditions in which the proximal and distal landmarks were not present, the visually-similar generic buildings and the surrounding roads looked similar from each of the internal intersections of the town. Without the distal landmarks, the town's edges were not differentiable from each other and due to the render distance were visible to navigators only when they were driving on a road close to the edge. Although there is an illusion of simplicity when looking at the top-down view of the town in Figure 2 (top-down view was not provided to participants), navigation was challenging enough to elicit strong individual variation in route-navigation performance.

2.4 Procedure

A demographic questionnaire collected self-report data including gender and average daily hours of driving, playing video/computerized games, and computer use outside of games. Participants practiced driving in the simulator (e.g., making left and right turns, accelerating and braking) until they were comfortable with the operation of the steering wheel, pedals, and immersive visual environment.

The experimental design consisted of 2 blocks (a Training block followed by a Transfer block), 2 phases per block (a Guided Navigation phase followed by a Testing phase), and 4 navigation trials per phase. Participants were randomly assigned to 1 of 4 groups defined by the type of landmarks presented in the Training block: both proximal and distal landmarks combined (PD), proximal landmarks only (P), distal landmarks only (D), or no landmarks (N). Importantly, landmarks were present during the Guided Navigation and Testing phases of the Training block only.

Training block: In the Guided Navigation phase of the Training block, participants were guided along 4 different routes. Each route had a different starting point, traversed four intersections (4 decision points), and terminated at the target destination (dead-end road in the center of town). Navigation at each intersection was guided by a left, right, or forward arrow displayed at the bottom of the screen as the car approached the intersection. In the Testing phase, the same 4 routes were tested in the same order, but this time without the guided-navigation arrows. For each route, the car was placed at the same starting point as the guided navigation phase. Participants were instructed to drive to the target destination by retracing the learned route exactly. However, if they took a wrong turn or were unable to remember the exact route, they should try to reach the target destination via an alternate route. There was a 90 s time limit after which the trial terminated even if the participant failed to reach the target destination.

Transfer block: The procedure in the Guided Navigation and Testing phases was the same as in the Training block, except for two differences: (1) there were no landmarks present for any of the 4 landmark groups, and (2) a different set of 4 routes were used for all 4 landmark groups.

The Training and Transfer blocks were each about 10 min in duration and participants were offered a short break (2–4 min) after the Training block. The entire experiment was about 45 min in duration, including informed consent, the demographic questionnaire, driving practice, instructions, the two experimental blocks, and final debriefing which clarified the design and purpose of the experiment.

3. Results

3.1 Data Analysis

We assessed route navigation performance in the testing phase of each Training and Transfer block by evaluating two dependent variables: success and route retracing.

Success: Success was the percentage of trials for which the target destination was found before the 90 s time limit. There were 4 trials (routes) in each testing phase, and the outcome of each trial was either a success or fail, thus success rate was treated as a binomial variable.

Route retracing: In the testing phase, participants were instructed to find the target destination by retracing the corresponding routes from the guided navigation phase, however they were permitted to take alternate routes. Route retracing included all success and failure trials to capture memory for the learned route. The route retracing score was calculated as a percentage of the length of the route taken in the testing phase that overlapped with the route taken in the guided navigation phase (see Figure 2). A route retracing score of 100% would indicate that the route taken in the testing phase overlapped the entire length of the guided navigation route.

Generalized linear mixed model (GLMM): Our models included two independent fixed variables of Landmark Group (PD, P, D, & N) and Block (training & transfer). The Trial Order variable was analyzed as both fixed (Trial Order) and random (Trial Order x participants). Treating Trial Order as a fixed effect accounted for overall learning effects; treating Trial Order as a random slope across participants accounted for individual differences in learning rates. Since the dependent variable success (S) was a binomial variable (success or failure), we used a logit link function to create a logistic regression model, by applying a generalized linear mixed model (GLMM) (Agresti, 2015; Dunteman & Ho, 2006). In the regression summary, the first category is used as a reference category. Which category is selected as the reference does not affect the results, it only determines the specific comparisons that the model reports. We selected PD (training block) as the reference category. We hypothesized that due to the availability of both types of landmarks, this group would have the highest level of predicted value (success). Thus, using PD as the reference category against which the other landmark conditions are compared is an intuitive way to interpret the output of the model.

The four questionnaire variables were gender, average daily gaming computer hours, average daily non-gaming computer hours, and average daily driving hours. Of the questionnaire variables, only computer hours predicted success ($z = 2.227$, $p = 0.026$), and none predicted route retracing. Final models excluded these non-significant questionnaire predictor variables (see Wilkinson notation below). The estimate (β) of each term in the logistic regression model is the log-odds ratio between the term and the reference category. The odds ratio (OR) is equal to exp (β) and describes the ratio of the likelihood of success between the two categories. Since route retracing was a continuous variable, it was modelled with a linear mixed model (LMM) with the same independent variables. In Wilkinson notation (Wilkinson & Rogers, 1973) the models are as follows:

Success (S):

S ~ landmark group * block + trial + computer hrs + (0 + trial | participants)

Success learning effect:

S ~ landmark group * trial + computer hrs + (0 + trial | participants)

Route Retracing (RR):

RR ~ landmark group * block + trial + (1 + trial | participants)

Route retracing learning effect:

RR ~ landmark group * trial + (1 + trial | participants)

3.2 Success

The statistical results of the generalized linear mixed model are reported in Table 1. In the training block, both the D group ($\beta = -1.370$, $z = -4.117$, $p < 0.001$) and the N group ($\beta = -0.838$, $z = -2.495$; $p = 0.0125$) were less successful in finding the target location compared to the PD group. Success of the P group did not differ from the PD group ($p = 0.714$). Significant interactions revealed that the success in PD across training and transfer blocks differed from those of D ($\beta = 2.413$, $z = 4.843$, $p < 0.001$) and from N ($\beta = 1.490$, $z = 3.125$, $p = 0.0017$). No significant interaction was observed for the P group ($p = 0.799$) (Figure 3 and Table 1).

Table 1: Results of the generalized linear mixed model with success modelled by Landmark group and Block. Asterisks "***", "**", and "*" denote $p < .001$, $p < .01$, $p < .05$, respectively.

Landmark*Block	**Estimate (β)**	**SE**	**OR**	**CI (95%)**		***z* value**	**Pr(>|z|)**
PD, Training Block (reference)	2.805	0.414	16.52	2.01	3.64	6.770	< .001***
P, Training Block	0.138	0.378	1.15	-0.60	0.89	0.366	0.714
D, Training Block	-1.370	0.332	0.25	-2.04	-0.73	-4.117	< .001***
N, Training Block	-0.838	0.336	0.43	-1.51	-0.19	-2.495	0.0125*
Transfer Block	0.254	0.443	1.29	-0.62	1.12	0.573	0.566
Trial Order	-0.261	0.074	0.77	-0.41	-0.12	-3.51	< .001***
P, Transfer Block	0.127	0.498	1.14	-0.85	1.11	0.254	0.799
D, Transfer Block	2.413	0.498	11.17	1.46	3.42	4.843	< .001***
N, Transfer Block	1.490	0.477	4.43	0.57	2.44	3.125	0.0017 **

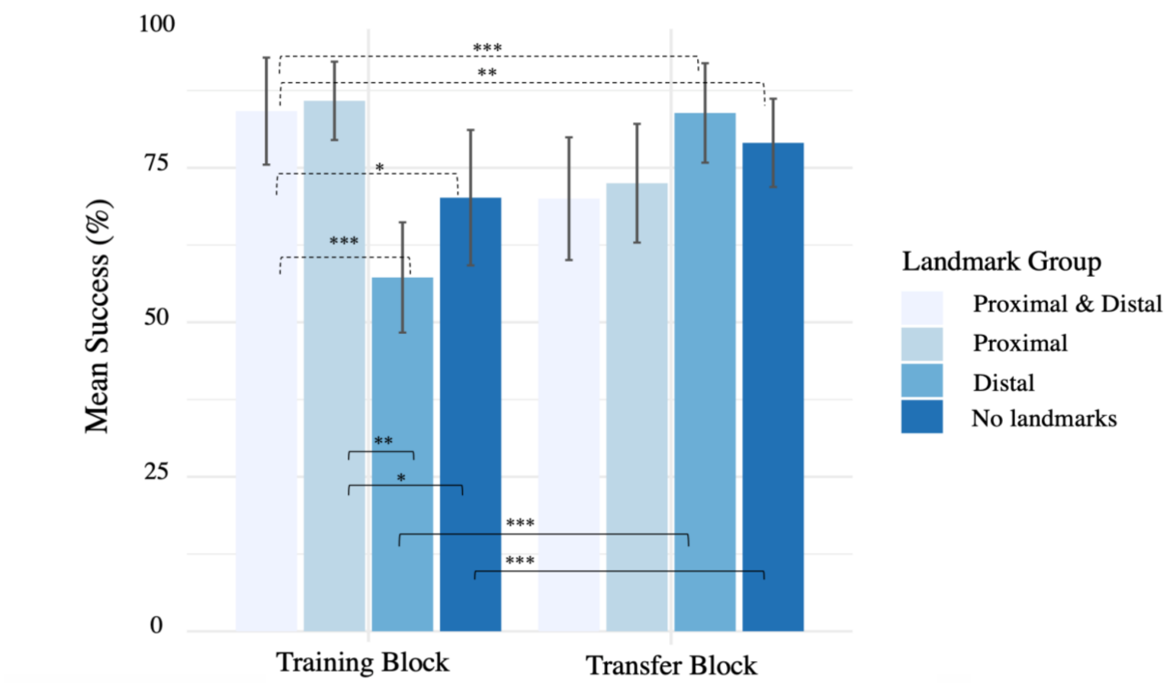

Figure 3: Success for each Landmark group and Block. Error bars are 95% confidence intervals. Black dashed lines indicate significant model interactions and black solid lines indicate significant pairwise comparisons. Asterisks "***", "**", and "*" denote $p < .001$, $p < .01$, $p < .05$, respectively.

Pairwise comparisons with Tukey adjustments were used to test the difference in success between the training and transfer block of each group (a repeated-measures comparison). Success in the D group was significantly lower in the training block compared with the transfer block (Training: M = 0.572, SE = 0.044 vs Transfer: M = 0.838, SE = 0.033; $\beta = -2.667$, $z = -5.656$, $p \leq 0.0001$). Similarly, success in the N group was lower in the training block (Training: M = 0.701, SE = 0.041 vs Transfer: M = 0.790, SE = 0.036; $\beta = -1.744$, $z = -3.938$, $p \leq 0.0001$). No significant difference was observed between the training and transfer block for the P group (Training: M = 0.858, SE = 0.031 vs Transfer: M = 0.725, SE = 0.040; $\beta = -0.380$, $z = -0.830$, $p = 0.407$) or for the PD group (Training: M = 0.841, SE = 0.033 vs Transfer: M = 0.700, SE = 0.042; $\beta = -0.254$, $z = -0.573$, $p = 0.567$).

Additional pairwise comparisons assessing the success difference between groups within each block showed that, in the training block, success of the P group was significantly higher than the D group ($\beta = 1.509$, $z = 4.399$, $p = 0.001$) and the N group ($\beta = 0.977$, $z = 2.823$, $p = 0.024$). There were no other significant pairwise comparisons between the non-referenced groups. Overall, these results suggested that prior exposure to distal landmarks or no landmarks may have facilitated later route navigation in the same environment when no landmarks were present.

3.2.1 Success learning effect

There was a significant effect of Trial Order on success ($\beta = -0.261$, $z = -3.51$, $p < 0.001$), such that success improved over time. We analyzed interactions between Landmark groups and Trial Order to see if the learning effect differed across groups. We observed a significant interaction of the learning effect for success in the D group ($\beta = 0.360$, $z = 3.493$, $p \leq 0.001$) as well as the N group ($\beta = 0.207$, $z = 2{,}040$, $p = 0.041$) compared to the PD group, suggesting a positive learning effect across trials for these two groups. We did not observe a significant interaction for the P group ($\beta = -0.075$, $z = -0.683$, $p = 0.494$).

3.3 Route retracing

Results of the linear mixed model for Route Retracing are reported in Table 2. In general, route retracing scores had a strong positive correlation with success ($r = 0.619$, $p < 0.001$). Marginal mean route retracing scores (percent) of successful trials in both training and transfer blocks was high (M = 79.3, SE = 0.96) compared to failed trials (M = 31.7, SE = 1.68).

Table 2: Results of the linear mixed model with route retracing modelled by Landmark group (PD, P, D & N) and Block (Training & Transfer). Asterisks "***", "**", and "*" denote $p < .001$, $p < .01$, $p < .05$, respectively.

Block*Landmark	**Estimate (β)**	**SE**	**CI (95%)**		***t* value**	**Pr(>|t|)**
PD, Training Block (Intercept)	82.944	4.220	74.66	91.23	19.653	<0.001***
P, Training Block	9.886	4.969	0.05	19.73	1.990	0.049*
D, Training Block	-8.091	4.929	-17.85	1.67	-1.642	0.103
N, Training Block	-2.768	4.929	-12.53	6.99	-0.562	0.576
Transfer Block	14.208	5.392	3.63	24.79	2.635	0.009**
Trial Order	-5.518	0.886	-7.26	-3.78	-6.229	<0.001***
P, Transfer Block	-7.340	6.073	-19.26	4.58	-1.209	0.227
D, Transfer Block	16.585	6.024	4.76	28.41	2.753	0.006**
N, Transfer Block	11.341	6.024	-0.48	23.16	1.883	0.060

The P group had significantly higher route retracing scores than the PD group ($\beta = 9.886$, $t = 1.990$, $p = 0.049$). Route retracing scores in the D group ($p = 0.103$) and the N group ($p = 0.576$) did not differ from the PD group. A significant interaction revealed that the route retracing in PD across training and transfer blocks differed from those of D ($\beta = 16.585$, $t = 2.753$, $p = 0.006$) (Figure 4). There was no significant interaction for the N group ($p = 0.060$) or the P group ($p = 0.227$) (Table 2).

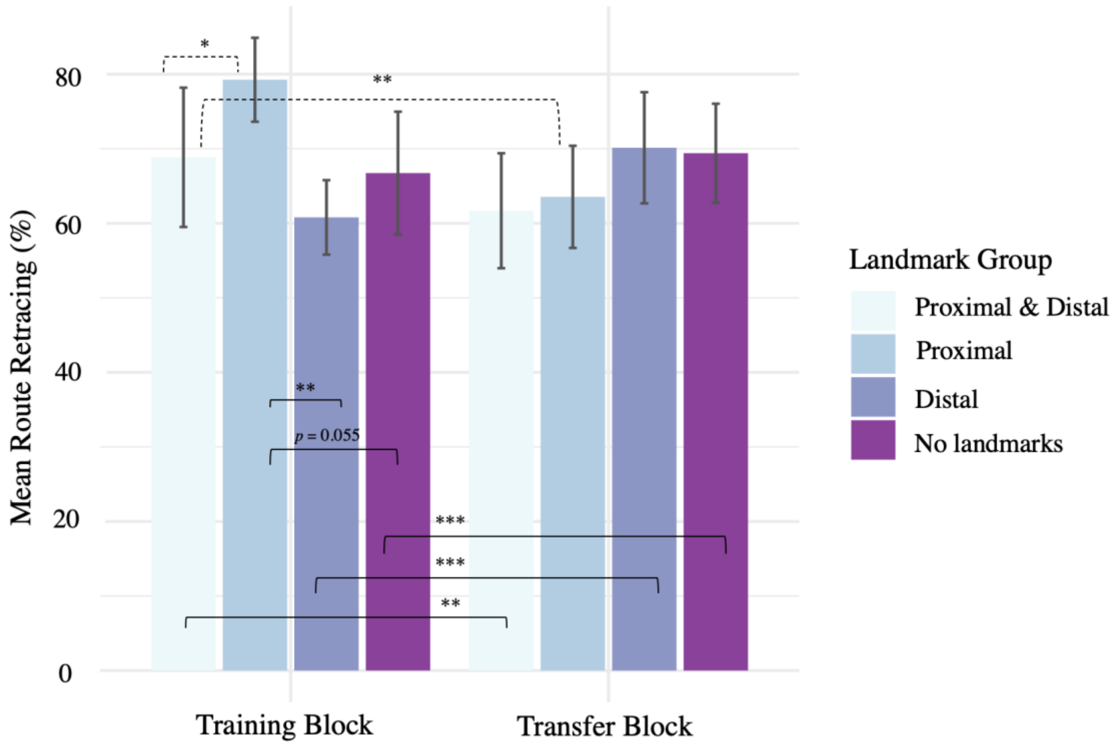

Figure 4: Route retracing for each Landmark group and Block, for all trials. Error bars are 95% confidence intervals. Black dashed lines indicate significant model interactions and black solid lines indicate significant pairwise comparisons. Asterisks "***", "**", and "*" denote $p < .001$, $p < .01$, $p < .05$, respectively.

Repeated measures pairwise comparisons showed that the route retracing scores of the D group (Training: M = 60.79, SE = 2.85 vs Transfer: M = 70.13, SE = 2.95; $\beta = -30.79$, $t = -5.770$, $p < 0.0001$), N group (Training: M = 66.73, SE = 3.07 vs Transfer: M = 69.40, SE = 3.02; $\beta = -25.55$, $t = -4.788$, $p < 0.0001$), and the PD group (Training: M = 68.84, SE = 3.12 vs Transfer: M = 61.67, SE = 3.11; $\beta = 14.21$, $t = -2.635$, $p = 0.008$) were significantly different in the training block compared with the transfer block. No significant difference was observed between training and transfer blocks of the P group (Training:

M = 79.25, SE = 2.66 vs Transfer: M = 63.54, SE = 3.02; $\beta = -6.87$, $t = -1.274$, $p = 0.203$). Pairwise comparison within blocks indicated that, in the training block, route retracing scores of the P group were significantly higher than the D group ($\beta = 17.977$, $t = 3.647$, $p = 0.002$) and marginally higher than N group ($\beta = 12.654$, $t = 2.567$, $p = 0.055$). No other significant pairwise comparisons were observed between the non-referenced groups. Overall, these results suggested that in the presence of proximal landmarks only (P group) drivers were more likely to retrace the exact training routes. Moreover, similar to the success results observed in the transfer block, prior driving experience in the presence of distal landmarks appeared to improve route retracing performance in the transfer block in which no landmarks were present.

3.3.1 Route retracing learning effect

A significant effect of Trial Order on route retracing was observed ($\beta = -5.518$, $t = -6.229$, $p < 0.001$). There was a significant interaction of the learning effect for route retracing scores in the D group ($\beta = 3.082$, $t = 2.256$, $p = 0.0243$) compared to the PD group, indicating a positive learning effect across the order of trials.

4. Discussion

Navigation research has shown that there are differences in the way that proximal vs. distal landmarks influence survey vs. route knowledge (Bullens et al., 2011; De Condappa, 2016; Doeller & Burgess, 2008; Hurlebaus et al., 2008; Steck & Mallot, 2000; Wilson & Alexander, 2008). Our goal in the present study was to understand whether and how these findings extend to route navigation while actively driving. We used a driving simulator to assess route navigation memory in an ecologically-relevant virtual town. We manipulated the presence of different types of landmarks in the training block and tested the effect of prior exposure to different types of landmarks on route navigation in the transfer block where no landmarks were available. In each block, we operationalized route navigation performance in two ways: "success", which was the binomial record of the passed or failed trials in the testing phase, and "route retracing", which was the percentage of overlap between the routes taken in the guided navigation and testing phase.

Success

In the training block, groups exposed to proximal landmarks (PD and P groups) had significantly higher success than groups exposed to distal or no landmarks (D and N groups). This is consistent with past research showing that proximal landmarks support route knowledge (e.g., Hurlebaus et al., 2008; Ruddle et al., 2011). Proximal landmarks provide local relative positional information (Benhamou & Poucet, 1998; Biegler & Morris, 1996) which is useful in route-based navigation tasks. Even though the presence of proximal landmarks in the training block significantly improved route learning, the relatively poorer performance of the PD compared to the D group in the transfer block suggested that the mere presence of the distal landmarks is not what facilitated successful route navigation, but rather the lack of proximal landmarks. In other words, drivers' successful use of proximal landmarks when they were available resulted in less well-formed survey-like representations of the environment; this hurt performance when subsequently tested in the absence of landmarks (transfer block). We suggest that when proximal landmarks were not available in the training block (e.g., the D and N groups), drivers formed a more effective map-like representation of the environment which supported route navigation in the absence of landmarks in the transfer block.

Route retracing

The same general pattern of results was observed in the route retracing measure, corroborating the success results. The route retracing score was an indicator of successful guided navigation phase route learning. Participants were encouraged to navigate by retracing the routes learned in the guided navigation phase, which were the most efficient routes to the target destination but were allowed to take alternate routes.

In the training block, the P group had significantly higher route retracing scores than all other groups (PD, D, & N groups). This suggests that in the presence of proximal landmarks drivers are more likely to retrace the learned routes from the guided navigation phase, whereas in the presence of distal landmarks or absence of proximal landmarks drivers can afford more flexible navigation. Drivers benefit from proximal landmarks during navigation as they can be associated directly to turns at intersections. Distal landmarks do not provide the same highly reliable local positional information because they are too distant to link a specific turn direction to a particular intersection. However, drivers may still attend to distal landmarks when learning a route and this will lead to better map-like knowledge.

In the transfer block, where landmarks were not available, prior exposure to distal landmarks increased the retracing scores of the D group. This could mean that even though distal landmarks were not as useful to route retracing as proximal landmarks, they did help to generate a mental representation of the town which was helpful for route retracing in the transfer block. An important question is why precise route retracing in the PD group was lower when compared to the P group in the training block or D group in the transfer block. Presence of both types of landmarks together might draw attention away from efficient use of the navigational strategy that uses either type of landmarks. Efficient navigation requires the ability to dynamically weight different navigation strategies based on available landmarks (Montello, 2005; Steck & Mallot, 2000; Wiener et al., 2004, 2009). Drivers in the PD group may have attempted to use both proximal and distal landmarks, leading to a lower route retracing score.

Summary

Many navigation studies have analyzed joystick or keyboard responses in tasks involving desktop virtual environments (e.g., Andersen et al., 2012; Bakdash et al., 2008; Carassa et al., 2002; Gardony et al., 2011; Hurlebaus et al., 2008; Janzen & Turennout, 2004; Knorr et al., 2014; Péruch et al., 1995; Stankiewicz & Kalia, 2007; Viaud-Delmon & Warusfel, 2014; Wallet et al., 2011). Some studies have used both real and virtual setups (e.g., Farrell et al., 2003; Grant & Magee, 1998), and several have examined navigation while participants walked in the real world (e.g., Münzer et al., 2006; Wallet et al., 2008; Willis et al., 2009; Zhong & Kozhevnikov, 2016). A few studies have assessed navigation and driving in the real world (e.g., Antrobus et al., 2016; Fu et al., 2019; Stülpnagel & Steffens, 2012), and only a few have tested navigation using an immersive virtual reality driving simulator (e.g., Cochran & Dickerson, 2019; Kunishige et al., 2019; Pankok Jr & Kaber, 2018; Smyth, 2007; Yi et al., 2015). It could be argued that navigating while driving is substantially more difficult than navigating by means of keyboard or joystick for multiple reasons. There is additional cognitive load due to following the rules of the road, staying in the lane, and making turns at the appropriate speed. Additional sensorimotor control involved in driving with a steering wheel and pedals might also impact navigation performance. Other studies have demonstrated that cognitive load (e.g. cell phone use) while driving negatively impacts memory for landmarks (e.g. Blalock et al., 2014). It is possible that the increased cognitive load could influence spatial memory and therefore route navigation.

We assessed navigation in an ecologically valid setup. We provided a large-scale virtual environment which required an active application of wayfinding strategies (e.g., Diersch & Wolbers, 2019; Loomis et al., 1993; Poucet, 1993; Wolbers & Wiener, 2014; Zhang et al., 2014). Size of the environmental space plays an important role in the emergence and development of allocentric survey-based navigation strategies from egocentric route-based navigation strategies (Ekstrom & Isham, 2017; Siegel & White, 1975; Török et al., 2014; Zhang et al., 2014; Zhang et al., 2014). For the D group in the present study, the development of survey knowledge was not observed immediately in the training block, but rather later in the transfer block. This is in accordance with theories indicating that the development of navigational strategies is hierarchical, with egocentric route-based strategies emerging before more cognitively demanding allocentric map-based strategies (e.g., Gagnon, et al, 2014; Han & Becker, 2014; McNamara et al., 1989; Siegel & White, 1975).

The results of the present study suggest that landmark-specific effects on route navigation in the extant literature do carry over to the elevated difficulty of navigating while driving in complex virtual environments. Specifically, we found that the presence of proximal landmarks was more likely to result in successful route navigation in the training block. In contrast, the presence of distal landmarks in the training block was more likely to result in successful route navigation in the transfer block, suggesting that drivers may have obtained survey knowledge from the distal landmarks that carried over to route navigation when no landmarks were present.

Limitations and future approaches

In this study, we used distal and proximal landmarks that simulated those found in a typical urban driving environment. Objects that are more conspicuous relative to their environment tend to function as more salient landmarks (e.g., Caduff & Timpf, 2008; Sorrows & Hirtle, 1999). Our salient landmarks were present in the training block only and not the transfer block. A limitation of this design is that landmarks do not tend to disappear in a real environment. A future experiment might set up a scenario to explain the removal of the landmarks (e.g., major construction underway to replace infrastructure in the town). Other tests for survey knowledge could be employed. An advantage to the present design is that it retains active driving in the transfer block, which may be important in revealing transferred route knowledge.

The time required to drive from the starting point to the target destination limited the number of routes tested in each condition, which limited our ability to perform reliable statistical comparisons on route retracing for successful and failed trials separately. Future study designs should address this.

We asked participants to report their driving frequency in an average week. It would have been informative to know their overall driving experience by asking for years of driving experience, because it is conceivable that beginner drivers might experience higher cognitive load from simultaneous driving and navigation compared to more experienced drivers.

We designed the town to be relatively small with only four turns per route to avoid cybersickness. A larger town would provide additional flexibility to incorporate a larger number of routes to test different arrangements of the landmarks. No participants dropped out of the present experiment due to cybersickness, although they were given multiple opportunities to do so without penalty, however, a larger virtual environment might increase the probability of cybersickness. There are various approaches that could overcome this limitation and make it a more representative task. For example, reducing the number of stops and turns, and restricting optic flow to a smaller field-of-view has been shown to reduce cybersickness (Lin et al., 2002). The presence of vestibular motion cues may also reduce cybersickness, however this effect remains controversial (Keshavarz et al., 2018; Weech et al., 2020).

Availability of Data & Materials

The datasets, R code, examples of route retracing plots, and Omnibus test results tables are publicly available at: https://github.com/Jabbariy/Manuscript1_CRPI_2022.

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CHAPTER 3: Vestibular Cues Improve Landmark-Based Route Navigation: a Simulated Driving Study

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Preface

Chapter 3 presents the results of an experiment in which the effect of self-motion cues like vestibular cues on the route learning of drivers was examined. In this experiment, participants actively drove in a virtual town using a motion simulator. One group of participants received motion responses from the simulator during driving while the other group did not receive any motion cues. Participants were guided through some routes leading to a target destination in the presence of different environmental cues such as proximal landmarks (local objects) and distal landmarks (distant objects). Their memory for the routes in finding the target destination was examined later. It was observed that self-motion vestibular cues improved route learning of drivers. This improvement was most effective in the presence of proximal landmarks.

Abstract

It is well established that humans use self-motion and landmark cues to successfully navigate their environment. Existing research has demonstrated a critical role of the vestibular system in supporting navigation across many species. However, less is known about how vestibular cues interact with landmarks to promote successful navigation in humans. In the present study, we used a motion simulator to manipulate the presence or absence of vestibular cues during a virtual navigation task. Participants learned routes to a target destination in three different landmark blocks in a virtual town: one with proximal landmarks, one with distal landmarks, and one with no landmarks present. Afterwards, they were tested on their ability to retrace the route and find the target destination. We observed a significant interaction between vestibular cues and proximal landmarks, demonstrating that the potential for vestibular cues to improve route navigation is dependent on landmarks that are present in the environment. In particular, vestibular cues significantly improved route navigation when proximal landmarks were present, but this was not significant when distal landmarks or no landmarks were present. Overall, our results indicate that landmarks play an important role in the successful incorporation of vestibular cues to human spatial navigation.

1. Introduction

Humans tend to rely on multiple sources of information when navigating complex environments. This information can be divided into landmark cues originating from the environment, and self-motion cues originating from body movement. Among the many sensory systems that process self-motion is the vestibular system, which transduces the inertial cues arising from physical motion. The vestibular system has been regarded as the foundation to spatial orientation, as very early in our evolutionary history it provided a sense of orientation relative to gravity (Day & Fitzpatrick, 2005; Smith, 2017). The vestibular system is composed of the semicircular canals, which transduce angular acceleration cue arising from rotations, and the otolith organs, which transduce linear acceleration cues arising from translations (Beisel et al., 2005). Although the vestibular system is most often described as providing our sense of balance and orientation, recent work has just begun to appreciate its immense contributions to spatial navigation.

During spatial navigation, there is a continuous integration of body-based self-motion cues from the visual, vestibular, and the proprioceptive systems (Loomis et al., 1993; Mittelstaedt & Mittelstaedt, 1980; Wallace et al., 2002; for a review see Cullen & Taube, 2017). The visual system contributes information about optic flow (the pattern of visual motion on the retina as one moves through the environment), the vestibular system contributes information about physical forces (acceleration cues) acting on the observer, and the proprioceptive system contributes information about joint position during self-generated movements (Waller et al., 2004). Although body-based self-motion cues can be used for real-time spatial updating, these cues are prone to the accumulation of uncertainty over time (Chrastil & Warren, 2012; Etienne et al., 2004; Lakshminarasimhan et al., 2018). Thus, the ability to encode and represent the spatial relationships between landmarks in the environment in the form of a "cognitive map" is thought to be critical for reliable spatial navigation in large environments, because it allows for a recalibration of the accumulated error (O'Keefe & Nadel, 1978; Tolman, 1948).

It is commonly found that navigational strategies are flexible and can vary based on the types of landmarks that are present (Foo et al., 2005; Riecke et al., 2002; Spetch et al., 1997). Proximal (nearby) landmarks often lead to an egocentric encoding of the environment, whereby information is encoded relative to the body. As a result, proximal landmarks tend to support route-based navigation, and are more likely to evoke episodic memory of previously learned routes (Conway, 2005; Greenberg & Knowlton, 2014; Tulving, 2002). Route-based navigation involves knowledge of the sequence of turns and routes decisions as well as available landmarks in the environment to move toward a desired destination (Hartley et al., 2003; Klatzky, 1998; Siegel & White, 1975; Waller & Lippa, 2007). Conversely, distal (far away) landmarks often lead to an allocentric encoding of the environment, whereby information is encoded relative to the environment. As a result, distal landmarks tend to support survey-based navigation, and are more likely to be used in reference to a cognitive map (Chan et al., 2012; Foo et al., 2005; Hurlebaus et al., 2008; Janzen, 2006; Livingstone-Lee et al., 2011; Steck & Mallot, 2000). Survey-based navigation involves knowledge of the spatial relationships between landmarks, which is obtained through encoding the environment flexibly from an allocentric point of view (Foo et al., 2005; O'Keefe & Nadel, 1978; Siegel & White, 1975; Tolman, 1948).

Research over the last few decades has suggested that vestibular cues play an important role in spatial cognition. Rodent navigation studies have shown that lesions to the vestibular labyrinth result in significant deficits in spatial navigation (Wallace et al., 2002; Zheng et al., 2009). However, these deficits could be just as easily interpreted as the vestibular system playing a role in stimulating the hippocampal navigation system, with no influence from the vestibular cues themselves. Furthermore, the majority of our existing knowledge about how vestibular cues influence spatial navigation in humans is observational. For instance, aging studies have shown that vestibular loss predicts a decline in spatial memory in older adults (Previc et al., 2014; Xie et al., 2017), and epidemiological studies have shown strong correlations between vestibular decline and cognitive impairment (Bigelow et al., 2015; Harun et al., 2015; Semenov et al., 2016; Wackym et al., 2016). However, more direct evidence is needed to make stronger conclusions about how vestibular cues influence human spatial navigation. The first goal of this study was to find direct experimental evidence on whether vestibular cues facilitate route-based navigation in humans.

Previous studies have demonstrated that the integration of self-motion and landmark cues can reduce response variance and improve navigation (Nardini et al., 2008; Sjolund et al., 2018; Zhang et al., 2020; Zhao & Warren, 2015). Rodent studies have demonstrated that in the absence of vestibular cues, landmarks are necessary for successful navigation (Stackman & Herbert, 2002; Youngstrom & Strowbridge, 2012). However, no existing studies have tested how vestibular cues interact with landmarks in human route-learning and route-based navigation. We outline three hypotheses: (1) It is possible that vestibular cues will be independent from landmarks and therefore have a uniform effect on route navigation. (2) It is also possible the relative contribution of vestibular cues will increase when less reliable landmarks are present, or when there are no landmarks, (3) Finally, it is also possible that vestibular cues will be integrated more effectively when combined with landmarks that promote body-based (egocentric) navigation strategies, such as proximal landmarks. The third hypothesis would also predict that vestibular cues will be less effective when combined with landmarks that promote an external frame of reference, such as distal landmarks. The second goal of this study was to resolve these potential hypotheses and understand how vestibular cues interact with landmarks during route-based navigation. This was assessed with a route navigation task in a driving simulator. Participants were instructed to navigate through a virtual town in the presence of either proximal, distal, or no landmarks, and the presence or absence of vestibular cues was manipulated with a motion platform.

2. Method

2.1 Participants

Sixty-four participants (29 males) between the ages of 18 and 25 years (M = 19 years, SD = 1.4) were recruited from McMaster University's psychology participant pool. Two participants did not complete the driving task and were not included in the sample. Participants received course credit for their participation. Participants reported normal or corrected-to-normal vision as well as a valid driving license to qualify for the study. They reported a rate for playing video/computer games and virtual reality games, and a weekly driving frequency. Participants provided written informed consent to participate in the study; the study was approved by the Hamilton Health Research Ethics Board.

2.2 Experimental setup

Participants completed a spatial navigation task in a fully immersive motion simulator supported by a MOOG Stewart platform with 6 degrees of freedom (see Figure 1a; MOOG Series 6DOF2000E). Participants sat in a bucket seat with a basic driving interface consisting of a steering wheel and gas and brake pedals (Logitech International S.A., Lausanne, Switzerland). Data were recorded from the steering wheel, gas, and brake pedals continuously at 60 Hz. The virtual town was presented on three 43-inch LCD panels, each with a resolution of 1,920 × 1,080 px and a refresh rate of 60 Hz. The panels provided a 35° vertical field-of-view and collectively formed a 120° horizontal field-of-view (see Figure 1b). The center panel was located approximately 130 cm from the participant. There were two cameras inside the simulator pod, one providing a frontal view of the participant and another providing a bird's-eye view of the screens in order to monitor the participant. An intercom system allowed communication between the participant and the experimenter.

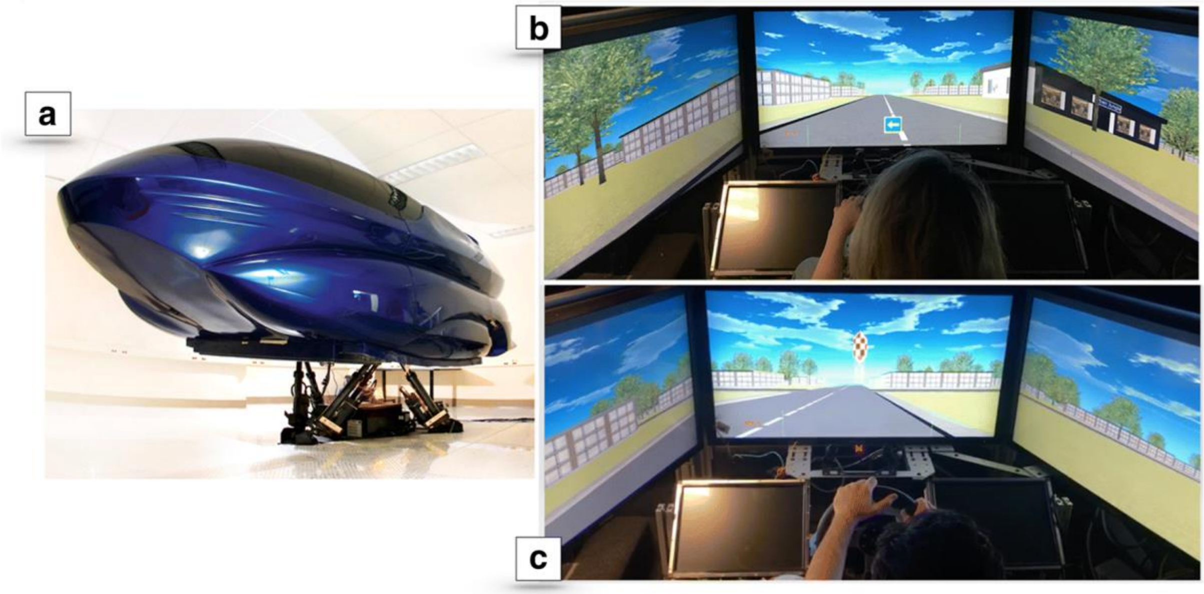

Figure 1: Outside view of the motion simulator supported by a MOOG motion platform. b Snapshot of a trial from the guided navigation phase, with an arrow at the bottom of the middle screen indicating the direction to turn at the next intersection. From here, a shop is visible on the right side at the upcoming intersection (proximal landmark). c Snapshot of a trial from the testing phase, where there were no guiding arrows. From here, a water tower is visible off in the distance (distal landmark).

2.2 Virtual environment

The virtual town was coded in C++ using the Vega Prime (Presagis) library. The spatial layout of the virtual town was a 3 × 3 grid with four horizontal and vertical roads, and four central intersections (see Figure 2 for a bird's-eye view). The target destination was a dead-end in the middle of the town, denoted by the red X in Figure 2. Depending on the block, there were one of two types of landmarks present: proximal landmarks (buildings located at intersections) and/or distal landmarks (towers located at the edge of the town). In the proximal block, landmarks were located at each of the four central intersections, giving cues to relative position and direction (see Figure 2b). Proximal landmarks were 3D renderings of a church, a store, a house, and a gas station. In the distal block, landmarks were located at the four edges of the town and were visible from a distance, giving cues to absolute position and direction (see Figure 2c). Distal landmarks were 3D renderings of a radar tower, a control tower, a water tower, and a wind tower. All remaining buildings in the town were generic with the same visual pattern, serving the purpose of obstructing proximal landmarks so they could not be used as distal cues, and obstructing the target destination. In the no landmark block (see Figure 2d), only the generic buildings remained. The four edges of the town were not differentiable from each other and not visible when navigators were not driving on the edge due to the render distance. From all interior intersections of the town, the road looked identical aside from the landmarks.

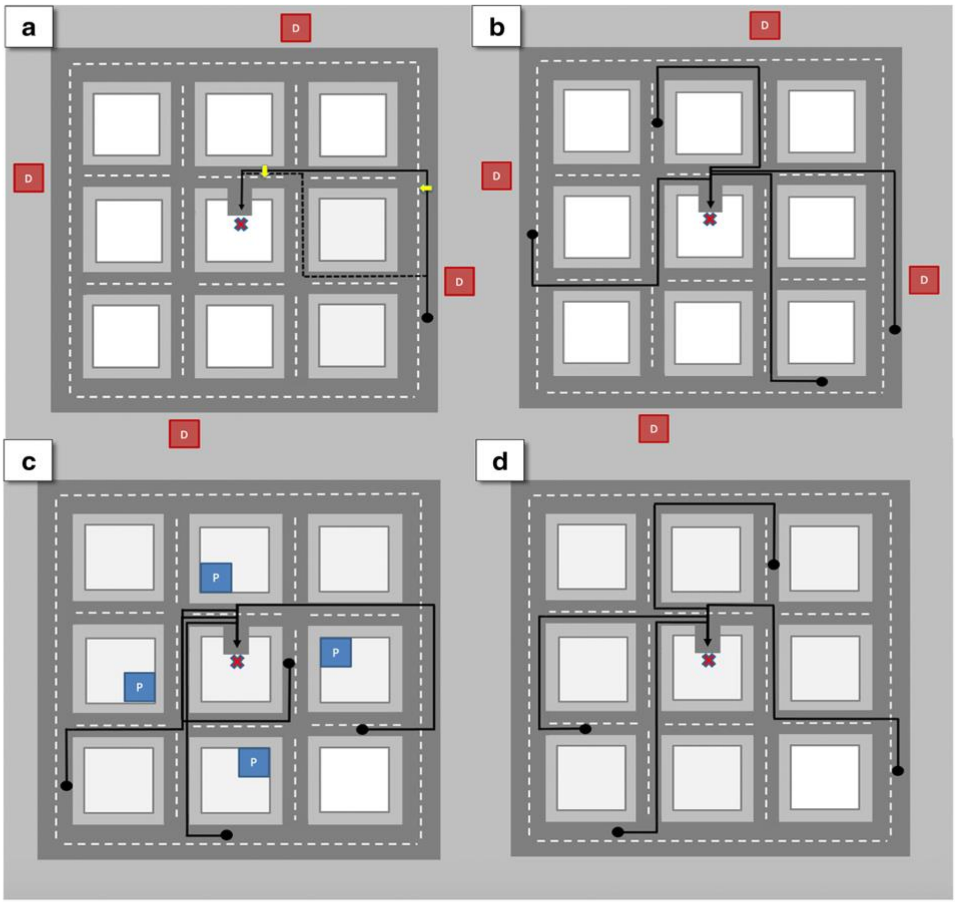

Figure 2: Top-down view of the virtual town with various landmarks and routes. a Example guided navigation and testing routes. The solid black route indicates a guided navigation route with arrows from start to end, and the dashed route indicates a testing route. In this example, the participant chose a different route but successfully reached the destination (indicated by the red X). The overlap between guided navigation and testing routes (route retracing score) was approximately 33%. b–d Illustration of the four unique routes used in the distal block (b), proximal block (c), and no landmark

block (d). Blue boxes with the letter P indicate locations of the proximal landmarks (e.g., gas station, church), and red boxes with the letter D indicate locations of the distal landmarks (e.g., control tower, water tower).

2.3 Experimental design

Participants were randomly assigned to two different groups: one receiving both visual and vestibular self-motion cues (V+) and another receiving only visual self-motion cues (V−). For the V+ group, the motion platform delivered vestibular self-motion cues that corresponded to the vehicle's motion, and for the V− group, the motion platform remained stationary. The visual stimuli were identical in both V+ and V− groups. Cues from the motion simulator stimulated all organs of the vestibular system, as they were presented on 6 degrees of freedom (3 translational and 3 rotational).

The experiment included three blocks, each with different landmarks: proximal landmarks (P), distal landmarks (D), and no landmarks (N). The order of the blocks was counterbalanced between participants and groups. Each block included a guided navigation phase followed by a testing phase, each consisting of four routes. The routes were unique for each landmark block, so there were a total of twelve unique routes (see Figure 2b–d). All routes passed through four intersections to ensure that there were four decision points during the testing phase.

During the guided navigation phase, participants were dropped at four unique locations in the town and were guided to the destination in real time. At each intersection, an arrow appeared at the bottom of the screen, indicating which direction to turn. During the testing phase, participants were dropped at the same four locations in the same order and were instructed to find the same target destination without help from the arrows. Although participants were instructed to retrace the corresponding route from the guided navigation phase, they were encouraged to find it from alternative routes if they could not remember the exact route. The task instructions for the testing phase are as follows:

Following the training trials, there are four test trials. You will start at the same locations and directions that you saw in the training trials, but this time there will be no directing arrow to lead you to the target. Test 1 matches Training 1, Test 2 matches Training 2, and so on. Your task is to retrace the routes that you learned in the training and find the target. In any test trial if you cannot remember the corresponding training route, we encourage you to find the goal from other routes that you know. You will have 90 seconds to complete each test trial.

Therefore, instances where the target destination was found partially through an alternative route to the destination were also considered successful. If participants were unable to find the target destination within 90 seconds, the trial for that route ended and participants were automatically sent to the next trial. In both phases, participants were instructed to drive in the middle of the right lane at a speed of around 30 km/h while following standard traffic rules. Sample size for this study was chosen based on the effect sizes we observed in previous experiments which indicated the sample size required to observe moderate effect sizes; thus, we did not conduct a power analysis for this experiment.

2.4 Experimental protocol

When participants arrived at the lab, they filled out a consent form, a demographic questionnaire, and the navigational strategy questionnaire (NSQ). Participants were then trained in the driving simulator to ensure they were familiar with the steering wheel, gas, and brake pedals, and interacting with the visual display. The experimenter gave verbal task instructions while the participant completed a 90-s practice session with the motion simulator inactive where they were able to drive around at their leisure. Once participants indicated that they felt comfortable driving, they began the main task. The entire session lasted approximately 1 hour, which included the time taken for completing the questionnaires, practice session, driving task, and debriefing.

The demographic questionnaire covered basic demographic information and included self-report questions such as frequency of driving and level of familiarity with video/computer games on a 7-point Likert scale, with 0 indicating *no experience* and 7 indicating *professional experience*. There were no differences in task performance between those who reported driving every day and those who reported driving 2–3 times a week. The mean familiarity with video/computer games was 2.81 (0.21) and virtual reality games was 0.55 (0.12). We did not observe any correlations between experience with video/computer games or virtual environment games and task performance.

The NSQ is a 44-item survey that assesses self-reported navigational and spatial abilities on a 5-point Likert scale (Zhong, 2013; Zhong & Kozhevnikov, 2016). The NSQ contains three general categories: survey-based strategy, procedural strategy, and egocentric spatial updating strategy. The survey-based strategy scale (12 items) assesses one's ability to reference their cognitive map using fixed allocentric coordinates and cardinal directions (e.g., "When I reconstruct my mental map, its environmental orientation is fixed and does not change with my imagined heading directions"). The procedural strategy scale (15 items) assesses one's ability to depend on visual memory or use a set of procedural strategies for wayfinding (e.g., "When I navigate, I pay attention to the landmarks at the turning points and try to remember their sequence"). The egocentric spatial updating strategy scale (17 items) assesses one's ability to update their position relative to a point of origin in real time by relying on path integration and their internal compass (e.g., "I can easily keep track of my direction of travel on my route with respect to the starting point").

2.5 Data analysis

We assessed route navigation of the two groups with two dependent variables. The first navigation metric, “success rate,” was the proportion of successful trials where the participant was able to find the target destination in under 90 seconds. Since the outcome of each trial was either a success or fail, success rate was treated as a binomial random variable. The second route navigation metric, “route retracing,” was the percentage overlap between the routes taken in the guided navigation and testing phase (see Figure 2a). In the testing phase, participants were instructed to find the target destination by retracing the corresponding routes from the guided navigation phase; however, they were permitted to take alternate routes. A route retracing score of 100% indicates that the participant took the same route as the guided navigation phase. While success rate was a direct measure of their navigational success, route retracing measured their overall tendency to use route-based navigation with an egocentric frame of reference.

We assessed the success rate data using a generalized linear mixed model (GLMM), where it was treated as a binomial random variable (Agresti, 2015; Dunteman & Ho, 2006), and the route retracing data using a linear mixed model (LMM). The independent variables in both models were the motion group (V−, V+) and landmark block (N, D, and P). Participants were treated as a random effect to account for the repeated measures. Finally, to account for the potential learning effects due to completing more trials, we treated “trial number” as a fixed effect and random slope. Treating trial as a fixed effect allowed us to look at the overall effect of completing more trials on the response variables and treating trial as a random slope for each participant allowed us to account for individual variation in learning rate between participants.

In Wilkinson notation (Wilkinson & Rogers, 1973), the generalized linear mixed model for success rate (SR) and linear mixed model for route retracing (RR) are:

SR ~ landmark × motion + trial + (0 + trial | participant)

RR ~ landmark × motion + trial + (1 + trial |participant)

This analysis was conducted in R, which by default takes the first category of the factor as a reference category; here, the N condition and V− group were chosen as the reference categories. Data and R code are publicly available (https://github.com/Jabbariy/Manuscript2_Memory-and-Cognition).

3. Results

3.1 Success rate

We reported the results of the generalized linear model in Table 1. When there were no vestibular cues, success rate was significantly higher with proximal landmarks (P, V−) compared with no landmarks (N, V−) (OR = 2.570, z = 2.791, p = .005). However, when there were no vestibular cues, success rate did not significantly differ between the distal landmarks block (D, V−) and the no landmarks block (N, V−) (p = .708).

Table 1: Results of the generalized linear mixed model with success rate modelled by motion group (V- and V+) and landmark block (N, D, or P). Here, no landmarks (N) and no vestibular cues (V-) are used as the reference categories since they are the control conditions. Estimate (β) is the log-odds ratio between the term and the reference category. For instance, the estimate for D, V- indicates the log-odds between the D block when V- and N block when V-. "***", "*" and "~" denote $p < .001$, $p < .05$, $p < .10$, respectively.

Motion*Landmark	**Estimate**	**SE**	**OR**	**CI (95%)**	***z* value**	**Pr(>|z|)**
N, V- (Intercept)	-0.202	0.274	0.817	0.477, 1.398	-0.738	0.461
D	0.113	0.303	1.120	0.619, 2.026	0.374	0.708
P	0.944	0.338	2.570	1.325, 4.985	2.791	0.005 **
V+	0.274	0.323	1.315	0.698, 2.478	0.847	0.397
Trial	0.207	0.037	1.230	1.145, 1.321	5.640	< .001 ***
D, V+	0.229	0.444	1.257	0.527, 3.001	0.516	0.606
P, V+	1.376	0.652	3.957	1.102, 14.196	2.110	0.035 *

Most interestingly, we observed a significant interaction between the vestibular cues and proximal landmarks. Specifically, the significant interaction was between no landmarks and no vestibular cues (N, V−), compared with proximal landmarks and vestibular cues (P, V+) (OR = 3.957, z = 2.110, p = .035). This interaction had an odds ratio of 3.957, indicating that the relative probability of finding the destination was around 3.957 times higher in the P, V+ condition compared with the N, V− condition. In Table 2, we tested pairwise comparisons to verify that success rate was significantly higher in the presence of proximal landmarks (P) when there were vestibular cues (V+) compared with no vestibular cues (V−) (OR = 5.072, z = 2.859, p = 0.045). In contrast, the success rate was not significantly different when vestibular cues were present for the distal landmark (p = .825), and no landmark conditions (p = .953). Overall, these findings suggest that vestibular motion cues were selectively improving route navigation when proximal landmarks were available. Finally, we observed a significant effect of trial (OR = 1.230, z = 5.640, p < .001), which was to be expected as a result of learning effects.

Table 2: Additional pairwise comparisons of success rate. "***", "**", "*" and "~" indicate $p < .001$, $p < .01$, $p < .05$, and $p < .10$, respectively.

Landmark	**Contrast**	**Estimate**	**SE**	**OR**	**CI (95%)**	***z* value**	**Pr(>|z|)**
P	*V+, V-*	1.624	0.568	5.072	1.019, 25.242	2.859	0.045 *
D	*V+, V-*	0.368	0.305	1.444	0.610, 3.417	1.206	0.826
N	*V+, V-*	0.245	0.287	1.278	0.569, 2.872	0.856	0.954
Motion	**Contrast**	**Estimate**	**SE**	**OR**	**CI (95%)**	***z* value**	**Pr(>|z|)**
	D, N	0.282	0.308	1.327	0.556, 3.166	0.918	0.939
V+	*P, N*	2.250	0.550	9.490	2.012, 44.768	4.097	< 0.001***
	P, D	1.968	0.556	7.154	1.487, 34.423	3.538	0.005 **
	D, N	0.160	0.2834	1.174	0.527, 2.614	0.566	0.993
V-	*P, N*	0.872	0.321	2.391	0.965, 5.928	2.713	0.068
	P, D	0.711	0.326	2.037	0.811, 5.117	2.182	0.234

We treated participant and trial as random effects in the model to account for individual variation in overall success rate, as well as individual variation in learning effects. This also accounted for the repeated-measure aspect of our design. "Participant" was treated as a random intercept (SD = 0.879), and "trial" was treated as a random slope (SD = 0.126) Figure 3.

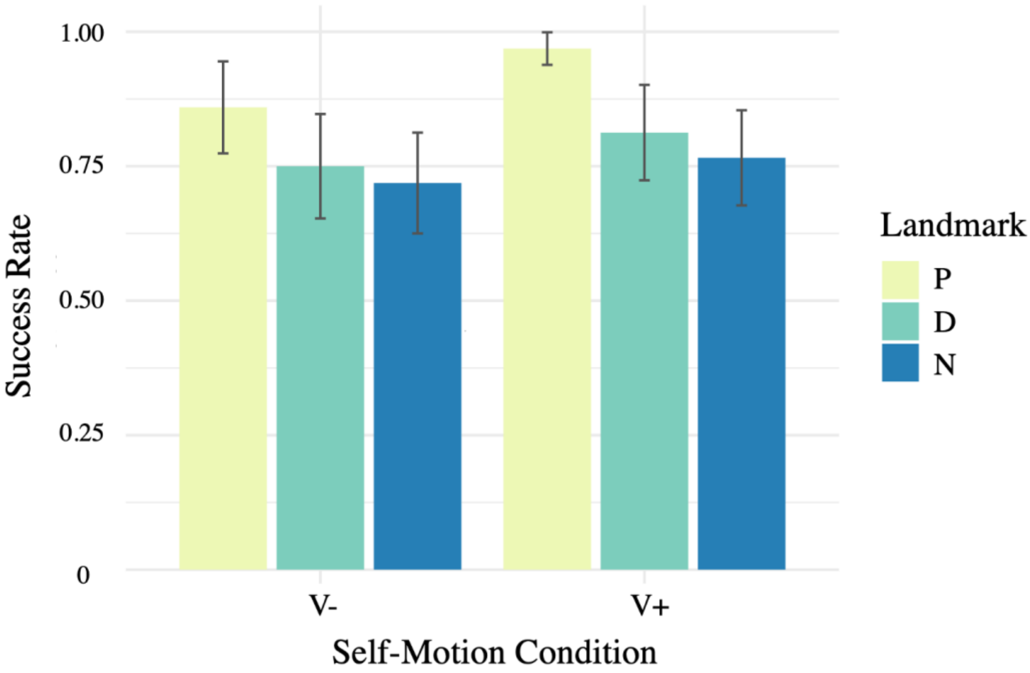

Figure 3: Success rate by motion groups (V- and V+) and landmark blocks (N, D, or P). The error bars are 95% confidence intervals.

3.2 Route retracing

In order to find the destination, participants were asked to retrace the corresponding routes learned in the guided navigation phase. The percentage of overlap between the routes travelled in the guided navigation and testing phase was called route retracing score. Although participants were instructed to retrace the corresponding route they learned in the guided navigation phase, deviation from a perfect route retracing score could indicate that participants were finding a shortcut or alternative path to reach the destination.

Overall, the route retracing score was significantly higher for proximal landmarks (*P*) compared with no landmarks (N) when there were no vestibular cues (V−) (Estimate = 14.29, t= 3.77, $p < .001$). In the no landmarks condition, the effect of vestibular cues on route retracing was not significant (Estimate = −1.65, t = −0.39, $p = .698$). We observed an insignificant but trending positive interaction between distal landmarks and vestibular cues (D, V+) compared with no landmarks and no vestibular cues (N, V−) on route retracing (Estimate = 10.06, t = 1.876, $p = .061$), and an insignificant interaction between proximal landmarks and vestibular cues (P, V+) compared with no landmarks and no vestibular cues (N, V−) on route retracing (Estimate = 6.86, t = 1.28, $p = .20$).

In this model, the random intercept of participants had a standard deviation of 13.13 and the random slope of trial had a standard deviation of 1.004 Table 3.

Table 3: Results of the linear mixed model with route retracing modelled by motion group (V- and V+) and landmark block (N, D, or P). Here, no landmarks (N) and no vestibular cues (V-) are used as the reference categories since they are the control conditions. "***", "*" and "~" denote $p < .001$, $p < .05$, and $p < .10$, respectively.

Landmark*Motion	Estimate	SE	CI (95%)	t value	Pr(>|t|)
N, V- (Intercept)	58.264	3.817	50.769, 65.759	15.262	< .001 ***
D	-4.468	3.786	-11.900, 2.964	-1.180	0.238
P	14.293	3.790	6.851, 21.734	3.771	< .001 ***
V+	-1.654	4.243	-10.134, 6.827	-0.390	0.698
Trial	1.136	0.333	0.482, 1.789	3.414	< .001 ***
D, V+	10.064	5.364	-0.468, 20.596	1.876	0.061 ~
P, V+	6.858	5.353	-3.650, 17.367	1.281	0.201

3.3 Navigational Strategy Questionnaire (NSQ)

An overview of the different components of the NSQ is provided in Experimental Protocol section. We found a positive correlation between survey-based strategy items and mean route retracing score in the no landmarks condition, r (63) = .262, $p = .036$. This suggested that individuals who self-reported using allocentric navigation strategies and cardinal directions were able to more effectively retrace their path when no visual landmarks were available. This suggests that individuals who self-reported to depend on visual landmarks and procedural wayfinding strategies faced more difficulty in finding the destination when no visual landmarks were available. We did not observe any correlations between egocentric spatial updating score and score on navigation or driving performance. We found that participants randomly assigned to the V+ group tended to have significantly lower procedural scores than the V− group (M = 3.67, SE = .068 compared with M = 3.90, SE = .082, F (1, 63) = 4.386, p = .040, suggesting that those assigned to the V+ group reported being less dependent on visual landmarks and procedural wayfinding strategies. Despite this group's reported limitations in their wayfinding strategies, they managed to perform significantly better than the V− group in the presence of proximal landmarks.

4. Discussion

In the present study, we manipulated the presence of vestibular cues during a route navigation task with various types of landmark cues. We used a mixed design, where participants were randomly assigned to a group either receiving vestibular cues from the motion simulator (V+) or no vestibular cues (V−). Each participant completed all three landmark blocks (no landmark, distal landmarks, proximal landmarks), with the order counterbalanced. In the guided navigation phase of each landmark block, participants were dropped in four locations in the virtual town and instructed to follow arrows to reach a common target destination (see Figure 2). In the subsequent testing phase, participants were instructed to find the same target destination without the guidance of the arrows. We quantified spatial navigation with a measure of success rate, which was the proportion of trials where participants were able to successfully find the target destination within a 90-

second time limit, and route retracing, which was the percentage overlap between the routes taken in the guided navigation and testing phase.

To reiterate, our first goal of the study was to test whether vestibular cues significantly facilitate route-based navigation in humans, and our second goal was to understand how (if at all) vestibular cues interact with landmarks. In this study, we found evidence that route-based navigation was facilitated by vestibular cues; however, vestibular cues only had a significant effect on route navigation when combined with proximal landmarks. This was supported by a significant interaction between the vestibular cues and proximal landmarks on success rate. Out of the three hypotheses outlined in the Introduction, we found support for the third hypothesis. In particular, the presence of vestibular cues and proximal landmarks had a super-additive effect on success rate compared with no vestibular cues and no landmarks. In contrast, such super-additive effect of vestibular cues and distal landmarks was not observed. These results support the hypothesis that vestibular cues can improve proximal landmark-based route navigation, but it remains unclear whether vestibular cues can improve route navigation with distal landmarks or no landmarks.

Encoding a route-based spatial representation of an environment could occur while navigating with either proximal or distal landmarks (Wang & Spelke, 2002). However, route-based navigation in the presence of proximal landmarks may be more convenient than distal landmarks because distal landmarks tend to engage cognitive maps (Hartley et al., 2003; Poldrack et al., 2001). Route-based navigation is less cognitively demanding than survey-based navigation, occurs faster, and does not usually require complex perceptual processes such as mental rotation (Hartley et al., 2003; Thorndyke & Hayes-Roth, 1982). This may explain why the majority of our participants performed better with proximal landmarks in a task where they were instructed to retrace previously learned routes (Hurlebaus et al., 2008; Jabbari et al., 2021; Ruddle et al., 2011).

Furthermore, since proximal landmarks tend to evoke route-based navigation strategies that use an egocentric frame of reference, participants may have shifted their attention towards body-based vestibular cues. In contrast, since distal landmarks tend to evoke survey-based navigation strategies that use an allocentric frame of reference, participants may have shifted their attention away from the vestibular cues since they were inconsistent with this frame of reference. In addition, the proximal landmarks were located at intersections, which correlated with strong inertial forces due to braking and turning, something that may have served as a salient vestibular cue that enhanced the episodic recall of the previously learned route.

Overall, we did not find significant interactions between vestibular and landmark conditions on route retracing score. The lack of a significant interaction between vestibular cues and proximal landmarks on route retracing could be because proximal landmarks were effective enough for successful route retracing, resulting in a ceiling effect. However, there was a trending interaction between vestibular cues and distal landmarks on route retracing ($p = .06$). Route retracing measures participants' tendency to use route-based navigation with an egocentric frame of reference. Accordingly, participants in the distal landmark condition may have had a greater tendency to use route-based strategies when they were presented with the body-based (egocentric) vestibular cues.

To the best of our knowledge, this is the first study to experimentally manipulate vestibular and landmark cues in a virtual navigation task and observed a super-additive result for cue combination of proximal landmarks and vestibular cues. Chance et al. (1998) employed a virtual navigation task in which human participants travelled through a maze with various objects. At the end of the maze, they were instructed to face various objects in the maze. Participants either physically walked through the maze (recruiting visual, proprioceptive, and vestibular inputs), virtually traveled the maze with physical rotations during turns alone (recruiting visual inputs, and proprioceptive and vestibular inputs during rotations only), or virtually traveled the maze with only a joystick (recruiting only visual inputs). Participants had the lowest point errors when they physically walked through the environment, slightly higher errors when they were physically rotated, and highest when they were only given visual cues. Similar findings have been observed by Ruddle and Lessels (2006, 2009) during a virtual search task, and Ruddle et al. (2011) during a route-based navigation task. Collectively, these studies demonstrated that self-motion cues can enhance route-based navigation, however the relative contribution of vestibular cues has yet to be investigated before this study (for a review, see Chrastil & Warren, 2012).

The majority of other studies have tested how self-motion cues influence survey-based navigation. It is unclear whether vestibular cues contribute to the encoding of survey knowledge. For instance, Waller et al. (2003) found that vestibular cues alone were insufficient for the encoding of survey knowledge, and concluded that the contributions of vestibular cues to survey knowledge is minimal. However, a follow-up study from the same research group introduced proprioceptive and motor efferent cues by having participants actively walk through the environment, and found that this resulted in an improvement to the encoding of survey knowledge (Waller et al., 2004). In contrast, Hilliard et al. (2019) observed that noisy subthreshold galvanic vestibular stimulation can enhance hippocampal-based spatial representations, which is linked to survey knowledge. In the present study, we observed that vestibular cues did not significantly improve route navigation in the presence of distal landmarks, which tend to evoke an allocentric representation of the environment.

Finally, although a review of the rodent navigation literature is beyond the scope of this paper, it is important to note that there has been extensive work in this field that has stressed the importance of vestibular input to the development of spatial memory and navigation in rodents (Mittelstaedt & Mittelstaedt, 1980; Russell et al., 2003; Stackman et al., 2002; Wallace et al., 2002; Zheng et al., 2007, 2009). Besnard et al. (2012) demonstrated that in rodents, the contributions of vestibular cues may extend beyond spatial navigation, influencing basic cognitive processes as well. However, since there are many differences between the vestibular systems of rodents and primates (Straka et al., 2016), it is difficult to directly compare these findings to humans. Nonetheless, this body of work has demonstrated that vestibular input travels to the hippocampal formation through at least four neural pathways, suggesting that vestibular input plays a very critical role in spatial cognition (reviewed in Hitier et al., 2014; Moossavi & Jafari, 2019). Moreover, special emphasis has been placed on the contribution of vestibular cues to the head direction network via the anterior thalamocortical pathway. This is because vestibular (inertial) and visual (optic flow) cues provide rotational velocity inputs that update the firing of head direction (HD) cells to track head direction relative to landmarks, resulting in an internal compass (Zheng et al., 2009; reviewed by Yoder & Taube 2014; Laurens & Angelaki, 2018).

4.1 Limitations and future directions

The specific paradigm of the current experiment may have influenced the observed results. For instance, it is possible that learning the environment in a set of four routes could have resulted in decay of the immediate vestibular representation or interference between learning the routes. However, we argue that if participants were tasked with immediately retracing the learned routes, they would have been able to rely on immediate memorization of a sequence of turns rather than a robust spatial representation. However, understanding how these landmark-specific interactions with vestibular cues extend to other forms of spatial navigation is an interesting question that should be explored in future research. Future experiments will allow us to better understand why individuals benefited more from the combination of proximal landmarks and vestibular cues.

In the present study, participants were instructed to retrace the corresponding route from the guided navigation phase, but were encouraged to find the target destination from an alternative route if they could not remember the exact route. As we did not directly manipulate the navigational strategy of participants, we were limited from using dual-solution paradigm, which would have allowed us to test navigational strategy more directly (Furman et al., 2014).

There is a great deal of individual variation in preferred navigation strategy and strategies for encoding information from the environment. Accordingly, randomly assigning participants to receive either motion or no motion may have been a limitation to the present study. For instance, a post hoc analysis of the two motion groups revealed that individuals randomly assigned to the V+ group had lower procedural scores on the NSQ. Individual differences might have been better mitigated and controlled if the same individuals were assigned to both motion conditions (i.e., a repeated-measures design).

The driving simulator produced a realistic and active driving experience. As explained in the Methods section, the test trials in this study were time-based (90 seconds); accordingly, we looked at participants driving time and speed. However, there are many possible variables contributing to the variance of these metrics (e.g., deviating from the learned routes in the guided navigation phase might lead to a longer driving time). As a result, we did not report results of these metrics in the paper, but the data and results are added as supplementary materials to the same Github repository linked in the Methods section.

Conclusion

In the present study, we found novel evidence that vestibular cues interact with landmarks to improve route navigation of drivers in a virtual environment. In particular, we found that vestibular cues resulted in a significant improvement in route navigation when paired with proximal landmarks. In this experiment as well as preceding experiments (Jabbari et al., 2021), we found that proximal landmarks are the most useful type of landmark for route navigation. We speculate that proximal landmarks promote an egocentric or body-based navigation strategy whereby vestibular cues can be more easily incorporated, resulting in a super-additive interaction between vestibular cues and proximal landmarks.

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CHAPTER 4: Navigation in a Simulated Driving Task: Visual Spatial Abilities and Self-Reported Navigation Skills

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Preface

Chapter 4 presents the results of an experiment in which the relationship between visual-spatial and navigational skills of drivers was examined. Participants completed various cognitive tasks assessing spatial working memory and mental rotation skills, as well as surveys on navigational skills. Using a driving simulator, they drove in a virtual town. They were trained on some routes leading to a target destination, and later their route memory in finding the target was assessed. The virtual town had different environmental landmark conditions. It was observed that navigation success of drivers in finding the target destination was related to different self-reported or cognitive spatial skills, and varied based on the type of the available environmental landmarks. For instance, mental rotation skill was a predictor of navigation success in finding the target only when drivers guided through the virtual town in the presence of distal landmarks (distant objects) rather than proximal landmarks (local objects).

Abstract

The ability to navigate through our spatial environment plays a significant role in our daily functions. Visual spatial skills, spatial working memory span, and self-reported navigational skills are all cognitive abilities identified as being essential to navigation. While these areas have been researched, the importance of these functions, and their effect on route learning while driving in relation to landmark-based environments still not well understood. In this study, using a driving simulator, young adults were tested on their ability to learn routes and find a target location while driving. Participants navigated environments with different landmark conditions: proximal and distal landmarks, proximal only, distal only, or no landmarks. A range of questionnaires were administered to estimate visual-spatial (Mental Rotation test, Perspective taking/Spatial orientation task, Corsi span task, Digit span) and self-reported navigation skills (Navigation Skill questionnaire, Santa Barbara Sense of Direction scale). Results showed that scores on the visual-spatial tasks and self-report navigation assessments predicted success in finding the target location depending on the type and availability of landmarks within the simulation. Overall, greater visual-spatial skills were useful when available navigational resources in the environment were limited. Self-reported navigational skills were only useful when they were in accordance with available navigation resources (e.g., landmark-based wayfinding strategy skills are not useful when there are no landmarks in the environment).

Keywords: Visual-spatial abilities, Navigation, Proximal Landmarks, Distal landmarks, Simulator, Virtual Navigation, self-reported Navigation Skills, Mental Rotation

1. Introduction

How we orient ourselves in new environments is dependent on a wide variety of individual factors like gender, age, working memory capacity, mental rotation abilities, and navigation strategies (e.g., Blajenkova, et al., 2005; Hegarty, et al., 2002; Tascon et al. 2017; Lawton, 1994; Pazzaglia & De Beni, 2006; Meneghetti, et al., 2011). How we use different navigational strategies and visual spatial skills to locate and orient ourselves in an environment can be explored by studying different spatial strategies with respect to landmark usage.

Navigational strategies can be categorized in terms of route and survey knowledge, which incorporate the dominant use of proximal and distal landmarks, respectively (O'Keefe & Nadel, 1978; Siegel & White, 1975; Arleo & Rondi-Reig, 2007; Ekstrom & Isham, 2017). Distal landmarks are defined as being visible from far distances, and provide distance and orientational information. Conversely, proximal landmarks are those that can only be seen at immediate locations and provide local and positional information (Steck & Mallet, 2000; Ekstrom & Isham, 2017). Route-based navigation (aka egocentric navigation strategy) is based on the relationships between the navigator and landmarks. It involves incorporating a set of instructions with the use of proximal landmarks on how to get from one point to another (e.g., turning right at the gas station). In contrast, the survey-based navigation (aka allocentric navigation strategy) is based on the relationship of landmarks with the environment or other landmarks. Survey-based navigation involves using distal landmarks and employing cardinal directions to form a bird's eye view of the environment (e.g., the pharmacy is ahead of the gas station toward north) (Zhong & Kozhevnikov, 2016; O'Keefe & Nadal, 1978; Siegel & White, 1975; Arleo & Rondi-Reig, 2007; Ekstrom & Isham, 2017).

The effect of individual differences like age and visual spatial skills on acquisition and application of spatial navigation strategies has been assessed in laboratory-controlled navigation studies as well as questionnaire-based studies (e.g., Ariel & Moffat, 2018; Meneghetti et al., 2016; Tillade et al., 2016; Munzer & Lorch, 2020; Hegarty et al., 2002; van der Ham et al., 2020). For instance, age is associated with a tendency to use egocentric strategies rather than allocentric strategies (e.g., Ariel & Moffat, 2018). Visual spatial working memory (VSWM) has been shown to correlate with the encoding and retrieval of spatial information (e.g., Meneghetti et al., 2016). In various studies, mental rotation skills have been associated with route recall (e.g., Meneghetti et al., 2016) and map learning (e.g., Thoresen et al., 2016).

To the best of our knowledge, no studies have looked at the relationship of individual differences at visual spatial and self-reported levels with the navigation performance of drivers in different landmark-based environments. Most studies that looked at the relationship between visual spatial skills and navigation performance either didn't differentiate the types of landmarks that they used (e.g., Castelli et al., 2008; Meneghetti et al., 2016) or the used landmarks were icons or names indicated on a 2D map (e.g., Pazzaglia and Beni, 2006). In this study, the relationship of individual differences with the navigation performance of drivers was assessed in different environments where there were only proximal landmarks, only distal landmarks, a combination of both landmarks, or no landmarks. We used a motion simulator to simulate an ecologically valid setting of driving to assess the navigation skills of participants. Drivers explored the different landmark-based environments and were tasked with finding a target location. Success in finding the target was predicted by the various visual-spatial measures and self-reported navigation skill questionnaires.

We used a combination of visual-spatial tests and self-reported navigation questionnaires: two working memory tasks: 1. Corsi Span task (CST; Corsi, 1972), 2. Digit Span Task (DST; Wechsler, 1981); two spatial rotation tasks: 1. Mental Rotation Test (MRT; Vandenberg & Kuse, 1978), 2. Perspective Taking/Spatial Orientation Test (PTSOT; Hegarty

& Waller, 2004; Kozhevnikov & Hegarty, 2001); and two self-report navigation questionnaires: 1. Santa Barbara Sense of Direction Scale (SBSOD; Hegarty et al., 2002), 2. Navigation Strategy Questionnaire (NSQ; Zhong, 2013; 2020; Zhong & Kozhevnikov, 2016).

Wayfinding in the presence of different types of landmarks requires the application of various navigational strategies and spatial skills. For instance, allocentric navigation strategies usually require mental rotation skills, and egocentric navigation strategies require associating segments of the routes or turns to a landmark close to the route (e.g., turn left at the drugstore), or memorizing routes based on sequential turns (turn left, right, and then straight) (Zhong & Kozhevnikov, 2016; Arleo & Rondi-Reig, 2007; Ekstrom & Isham, 2017). Accordingly, we hypothesized that the prediction of navigation success by the visual spatial and self-reported navigation measures would vary based on the availability and types of environmental landmarks.

2. Method

2.1 Participants

Seventy three McMaster undergraduate students (32 Male, Mean age =18.79, SD=1.58) participated in this study and received course credit in compensation. Three participants were removed due to simulator sickness. Each participant held a valid driving license. Each reported having normal or corrected-to-normal vision and hearing, and each reported not being sensitive to motion sickness, vertigo, and claustrophobia. A written consent form was signed by each participant. The study was approved by the Hamilton Health Research Ethics Board and adhered to the Canadian tri-council policy.

2.2 Materials and stimuli

Visual-spatial tasks

2.2.1 Mental rotation test (MRT)

In the Mental Rotation Test (MRT) (Vandenberg & Kuse, 1978), participants were provided with 24 items; each item included a two-dimensional shape on the left and four three-dimensional shapes on the right. Participants were asked to identify 2 shapes from the right that matched the presented shape on the left. The three-dimensional shapes were rotated from different angles. Participants were given 10 minutes in total for the 24 items and were informed by the experimenter when there were 5 minutes left. We used a paper-pencil version of this task and only counted items in which participants could accurately identify both three-dimensional shapes on the left.

2.2.2 Corsi block tapping task

In the Corsi Span Task (CST) (Corsi, 1972), participants were shown 9 blue squares on a black screen. Trials progressed, where the color of various blocks, ranging from 2 to 9 blocks changed color to yellow one at a time. Participants were asked to reproduce the specific sequence in the same order that the blocks initially changed to yellow by clicking on the blocks. For each iteration of length, two unique sequences of blocks were provided (16 trials in total). An automated version of the forward CST coded in Python was used. The longest correct sequence of selected blocks was recorded as the CST score.

2.2.3 Digit span task

The digit span task (DST) (Wechsler, 1981) consisted of repeating sequences of numbers. Similar to the CST, participants were asked to reproduce increasingly long sequences of numbers ranging from 2 to 9 in forward order, and two different sequences were used for each length (16 trials in total). The longest sequence of accurately recalled numbers was recorded as the DST score.

2.2.4 Perspective taking/spatial orientation test (PTSOT)

The Perspective Taking/Spatial Orientation Test (PTSOT) (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001) consisted of 12 items that each included a configuration of 7 objects, and participants were asked to point to a specific object while imagining themselves standing at one object and facing another. An automated version of the PTSOT programmed in Python was used, in which participants were shown a circle on the screen with an arrow pointing from the center towards the edge of the circle. The arrow could be moved by clicking on the edge of the circle to indicate the selection of the object location. The time limit for this task was 5 minutes. The PTSOT score was the average error in degrees of pointing to the requested objects.

Self-report navigation strategy questionnaires

2.2.5 Santa Barbara sense of direction scale (SBSOD)

The Santa Barbara Sense of Direction Scale (SBSOD) is a navigation strategy questionnaire that features fifteen 7-point Likert scale questions probing an individual's perceived sense of direction and orientation, with 1 indicating “strongly agree” and 7 “strongly disagree” (Hegarty et al., 2002).

2.2.6 Navigational Strategy Questionnaire (NSQ)

The Navigational Strategy Questionnaire (NSQ) is used for individuals to report their spatial ability using 44 survey questions rated on a 5 point Likert scale (Zhong, 2013; 2020; Zhong & Kozhevnikov, 2016). The items on the NSQ fall under three categories: survey-based strategy (NSQ-S), procedural/route strategy (NSQ-P), and egocentric spatial updating strategy (NSQ-E). The survey-based strategy (12 items) was used to test cardinal directions skills and the ability to use fixed allocentric coordinates to view cognitive maps. The procedural/route-strategy (15 items) was used to assess one's dependence on visual memory by using their knowledge of landmarks. The egocentric spatial updating strategy (17 items) was used to assess one's ability to change their position depending on the point of origin, or attain a sense of direction/path integration using an internal compass.

2.2.7 Demographic Questionnaire

Participants filled out a demographic questionnaire reporting their age, sensitivity to motion sickness, claustrophobia, and vertigo. An open-ended question asked for any other health concerns of which they believed the experimenter should be made aware. The participants were also required to report the weekly average hours spent working on the computer, playing video games, or playing virtual reality games.

2.3 Stimuli and Design

The stimulus used in the driving task was a dynamic simulation of a small virtual town. The simulation was coded in C++, using the Vega Prime (Presagis) library. The simulation was displayed on three 42" (diagonal) LCD screens, arranged to provide participants with a field of view of 120° horizontally and 35° vertically (Figure 1). Each screen ran at a refresh rate of 60 Hz, with a resolution of 1920 x 1080 pixels. The LCD screens were fixed in place, such that the distance between the screens and the participants' eyes was maintained at approximately 120 cm. Two cameras were installed within the interior of the simulation pod. One was affixed at the front of the simulator, providing a view of the participant's face. The second was mounted at the back of the simulator, providing an overhead view of the interior of the simulation pod to allow for the monitoring of the experiment. Additionally, the intercom system allowed participants and experimenters to remain in constant communication. Inside the simulator, participants were seated in a bucket car seat facing a basic driving interface composed of a Logitech steering wheel, as well as a gas and brake pedal (Logitech International S.A., Lausanne, Switzerland). Data was continuously recorded from both the steering wheel and the pedals at a rate of 60 Hz. (Figure 2).

The virtual town consisted of a 4 x 4 grid of roadways intersecting a 3 x 3 grid of city blocks. The target destination of each trial was a parking space in the middle of the town, located such that it was not visible to participants until they drove within close proximity. The town was composed of three different types of structures: generic buildings, proximal landmark buildings, and distal landmark structures. There was a total of four different proximal landmarks positioned on the inner corners of four blocks closest to the end destination. These proximal landmarks (a church, store, house, and gas station) were only visible to participants from a relatively close distance. Conversely, the four distal landmarks could be seen by participants from any location in the town. The distal landmarks consisted of four different towers (a radar, control, wind and water tower), with one tower situated along each of the four outer edges bordering the town. The generic buildings comprising the rest of the town's composition were buildings identical in color and measurement (Figure 1 & 2).

2.4 Procedure

The duration of the experimental session was 2 hours and participants began by filling out the questionnaires and performing visual-spatial tasks identified in section 2.2. The order of the questionnaires and visual spatial tasks was random, and this part of the experiment was approximately 75 minutes in duration. Participants then moved to the driving simulator for basic driving training to become familiar with the simulator controls (e.g., accelerator, brake pedal, steering, and display). The experiment consisted of four blocks of trials, each with a unique configuration of environmental landmarks. In the combined proximal and distal block (PD), both proximal and distal landmarks were present. In the distal landmarks block (D), only distal landmarks were made available, whereas in the proximal landmarks block (P), only proximal cues were available. In the no landmark block (N), neither proximal or distal landmarks were present. The order in which these four blocks were presented was counterbalanced across all participants. Participants were not aware of the landmark condition before the onset of the blocks. Participants were instructed to follow standard residential area road rules such as driving in the right lane at 30- 40 km/h.

Each block consisted of four training trials followed by four test trials. The participant pressed a start key on the steering wheel to begin the trial. On each of the four training trials, participants were guided along a different route towards the same final destination. Each training route began at a different start location on the edge of town, and encountered 4 decision points at intersections on the way to the target destination. As the car approached a decision point, a guiding arrow was overlaid on the screen to indicate whether a left or right turn was required. Following the four training routes, participants were tested for their ability to remember and recreate the trained routes. The four test trials were presented in the same order as the training routes. On each test, the virtual car was placed at the same starting point and in the same orientation as the corresponding training trial. The task was to find the target location by driving the route they learned during training, but without the aid of the guiding arrows. There was a 90 second time limit after which the trial ended. The message “Goal reached!” was superimposed on the display screen at the end of the trial the target location was reached within 90 seconds, otherwise “Timeout!” was displayed.

Figure 1: Illustrations of the virtual towns with different types of landmarks. **Image 1** shows a participant driving in a virtual town where two distal landmarks are visible: a radar tower on the left and a water tower on the right. **Image 2** shows a virtual town with a proximal landmark (a store on the right) and a distal landmark (a water tower on the left). A green and white guiding arrow in the middle of the screen indicates an upcoming right turn. **Image 3** shows a virtual town with a proximal landmark on the right (a colorful house) and a distal landmark at the end of the road (a radar tower).

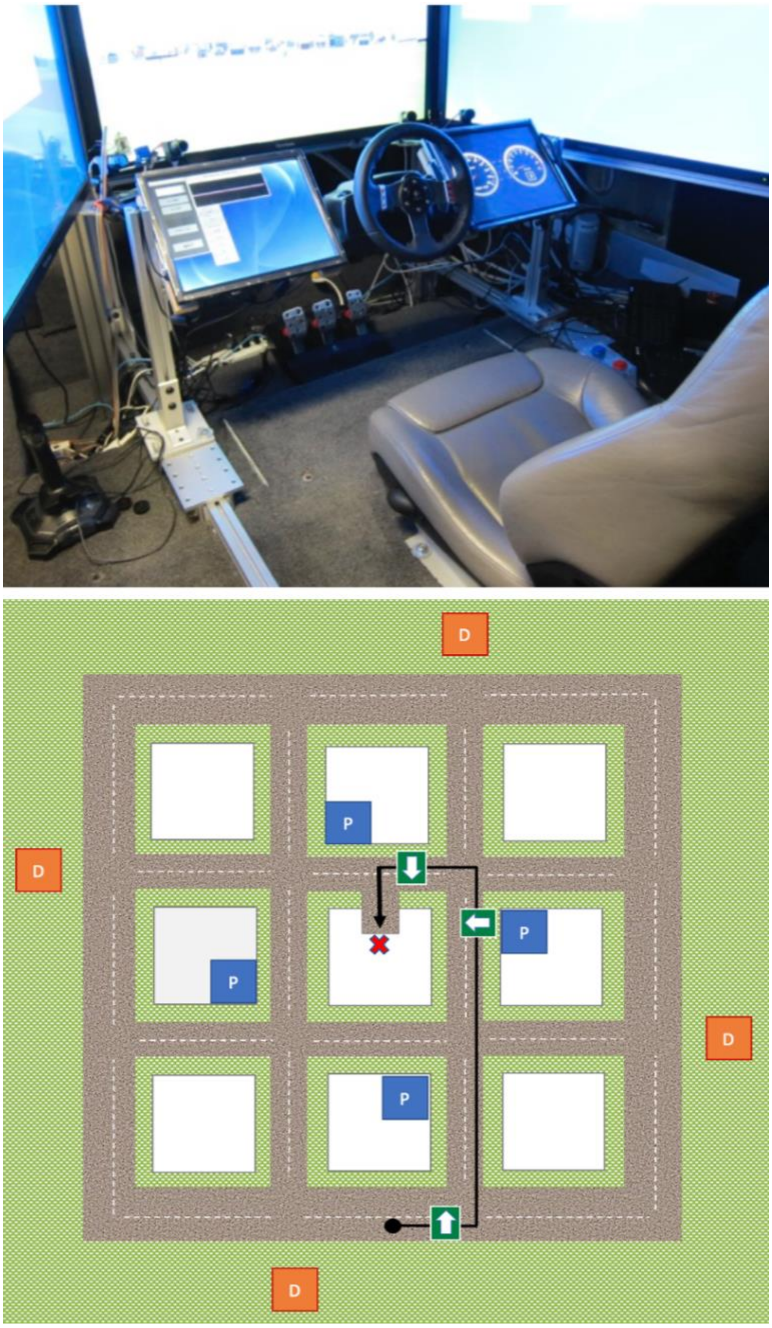

Figure 2: **Top figure:** Illustration of the inside the simulator where LCDs, steering, gas and brake pedals are located. **Bottom figure** is a top-down view of the virtual town's map. We illustrated an example of a guided navigation route with arrows from start to end in the Combined (Proximal & Distal) block. Blue squares with the letter P indicate locations of the proximal landmarks (e.g., gas station, store), and orange squares with the letter D indicate locations of the distal landmarks (e.g., radar tower, water tower). The red X in the middle of the town indicates the location of the target destination.

3. Results:

3.1 Statistical Analysis

Participants in the test trials were asked to find the target destination within the allotted time. Success was a binomial record of success or failure in finding the target location. We applied a mixed model logistic regression (GLMM) to assess how success in different landmark conditions (PD, P, D, & N) could be predicted by the visual spatial (MRT, PTSOT, CST, & DST) and self-reported measures (SBSOD & NSQ). The reference category in the logistic model was the No landmark block (N block) as it had the lowest success rate compared to the other groups and comparing the other landmark blocks to this block intuitively provided more interpretable results. In the demographic questionnaire, participants reported: gender, average weekly hours of driving, using computers and playing video and virtual reality games. We did not observe any statistically significant association between demographic factors and success rate. Gender was the only factor marginally associated with success ($\beta = 0.4841$, $z = 2.493$, $p = 0.053$). Participants were tested in a repeated measure design in four different landmark blocks across 16 trials (4 blocks x 4 test trials). As a result, we were able to control for the possible learning effect of *trials* on the response variable (success) by including the variable of "*trial*" in the model as a fixed effect and control for the learning variation among participants by including "*trial*" as a random slope in the model. The generalized linear mixed model used for all analyses is noted below in Wilkinson notation (Wilkinson and Rogers, 1973):

Success (S) ~ Landmark group * MRT (or any other measure) + trial +

(0 + trial | participants)

The model was separately run for PTSOT, CST, DST, NSQ, and SBSOD measures to check the interaction between the landmark group and these measurements. The estimate (β) of each term represents the log-odds ratio between the term and the reference category. Data and R code are available for interested readers at: https://github.com/Jabbariy/Manuscript3-Thesis.

In this section we discussed the interactions between success in different landmark blocks and performance in visual-spatial and self-reported navigation abilities measures. Descriptive statistics of performance in the landmark blocks and other administered measures are provided in Tables 1 and 2.

3.2 Visual Spatial Measures

PTSOT (Perspective Taking/Spatial Orientation Test): Success in the combined block (PD) had a significant interaction with the average error in the PTSOT (β = -0.035, z =-2.413, p =.015). The negative estimate indicated that a lower average error in spatial pointing was associated with a higher success rate in the combined block (PD). No other significant interactions were observed between the score in PTSOT and the success in other landmark blocks (see Table 3).

CST (Corsi Span Task): Success in the proximal landmarks block (P) marginally interacted with the CST score, such that larger spans were associated with higher success rates (β = 0.564, z = 1.921, p = .054). No other significant interactions were observed.

MRT (Mental Rotation Task): success in the distal landmark block (D) significantly interacted with the MRT score (β = 0.1114, z = 2.192, p = 0.028) indicating that higher MRT scores are associated with greater success. Success in the proximal landmark block (P) marginally interacted with the MRT score (β = 0.1138, z = 1.797, p = 0.072). We did not observe any significant interaction between MRT score and success rate of the other landmark blocks.

DST (Digit Span Task): We observed that success in the P block was marginally associated with the DST score, such that larger spans were associated with higher success rates (β = 0.674, z = 1.900, p = 0.057). No other significant interactions between the DST score and the success in other landmark blocks were observed.

3.3 Self-report questionnaire

SBSOD (Santa Barbara Sense of Direction): We did not observe any significant associations between scores from the SBSOD questionnaire and success rate in any of the landmark blocks. There was only one marginal association between SBSOD scores and success in the D block (β = 0.543, z = 1.870, p = 0.061).

NSQ-E (Navigation Skill Questionnaire - Egocentric): Success in the (D) block significantly associated with the score in the egocentric spatial updating strategy items of the NSQ questionnaire (β = 1.078, z = 2.456, p = 0.0141) indicating that the self-reported egocentric spatial updating skill is associated with success in the D block.

NSQ-P (Navigation Skill Questionnaire - Procedural): Score on the procedural strategy items of the NSQ questionnaires negatively associated with the success rate of the N block (β = -0.916, z = -2.461, p = .0138) indicating that self-reported dependency on visual cues and landmark-related procedures is associated with lower success rate in the no landmark environment. NSQ-P also marginally associated with the success in the PD block (β = 1.065, z = 1.93, p = 0.053). We did not observe any significant interaction between this score and the success in other landmark blocks.

NSQ-S (Navigation Skill Questionnaire - Survey): No significant interactions were observed between scores on survey-based strategy items of NSQ questionnaire and success in any of the landmark blocks (see Table 4). The scoring of the NSQ-S items was updated based on the recently released paper by the NSQ author (Zhong, 2020).

Table 1: Mean and standard error of success in different landmark blocks.

landmark	Mean	Standard Error

No landmark (N)	0.771	0.025
Distal (D)	0.835	0.022
Combined (PD)	0.903	0.017
Proximal (P)	0.925	0.019

Table 2: Mean and standard error of the administered visual-spatial and self-reported measures.

	Visual-Spatial Measures				**Self-Report Measures**			
	PTSOT	*CST*	*DST*	*MRT*	*NSQ-E*	*NSQ-S*	*NSQ-P*	*SBSOD*
Mean	28.472	6.5286	7.0857	13.543	3.0933	2.9864	3.6711	4.4020
SE	0.531	0.031	0.028	0.146	0.016	0.017	0.014	0.025

Table 3: Association of success in different landmark blocks (N, P, D & PD) with visual-spatial measures (PTSOT, MRT, CST & DST). "*" denote p < .05, and "." denote marginally significant results.

		β	**SE**	*z*	***p***			***β***	**SE**	*z*	***p***
PTSOT	*N:PTSOT*	0.002	0.01	0.2110	0.833	***MRT***	*N:MRT*	0.035	0.03	1.0430	0.297
	P:PTSOT	-0.024	0.02	-1.5330	0.125		*P:MRT*	0.114	0.06	1.7970	0.0724.
	D:PTSOT	0.005	0.01	0.3810	0.702		*D:MRT*	0.116	0.05	2.1920	0.0284*
	PD:PTSOT	-0.035	0.02	-2.4130	0.015 *		*PD:MRT*	0.036	0.06	0.6570	0.511
CST	*N:CST*	0.016	0.16	0.0990	0.9212	***DST***	*N:DST*	-0.093	0.20	-0.4720	0.6366
	P:CST	0.564	0.29	1.9210	0.0547.		*P:DST*	0.675	0.35	1.9000	0.0575.
	D:CST	-0.036	0.22	-0.1630	0.8703		*D:DST*	0.121	0.26	0.4730	0.6364
	PD:CST	-0.026	0.25	-0.1070	0.9146		*PD:DST*	0.226	0.29	0.7790	0.436

Table 4: Association of success in different landmark blocks (N, P, D & PD) with self-reported navigational skills measures (SBSOD, NSQ-E, NSQ-S & NSQ-P). "*" denote p < .05, and "." denote marginally significant results.

		β	**SE**	*z*	***P***			***β***	**SE**	*z*	***P***
SBSOD	*N:SBSOD*	-0.042	0.21	-0.1980	0.8433	***NSQ-E***	*N:NSQ-E*	-0.231	0.33	-0.7090	0.4782
	P:SBSOD	0.163	0.35	0.4670	0.6407		*P:NSO-E*	0.500	0.53	0.9450	0.3446
	D:SBSOD	0.544	0.29	1.8700	0.0615.		*D:NSO-E*	1.079	0.44	2.4560	0.0141*
	PD:SBSOD	0.223	0.32	0.6980	0.4853		*PD:NSO-E*	0.048	0.51	0.0940	0.9248
NSQ-S	*N:NSQ-S*	-0.296	0.30	-0.9790	0.327	***NSQ-P***	*N:NSQ-P*	-0.916	0.37	-2.4610	0.0138*

P:NSQ-S	0.274	0.50	0.5510	0.582	*P:NSQ-P*	1.027	0.61	1.6780 0.0933.
D:NSQ-S	0.469	0.41	1.1460	0.252	*D:NSQ-P*	0.310	0.51	0.6140 0.5393
PD:NSQ-S	0.467	0.47	0.9960	0.319	*PD:NSQ-P*	1.066	0.55	1.9330 0.0532.

4. Discussion

In this study, the relationship of visual spatial abilities and self-reported navigation skills with wayfinding performance of drivers was assessed. Drivers were trained to find a target destination in different landmark-based environments, and later their navigation accuracy in finding the destination was tested. Participants completed various visual-spatial and self-reported navigational skill assessments. Research has shown that strong performance in spatial-cognitive ability measures can indicate improved navigation performance (e.g., Meneghetti, et al., 2016; 2011; Gras et al., 2013; Boccia et al., 2017; Tascon et al. 2017; Kato & Takeuchi, 2003; Lawton, 1994). In the study presented in this paper, we aimed to assess if route learning of drivers in different landmark-based environments could be predicted by individual differences in cognitive spatial skills and self-reported navigation abilities.

We provided different sources of navigational cues, including distal and proximal landmarks, as leveraging these various navigational cues requires different cognitive and spatial skills. We investigated whether the type of landmark affected the importance of visual-spatial and self-reported skills in navigation performance. Importantly, navigation performance was tested in an ecologically valid setting in which drivers navigated while driving, similar to real-world challenges that combine driving and navigation. The findings of this study may help to better explain the extent to which the administered visual spatial and self-reported tests could be predictors of a driver's navigational performance.

4.1 Visual spatial measures

Below, we situate the findings of the study in the existing literature. The Mental rotation test (MRT; Vandenberg & Kuse, 1978) has been widely used as a test of spatial ability to approximate the ability of an individual to mentally rotate a representation. Previous research shows those with higher MRT scores have better navigation and orientation skills in wayfinding tasks in a real-world setting (Malinowski, 2001). Likewise, performance on the MRT has been shown to correlate with map-based route learning performance. When asked whether a route was the same or different to a previously traversed route, individuals with higher MRT scores were more accurate and more confident in their judgements (Thoresen et al., 2016). Higher MRT scores were correlated with fewer errors in the landmark pointing test (Castelli et al., 2008). Additionally, Pazzaglia and Beni (2006) observed that those with high MRT scores performed better in a directional judgment task that required the manipulation of spatial representations. The authors suggested the use of egocentric spatial representations by those with low MRT scores, as opposed to map-like or allocentric spatial representations by those with high MRT scores.

In line with previous studies, our findings showed that higher scores in the MRT were associated with navigation success. However, the type of landmark mattered. We showed specifically that higher MRT scores were a significant predictor of success in finding target location in the distal landmark only block (D block). It can be concluded that navigation with the presence of distal landmarks requires application of survey knowledge and mental rotation to utilize directional map-like information that distal landmarks may provide (e.g., Zhong & Kozhevnikov, 2016; O'Keefe & Nadal, 1978).

Distal landmarks were also available in the combined block (PD), but success rate in the PD block was not significantly associated with MRT scores. This supports the idea that drivers in the PD block relied more on the navigational information obtained from proximal landmarks to apply route-based navigation strategies. Route-based navigation strategies emerge faster in the presence of proximal cues and are easier to apply by most navigators as they are less cognitively demanding than survey-based strategies (Brunyé, et al., 2017; Waller & Lippa, 2007; Hurlebaus et al., 2008).

Spatial ability as measured by the Perspective taking/spatial orientation test (PTSOT; Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001) is positively correlated with the ability to find efficient routes in navigation studies (Battles & Fu, 2014). Oskarsson et al. (2014) found that those with low spatial ability measured by the PTSOT were less precise than those with medium or high spatial ability in transforming information on a map to positions in the terrain. However, such individual differences may not always be captured with the PTSOT. For instance, in a study by Weisberg et al. (2014), participants were tasked with pointing towards the location of various buildings in a virtual environment that they had previously learned about. Scores on the PTSOT did not differ between individuals who were grouped based on performance on this pointing task. Similarly, we found that high spatial ability measured by PTSOT improved route learning of drivers and helped them successfully localize the destination; however, only when navigational information from both proximal and distal landmarks were available to navigators.

In the present study, we measured visual spatial working memory (VSWM) span using the Corsi span task (CST) and verbal working memory (VWM) span using the Digit span task (DST). The CST measures the ability to retrieve visuospatial information from VSWM, where 2D and 3D representations are temporarily stored and processed simultaneously. While DST measures the ability to retrieve verbal information from VWM, where numerical information is temporarily stored and processed simultaneously (Wechsler, 1981; Berch et al., 1998).

Several studies looking at the relationship between working memory and navigation used a dual-task paradigm model, in which participants performed two tasks simultaneously during the learning phase of the study (e.g., Gras et al., 2013). The primary task is usually a navigation-based task, such as learning a map. The secondary task is a specific interference task, which is included to add cognitive load by competing for spatial information in VSWM or VWM and eventually impacting the encoding of the information. However, in this study, we tested the possible direct relationship that VSWM and VWM capacity might have on the route navigation of participants.

Previous research has shown that higher scores in the CST have been associated with better sustainment of spatial information and greater ability to recall routes (Meneghetti et al., 2016). Performance in CST has been associated with performance in tasks requiring the knowledge of the absolute location of landmarks (e.g., route recognition tasks) rather than tasks requiring the knowledge of relative location of landmarks (e.g., euclidean distance judgment and map section rotation) (Bosco et al., 2004; Coluccia, 2007). Lastly, Meneghetti, et al. (2019) observed a visually but not statistically high correlation between shortcut finding and VSWM performance in CST. The authors believed that this might be due to the difficulty of their shortcut finding task, as participants had a large number of turns to choose from and the provided environmental layout was complex.

In the present study, we observed that VSWM span measured by CST only marginally (p =.054) predicted route learning in the P block. It has been suggested that the role of VSWM might be more identifiable in route-based navigation tasks (e.g., P block) and difficult to detect in map-based navigation tasks (Meneghetti et al., 2019). The CST is considered a passive working memory task since it doesn't require an active processing of the encoded visual spatial information such as transformation or manipulation of the information after encoding (Vecchi & Cornoldi, 1999). However, drivers in the present experiment mainly required an active manipulation of spatial information to find their way toward the destination. As a result, it can be suggested that the CST (Corsi Span Task) might not be a strong predicting measure of navigation performance when navigators are involved in a higher level spatial tasks in terms of cognitive demand.

We observed a marginally significant association between VWM capacity measured by the Digital Span Task (DST) and the navigation performance of drivers in the P block (p = 0.057). Studies have shown that VWM is less involved in navigation tasks that require spatial rotation skills and survey knowledge of the environment. However, navigation tasks that involve route memory, association of landmark positions to routes, or reading landmark labels would involve both VWM and VSWM (Labate et al., 2014; Picucci et al., 2013; Gras, et al., 2013). In this study, it would be possible that drivers were using VWM to associate landmarks with turns in the presence of proximal landmarks (e.g., turn left at the gas station); however, this matter could have been systematically detected if we had a dual task paradigm with a VWM interference task.

4.2 Self-report measures

The influence of individual differences on navigation abilities can be measured through standardized self-report measures. One of the self-reported measures used in this study was the Santa Barbara Sense of Direction (SBSOD) questionnaire, which features fifteen 7-point Likert scale items probing an individual's sense of direction and orientation (Hegarty et al., 2002). SBSOD scores are correlated with memory consolidation of landmarks (Janzen, et al., 2008). In the present study, no significant interactions between SBSOD scores and success in any of the landmark blocks were observed. Although SBSOD is a standardized test for estimation of self-reported navigation skills, not all studies find correlations with test results (e.g., Boccia et al., 2016). Some studies have suggested that SBSOD might be a more accurate predictor of navigation success when correlated with performance in large-scale environments and direct real-world navigation experiences (Kozhevnikov & Hegarty, 2001;

Franke & Schweikart, 2017). Large scale environments call for different topological knowledge (Hegarty, 2006) than smaller scale virtual environments such as those used in the present experiment. However, on the large environmental scale where participants have direct navigation experience by walking or driving around, route learning is enhanced by both visual and vestibular inputs, which would highly affect the sense of direction and spatial updating abilities of navigators (Hegarty, 2006; Klatzky et al., 1998; Loomis et al., 1999). In the present experiment, the simulation did not include physical motion of the vehicle; however, we showed the improving effect of vestibular self-motion cues on route learning in Chapter 3.

Another self-reported measure that we administered in this study was the navigational strategy questionnaire (NSQ). NSQ is divided into three scales that estimate egocentric spatial updating strategy (NSQ-E), procedural/route strategy (NSQ-P), and survey strategy (NSQ-S) (Zhong & Kozhevnikov, 2016; Zhong, 2013; 2020). There were only two significant effects from this survey: the NSQ-E scale scores were positively correlated with success rate in the D block, and the NSQ-P scale scores were negatively correlated with success rate in the N block.

NSQ is a fairly new self-report measure, and there are not many findings in the literature on the correlation of NSQ subscales with navigation performance. It has been shown that scores in the egocentric spatial updating scale were correlated with egocentric navigation measures. Individuals who scored higher in egocentric spatial updating produced lower reaction times in pointing tasks, which are facilitated by the use of self-to-object relationships (Zhong & Kozhevnikov, 2016).

The present study showed that higher egocentric spatial updating scores were solely associated with the success rate in the distal landmarks only block (D block). Recall that the task was to retrace the training routes, a process facilitated by egocentric navigation involving proximal landmarks. Efficient navigation in the D and N blocks, which lack proximal landmarks, likely required greater administration of survey knowledge and mental rotation skills than was needed when proximal landmarks were available. The lower rate of success in the D block compared to the blocks with proximal landmarks, indicated the challenge that drivers faced in obtaining navigational information from distal landmarks to apply allocentric-based strategies. The association of the success in the D-block and the ability to egocentrically update one's spatial position (NSQ-E) might indicate a useful alternative skill to find the target in the D-block. This association was not observed in any other blocks. Probably, navigational information of proximal landmarks in the P and PD blocks was easy enough to refer to for wayfinding purposes that navigators did not need any spatial updating skills. Since there were no proximal and distal landmarks in the N block, participants might implement the "sequential response strategy" to remember the segments of the routes in temporal order to reach the destination (Iglói et al., 2009).

Furthermore, we observed that self-reported dependency on visual cues or spatial strategies based on landmarks as measured by NSQ-P was correlated with poor route learning in the no landmark block. NSQ-P also had a trending positive relationship with success in P and PD blocks, which indicated that the presence of proximal landmarks was helpful for individuals dependent on landmark-based wayfinding strategies.

In summary, our navigation performance is highly affected by our working memory capacity, visual-spatial and mental-rotational skills (e.g., Gras et al., 2013; Boccia et al., 2017). The results of this study replicated the findings of previous studies indicating that individual differences at visual spatial level and self-reported navigation skills highly predicted route learning. Furthermore, we showed that the effect of these individual factors can extend to route learning in an ecologically valid test setting of driving and varies based on the availability of different classes of environmental landmarks.

4.3. Limitations

In this study, we simulated a small virtual town with the consideration of preventing cybersickness. A bigger town with more landmarks, even though it might increase the chance of cybersickness, can demand more cognitive resources and provide different prediction outcomes. Participants in this study reported their frequency of driving on an average week. However, knowing the overall driving experience (e.g., number of years driving; frequency of city vs rural driving) could have been beneficial, since driving and navigating may be more cognitively demanding for less experienced drivers.

The CST and DST tasks in this study were administered only in a forward version, to only measure the WM span. The forward CST and DST, respectively, measure the visuospatial and verbal working memory and short-term memory span, but the backward version of these tasks, in addition to measuring memory span, measures executive function due to the increase in the working memory load (Thomas et al., 2003; Cherry et al., 1996; Hester et al., 2004; Kessels et al., 2010). However, it should be noted that there are studies that did not observe differences in performance between forward and backward versions of the CST task (Kessels et al., 2008).

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CHAPTER 5: Egocentric Spatial Encoding of Drivers is Preserved with Age: a Simulated Driving Study

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Preface

Chapter 5 presents the results of an experiment in which the relationship of age with the route learning of drivers was examined. We used a driving simulator and a virtual environment consisting of a small town; young, early middle-age, and late middle-age adults actively drove along routes through the town, leading to a target destination. They were then tested for their acquired route knowledge. Results revealed that all age groups performed similarly if their spatial representations of the routes were tested egocentrically. However, they performed differently if their spatial representations were tested allocentrically. The late middle-age group was less accurate in performing the navigation task allocentrically; however, their accuracy improved with training.

Abstract

Older drivers are more likely to experience inflexibility in their spatial abilities, such as mental rotation skills and switching between navigation strategies. This study aimed to examine how aging influences the spatial encoding of drivers from egocentric and allocentric points of view. Using a driving simulator, participants actively drove in a virtual town. Participants were initially trained to find a target destination through different routes in a guided navigation block. Later, during the test block, they were placed at different previously traversed intersections and asked to indicate the shortest path to the destination. The test trials showed the intersections in the same orientation/position as the guided navigation block (egocentric points of view) or in a different orientation/position (allocentric point of view). The results showed that while spatial encoding from an egocentric point of view was preserved with age, retrieving from an allocentric frame of reference was more difficult for older adults.

Keywords: Spatial Navigation, Driving Simulator, Allocentric and Egocentric frame of reference, Motion Sickness, Aging, Middle-age adults

1. Introduction

Two common wayfinding strategies that we use to navigate in the environment are allocentric and egocentric navigation strategies (e.g., O'Keef & Nadel, 1978; Klatzky, 1998; Iaria et al., 2009; Zhong & Kozhevnikov, 2016). There is an age-related effect on the application of navigation strategies. Aging sometimes leads to deficits in various cognitive functions that are important for navigation, such as spatial memory, mental rotation, and visual-spatial perception (e.g., Iaria et al., 2009; Verhaeghe, et al., 2005; Gazova et al., 2012). Research has shown a dramatic decline in the implementation of allocentric-based navigation strategies among older adults (e.g., Harris & Wolbert, 2014; Colombo et al., 2017). Compared to young adults, older adults are slower in generating cognitive maps and are less accurate in using them (Harris & Wolbert, 2014; Moffat & Resnick, 2002; Iaria et al., 2009).

An allocentric navigation strategy is when the spatial relationships between landmarks in the environment are encoded independent of the observer. This form of navigation often occurs through cognitive maps and can help navigators find new routes to their destination (e.g., O'Keefe & Nadel, 1978; Mou et al, 2004; Klatzky 1998; Maguire et al., 1998; Fergusen et al., 2019). Allocentric navigation is mediated by the medial temporal lobe structures, particularly the hippocampus, and neuroimaging research has revealed a decline in the performance of the hippocampus among older adults, in contrast to a stable performance among younger adults (e.g., Gron et al., 2000; Moffat et al., 2007; Antonova et al., 2009).

An egocentric navigation strategy is when the spatial relationships between landmarks are encoded relative to the observer. This often occurs through route-based navigation and requires constant spatial updating of the navigator's position relative to the point of origin (e.g., Kelly & McNamara, 2008; Burgess, 2006; Klatzky, 1998; Wolbers & Wiener, 2014; Mou et al, 2004; Waller & Lippa, 2007; O'Keefe & Nadel, 1978). To the best of our knowledge, literature has not reached an agreement on whether egocentric-based navigation is susceptible to decline with age. Egocentric navigation is mediated by the parietal lobe particularly caudate nucleus of striatum (Antonova et al., 2009; Moffat et al., 2006; Maguire et al., 1998), and neuroimaging studies have demonstrated small or absent age-related impairments in the activity of this region during egocentric navigation tasks (Antonova et al., 2009; Moffat et al., 2006). While some studies have indicated that egocentric spatial representation stays intact in older age (e.g., Gazova et al., 2013; Antonova, et al., 2009; Moffat et al., 2006; Fricke & Bock, 2018) and is preferred by older adults in contrast to allocentric spatial representation (e.g., Wiener et al., 2013; Rodgers et al., 2012), other studies have reported impaired egocentric spatial representation in older adults (e.g., Fernandez-Baizan et al., 2019, 2020; Ruggiero et al., 2016). For example, older adults may have difficulty in egocentric encoding of spatial information such as route learning, target localization, and encoding and retrieval of the temporal order of landmarks (e.g., Wilkniss et al., 1997; Moffat et al., 2001; Head & Isom, 2010).

In this study, we assessed how aging influences egocentric and allocentric spatial encoding of the environment while driving. Participants were first trained by driving along different routes to a target destination. Following training, they were presented with images of intersections along the traversed routes from various perspectives and asked to indicate the shortest path to the target destination. Some perspectives were directly experienced from an egocentric point of view during the training (egocentric trials), whereas other perspectives were experienced indirectly from an allocentric point of view at different angles/positions than experienced during training (allocentric trials).

Note that we assessed older adults while they were engaged in the cognitively demanding task of driving. Based on the existing literature, we expected that aging would be associated with a decline in implementing allocentric navigation strategies, but we were not certain about the performance of older adults in the egocentric trials in our driving task. One study did find an age-related difference between egocentric and allocentric processing (Fricke & Bock, 2018). They tested egocentric and allocentric navigation separately, using keyboard arrow keys and mouse movements to navigate along different routes. They found age-related deficits in the allocentric condition but not in the egocentric condition. Based on such results, we might predict that our assessment would reveal the preservation of egocentric spatial processing, but most findings in the current literature, including Fricke and Bock (2018), do not examine spatial knowledge during active driving. The studies that reported age-related deficits in both egocentric and allocentric navigational representations used either non-navigational spatial memory tasks (e.g., Fernandez-Baizan et al., 2019; Ruggiero et al., 2016) or desktop virtual navigation mazes (e.g., Head & Isam, 2010; Moffat et al., 2001) in which participants navigated through the environment using joysticks or keyboard keys.

Driving and navigating simultaneously, such as we often do, is likely to be a more challenging task for older adults compared to a desktop navigation experiment. They need to share limited cognitive resources between the two tasks and compensate for age-related deficits in physical, cognitive, and sensory functions to accurately drive and apply navigation strategies. Some research has suggested that older adults self-regulate by primarily driving in familiar environments and avoiding wayfinding challenges in unfamiliar environments (e.g., Rosenbaum et al., 2012; Wiener et al., 2013; Iaria et al., 2009). The findings of the present study may inform intervention strategies to improve spatial navigation skills in older drivers.

2. Method

2.1. Participants

Fifty-six participants (32 males; mean age = 38.66, SE = 2.10) with an age range of 18 to 66 completed the task for this study. Originally, seventy participants were recruited. However, 14 participants were excluded from the sample (technical issues, n = 4; motion sickness, n = 8; and other health issues (migraine and vertigo), n = 2). Participants were recruited from the undergraduate research pool, the McMaster community, and the city of Hamilton. Undergraduate participants received partial course credit and other participants received monetary compensation. Participants were part of a set of experiments and completed two tasks prior to the experiment analyzed in the present study (Kenney et al., 2021). We divided participants into three age groups: young adults (18–30, n = 18), early middle-age adults (30–45, n = 18), and late middle-age adults (45–66, n = 20). Participants were required to have a valid driver's license. They reported normal or corrected-to-normal vision and hearing and no sensitivity to claustrophobia and motion sickness. The experimental protocol was approved by the Hamilton Health Research Ethics Board and conformed to the Canadian Tri-Council policy on ethics. Participants provided written consent before participating in the study.

2.2. Experimental setup

Participants sat in a car seat inside an immersive driving simulator that induced motion through a MOOG© platform with six degrees of freedom (MOOG series 6DOF2000E). Three 43" LCD screens with a resolution of 1920 x 1080 pixels and a 60 Hz refresh rate were used to present visual stimuli. The screens were aligned to make 35° vertically and 120° horizontally field of view. The car seat maintained a distance of approximately 120 cm between the participant and screens. We used a Logitech steering wheel and gas and brake pedals (Logitech International S.A., Lausanne, Switzerland) (Figure 1). The pedals and steering wheel data were continually recorded at a 60 Hz rate. The experiment was monitored by two cameras inside the simulator, providing birds-eye views of the interior. Participants and the experimenter communicated through an intercom system.

To create the virtual environment, we used the Vega Prime (Presagis) library in C++.

We designed a 3 x 3 street virtual town that consisted of 9 city blocks. The target destination was a small dead-end placed inside the middle block. Eight landmarks were located in different areas of the town. Four proximal landmarks, which included a gas station, shopping store, house, and church, were located on the outside corners of the 4 internal blocks around the target destination. Four distal landmarks, which included a radar tower, wind tower, water tower, and control tower, were located outside the boundaries of the small town, one on each edge side of the town (Figure 2).

Participants received motion responses from the simulator while driving in the virtual town. For instance, when participants hit curbs, pressed the brake pedals, and turned the steering wheel, the simulator induced motion responses comparable to those experienced when driving a vehicle in the real world. The motion system induced motion in six degrees of freedom (three rotational motions and three translational or linear motions), which were all the possible motions for an object moving in a three-dimensional space. The three rotational motions were roll (tilting side to side on the X-axis), pitch (tilting forward and backward on the Y-axis), and yaw (turning left and right on the Z-axis). The three translational or linear motions were surge (moving forward and backward on the X-axis), sway (moving left and right on the Y-axis), and heave (moving up and down on the Z-axis).

Figure 15: Top: Outside view of the simulator and control interface. Bottom: Inside view of the simulator, showing a participant driving in the virtual town. A colorful house on the right and a radar tower at the end of the street are, respectively, proximal and distal landmarks.

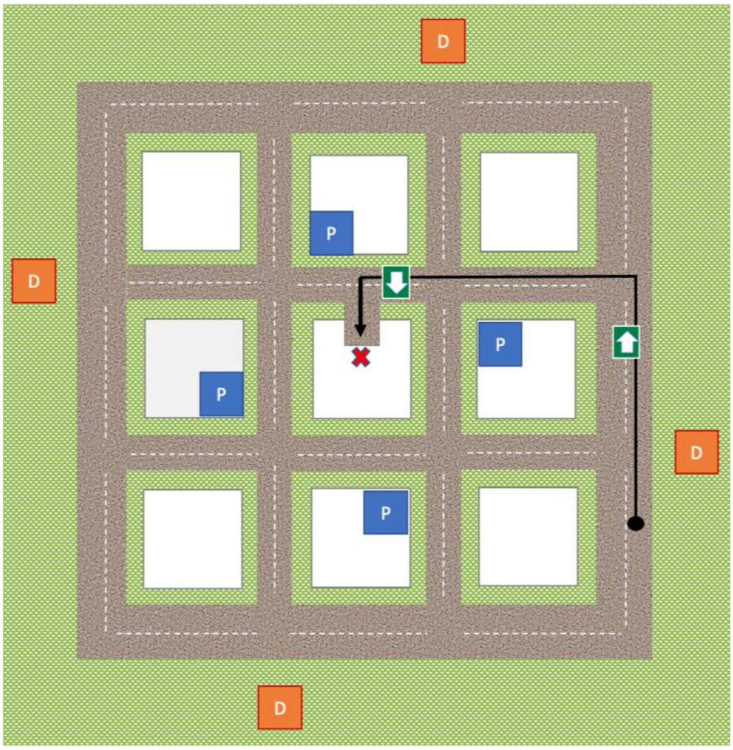

Figure 2: Top: an example of a test trial. Participants were shown an intersection of the town and were asked to indicate the shortest path to the destination. A gas station on the right (proximal landmark), a wind tower at the end (distal landmark), and a view of the rear of a church on the left side of the road (proximal landmark) are the visible landmarks at the intersection. Bottom: Top-down view of the virtual town. The orange boxes with the letter D, the blue boxes with the letter P, and the red "X", respectively, indicate the location of distal landmarks, proximal landmarks, and the target destination. The black line is an example of a training route with only left turns.

2.3 Procedure

Participants first completed a demographic questionnaire reporting age, gender, average weekly hours of (1) driving, (2) working with computers, and (3) playing video or driving games. This was followed by the driving experiment. The driving experiment began with a short 1.5 minute practice drive in the driving simulator, and was repeated for any participants who requested more practice.

Following the practice drive, participants were presented with two blocks; each block consisted of a guided navigation phase and a test phase. Each guided navigation phase consisted of four different routes through the virtual town, each leading to the target destination. The same four routes were repeated in the navigation phases of both blocks so that learning effects could be examined. Participants drove each of the four routes, one after the other, following guiding arrows that appeared as a heads-up display as the virtual car approached a decision point such as an intersection (see Figure 1 for an example). There were four decision points on each route. Each route took approximately 60 seconds to complete. Once the participant reached the target destination, the virtual car was reset at the beginning of the next route. Participants were instructed to pay attention to the environmental cues (e.g., landmarks) they encountered along the routes. They were instructed to maintain the speed limit of 40 km/h and follow standard traffic rules (e.g., staying in the middle of the right lane).

Following each guided navigation phase, participants completed a test phase with 24 test trials where they were shown images of intersections from the guided navigation phase. Images were from the driver's viewpoint and were either from the same orientation and direction experienced during the guided navigation phase (egocentric trials) or from a different direction/orientation (allocentric trials). An example of an allocentric trial might involve the virtual car facing north during guided navigation and east during test. For each image, participants used the arrow keys on a computer keyboard to indicate whether a left turn, right turn, or no turn would be the shortest route to the target destination.

Participants were then given a mandatory 5 to 10 minute break between the two guided navigation and test blocks to decrease the chance of motion sickness. The whole experiment including the break time was approximately 30 minutes in duration.

2.4 Virtual route design change due to motion sickness

After testing 15 participants (groups: young = 6, early middle-age = 3, late middle-age = 6), we made a modification to the design of the routes in the guiding navigation block, due to a substantial number of motion sickness reports in the late middle-age adults (see section 3.3 for more details). The earlier design of the routes included a combination of left and right turns to reach the destination. Previous research has suggested that sharp turns (i.e., right turns) are more likely to result in motion sickness symptoms due to the rapid changes in the viewpoint and the speed of optic flow (Koenderink, 1986; Stoner et al., 2011; Bertin et al., 2005). We thereby designed a new set of routes that included only left turns. The remaining 41 participants (groups: young = 12, early middle-age = 15, late middle-age = 14) were trained with the left-turn only routes.

3. Results

3.1 Data Analysis

We used linear mixed models (LMM) to analyze the relationship between accuracy (allocentric and egocentric) and age groups (young, early, and late middle-age adults). In the test trials, participants were asked to select the shortest path to the target, and they were given partial scores based on the length of their chosen path relative to the shortest path. The late middle-age group was considered as the reference group, and young and early middle-age adults were compared to this group. Among the demographic variables, gender was significantly associated with allocentric accuracy, $\beta = 0.122$, SE = 0.029, $t = 4.192$, $p = .0001$ and egocentric accuracy, $\beta = 0.085$, SE = 0.032, $t = 2.73$, $p = .0088$. Similarly, average weekly hours of driving were significantly associated with allocentric accuracy, β = - 0.067, SE = 0.03, t = -2.285, *p* =.0265 and egocentric accuracy, β = - 0.095, SE = 0.032, *t* = - 2.993, *p* = .0043. Average weekly hours of computer use was only associated with allocentric accuracy, β = 0.045, SE = 0.016, *t* = 2.932, *p* =.005. In order to account for the effect of these variables, they were added to the LMM models (please see below). We also controlled for the "route" type (e.g., routes that included left and right turns vs. routes that included left turns only) in the model to ensure the changes in route design did not affect the observed results. Participants completed 2 sets of guided navigation and test blocks. To analyze the learning effect, we added the block order to our model as a random and fixed effect. Furthermore, we analyzed the relationship of age as a continuous variable with accuracy scores using a partial correlation analysis. The data and R code can be found at the present study's Github repository: https://github.com/Jabbariy/Ch5_YJ. The linear mixed model used for the accuracy scores is noted below in Wilkinson notation (Wilkinson & Rogers, 1973). The demographic analysis determined the demographic variables included in the accuracy analyses.

Demographic variables:

Allocentric/Egocentric Accuracy ~ Video Game hrs + Driving Game hrs + Driving hrs + Gender + Route type + Block order + (1 + Block order | Participants)

Accuracy:

Allocentric Accuracy ~ Age groups + Route type + Gender + Computer hrs + Driving hrs + Block order + (1 + Block order | Participants)

Egocentric Accuracy ~ Age groups + Route type + Gender + Driving hrs + Block order + (1 + Block order | Participants)

3.2 Linear Mixed Model (LMM)

Allocentric Accuracy

The variable of age was significantly associated with the accuracy of the allocentric trials. Late middle-age adults had a significantly lower accuracy in allocentric trials compared to early middle-age adults, $\beta = 0.111$, $t = 3.398$, $p = .0014$; and young adults, $\beta = 0.0714$, $t = 2.201$, $p = .0325$. Post hoc test with Tukey correction indicated that there was no significant difference between early middle-age and young adults, $t = 1.295$, $p = .405$ (Table 1 & 2) (Figure 3).

Egocentric Accuracy

In contrast to the allocentric trials, we did not observe a significant association between the accuracy of egocentric trials and age groups. Accuracy of the late middle-age adults in egocentric trials did not statistically differ from the early middle-age adults, $\beta = 0.053$, $t = 1.410$, $p =.1649$; and young adults, $\beta = 0.407$, $t =1.107$, $p =.2736$. Post hoc tests with Bonferroni correction showed no significant difference between the accuracy scores of early middle-age and young adults, $t = 0.322$, $p = 0.9445$ (Table 1 & 2) (Figure 3).

Table 1: Results of the linear mixed models with accuracy (Allocentric & Egocentric) modeled by age groups (Young, Early middle-age, & Late middle-age). Late middle-age group was the reference group/control condition. Gender, average weekly hours of computer use, average weekly hours of driving, block order, and route design type were included in the model to control for their possible effects.

Allocentric Accuracy						
Variables	***β***	**SE**	**CI**		***t* value**	***p* value**
Intercept (late middle-age)	0.344	0.069	0.20	0.48	4.958	< 0.001
Early middle-age	0.111	0.033	0.05	0.18	3.398	0.001
Young	0.071	0.032	0.01	0.14	2.201	0.033
Route design	0.046	0.028	-0.01	0.10	1.639	0.108

Gender	0.125	0.026	0.07	0.18	4.832	< 0.001
Block order	0.104	0.023	0.06	0.15	4.575	< 0.001
Driving hrs	-0.079	0.024	-0.13	-0.03	-3.304	0.002
Computer hrs	0.027	0.015	0.00	0.06	1.831	0.053
Egocentric Accuracy						
Intercept (late middle-age)	0.446	0.059	0.33	0.57	7.503	< 0.001
Early middle-age	0.053	0.037	-0.02	0.13	1.410	0.165
Young	0.041	0.037	-0.03	0.11	1.107	0.274
Route design	0.101	0.034	0.03	0.17	2.929	0.005
Gender	0.100	0.032	0.04	0.16	3.161	0.003
Block order	0.127	0.027	0.07	0.18	4.749	< 0.001
Driving hrs	-0.073	0.029	-0.13	-0.01	-2.484	0.016

3.3 Partial Correlation

In line with the *LMM* results, partial correlation indicated that there was a significant negative correlation between the accuracy of allocentric trials and age (as a continuous variable) $r = -0.277$, $p = .003$ and also the age groups $r = -0.290$, $p = .002$. We did not observe any significant correlations between accuracy of egocentric trials and age (as a continuous variable) $r = -0.036$, $p = .710$ and neither the age groups $r = 0.280$, $p = .103$. Overall, these results suggested that accuracy in finding the shortest route to the target destination was preserved by age when the memory for the routes was retrieved from an egocentric frame of reference but decreased when it was retrieved from an allocentric frame of reference, indicating a possible decline in the allocentric encoding of the environment among late middle-aged adults.

3.4 Learning effect

Participants received two blocks of guided navigation and test phases. Results showed that the accuracy of the allocentric trials increased from the first to the second block in young adults, $t = 2.258$, $p = 0.037$, early middle-age adults, $t = 2.298$, $p = 0.034$, and late middle-age adults, $t = 3.268$, $p = 0.004$. Similarly, accuracy of egocentric trials increased from the first to the second block in young adults $t = 3.390$, $p = 0.003$, and early middle-age adults, $t = 3.77$, $p = 0.001$, but not in the late middle-age adults $t = 1.26$, $p = 0.222$ (Table 2). These findings indicated that allocentric navigation skills in older adults can be improved through training.

Table 2: Egocentric and Allocentric accuracy of different age groups (Young, Early middle-age, & Late middle-age) in the two guided navigation and test blocks (First block & Second block)

Age Group	Block order	N	Egocentric Accuracy		Allocentric Accuracy	
			Mean	SE	Mean	SE
Young	*First Block*	18	0.592	0.036	0.621	0.035
	Second Block	18	0.745	0.029	0.719	0.033
Early middle-age	*First Block*	18	0.567	0.046	0.662	0.028
	Second Block	18	0.751	0.035	0.737	0.033
Late middle-age	*First Block*	20	0.620	0.035	0.521	0.032
	Second Block	20	0.674	0.043	0.658	0.035

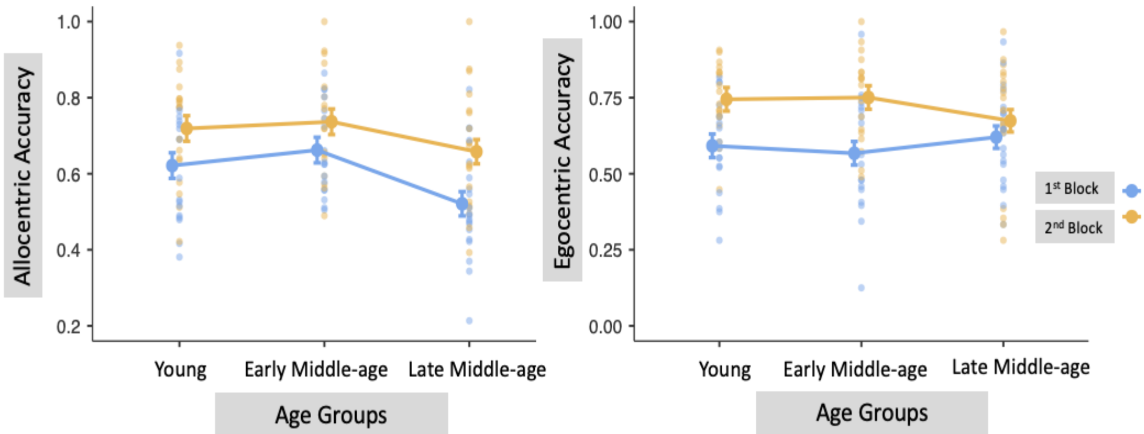

Figure 3: Illustration of the relationship between age groups (Young, Early Middle-Age & Late Middle-Age) and accuracy (Egocentric & Allocentric) across the two blocks (1st Block & 2nd block). Error bars are +/- 1 Standard Error.

3.5. Motion sickness and route design

Prior to the study, participants reported the frequency of experiencing motion sickness using the predefined options: 1 = never, 2 = very rarely, 3 = rarely, 4 = sometimes, and 5 = frequently. Results showed that participants who finished the experiment (excluding the dropouts) had the same propensity for motion sickness, $\chi 2$ (2) = 0.068, p =.966. Below, we reported the differences in motion sickness reports and dropout rates between the two route designs.

First route design (combination of right and left turns)

Half of the late middle-age adults (3 out of 6) voluntarily dropped out during the first training block due to motion sickness (all females with the ages of 51, 54, and 57 years old). The other age groups did not report any issues.

Second route design (only left turns)

Out of 24 late middle-age adults, 4 participants voluntarily dropped out of the study during the first training block due to motion sickness (all females with the ages of 54, 58, 58, and 69 years old) and 2 dropped out due to other health issues such as migraine (a 56-year old female) and vertigo (a 79-year old male). Out of 19 early middle-age adults, only 1 dropped out due to motion sickness (a 40-year-old female). The route design that only included left turns had a lower rate of motion sickness dropout in the late middle-age group compared to the earlier design of the routes. This may suggest that using wide left turns can decrease the experience of motion sickness in older adults.

3.6. Attention, Balance, and Energy

We checked the attention, balance, and energy state of the participants before and after starting the experiment. Participants were given 5 points Likert-scale questions prior and after the experiments for indicating attention state (1 = distracted to 5 = alert), energy state (1 = fatigued to 5 = energetic) and balance state (1= dizzy to 5 = stable). There were no group differences, neither before nor after the experiment (Table 3).

Table 3: Mean and standard error of self-reported Attention, Energy, and Balance status of different age groups before and after participating in the experiment.

	Before Experiment						***After Experiment***					
	Attention		*Energy*		*Balance*		*Attention*		*Energy*		*Balance*	
Age Group	M	(SE)	M	(SE)	M	(SE)	M	SE	M	SE	M	SE
Young	4.28	0.18	3.89	0.19	4.33	0.21	4.36	0.20	4.01	0.22	4.57	0.20
Early middle- age	4.17	0.17	3.83	0.25	4.56	0.14	4.28	0.13	3.67	0.26	4.22	0.22
Late middle-age	4.45	0.17	4.45	0.15	4.75	0.14	4.53	0.15	4.18	0.23	4.35	0.23

Using the driving simulator allowed participants to actively drive in the virtual environment in the guided navigation phase. Accordingly, we looked at the driving control of different age groups, such as driving speed and time, considering that driving control might affect the development of mental representations in participants. However, neither driving time nor driving speed was associated with egocentric and allocentric accuracy. The driving control data set is available in the Github repository linked in section 3.1.

4. Discussion

Allocentric and Egocentric representations

In this study, we investigated the relationship of age with spatial encoding of the environment in a driving task. The effect of age on egocentric and allocentric spatial representations has been mainly assessed in non-navigational spatial tasks (e.g., Fernandez-Baizan et al., 2019; Ruggiero et al., 2016) or less ecologically valid navigational tasks in which participants orient in virtual environments using keyboard keys or joysticks (e.g., Head & Isam, 2010; Moffat et al., 2001). Literature findings are in agreement about the age-related decline in the formation of allocentric representations (Harris & Wolbert, 2014; Moffat & Resnick, 2002; Iaria et al., 2009; Colombo et al., 2017; Moffat et al., 2006; Antonova et al., 2009). However, there are contradictory conclusions on the effect of age on the formation of egocentric representations. While some findings indicated an age-resistant effect on the development of egocentric representations (e.g., Gazova et al., 2013; Antonova, et al., 2009; Moffat, et al., 2006; Fricke & Bock, 2018), some others indicated age-related impairments (e.g., Fernandez-Baizan, et al., 2019, 2020; Ruggiero, et al., 2016; Wilkniss et al., 1997; Moffat et al., 2001; Head & Isom, 2010). The present study aimed to fill this gap in the literature by assessing the relationship between age and egocentric representation development in an ecologically valid setting of navigating while driving.

In accordance with the literature, we found that aging was associated with a decline in allocentric encoding of the environment (e.g., Harris & Wolbert, 2014; Moffat & Resnick, 2002; Iaria et al., 2009; Colombo et al., 2017). Specifically, late middle-age adults (45–66) had a significantly reduced accuracy in allocentric trials compared to early middle-age adults (30–45) and young adults (18-30). In contrast to allocentric navigation performance, we found no effect of age on egocentric encoding of the environment. The absence of a significant difference between the age groups in egocentric trials' performance was in accordance with studies claiming that there is no age-related impairment in egocentric navigational skills (e.g., Rodgers, et al., 2012; Wiener, et al., 2013) and in conflict with studies that found an age-related deterioration effect (e.g., Fernandez-Baizan, et al., 2019; 2020; Ruggiero, et al., 2016; Head & Isam, 2010; Moffat et al., 2001).

Age-related impairments on the application of navigation strategies and spatial cognitive skills such as visual-spatial skills have been documented (e.g., Iaria et al., 2009;

Verhaeghe, et al., 2005; Gazova et al., 2012). Furthermore, some research has suggested that the application of egocentric navigation is less cognitively demanding than allocentric navigation (Brunyé et al., 2017; Hartley et al., 2003; Poldrack et al., 2001; Brunyé & Taylor, 2008; Gagnon et al., 2014; Thorndyke & Hayes-Roth, 1982). In the context of the present study, it can be suggested that in contrast to allocentric representations, the formation of egocentric representations of an environment while driving, would remain intact in late middle-age (late sixties) because it may not exceed their, potentially limited, spatial cognitive span shared between the tasks of driving and navigating.

Accuracy of young adults (18-30) in allocentric trials were similar to the early middle-age adults (30-45) and the mean difference between early and late middle-age adults (45-66) was higher than the mean difference between young and late middle-age adults (Table 2 & Figure 3). This may indicate that, despite the fact that allocentric navigation accuracy declines with age, this ability peaks in early middle-age (30–45), when functional and efficient cognitive abilities combine with accumulated driving and navigation experiences. This suggestion is corroborative with the results of the study conducted by Rodrick and colleagues (2013). These researchers examined the lane change performance of three age groups (25–34, 35–45, and 55-year-old and above) in a simulated driving task under various dual-task conditions. They found 35–45-year-old participants had the best driving performance in dual-task conditions, suggesting that this age group could effectively share resources in dual-task conditions while prioritizing the primary task of driving.

Simulator sickness

Susceptibility to simulator sickness increases with age (e.g., Kawano et al., 2012; Classen, et al., 2011). It is argued that motion sickness in virtual environments arises from spatiotemporal conflicts between vestibular and visual sensory modalities (Oman, 1990; Reason, 1978; Brooks et al., 2010; Classen, et al., 2011; Keshavarz & Hecht, 2011). Motion-based driving simulators that provide vestibular cues may reduce simulator sickness compared to non-motion simulators (e.g., desktop driving simulator) (e.g., Weech et al., 2020). However, Keshavarz and colleagues (2018) found no effect of vestibular cues in decreasing simulator sickness dropout rates among older adults in a driving task. They observed simulator sickness rate was similar in different sensory conditions of 1) only visual cues, 2) combination of visual and auditory cues, 3) combination of visual and motion cues, 4) combination of visual, auditory & motion cues (a similar condition to the present study).

In the redesigning of the routes in the present study, we considered substituting visually sharp turns with wider turns to reduce the speed of lateral optic flow and consequently minimize the risk of motion sickness (Stoner et al., 2011; Bertin et al., 2005; Koenderink, 1986). The density and resolution of the visual scene contents and the movement speed of visual stimuli can highly affect the risk of motion sickness. High density and lower resolution of the visual contents and high speed of visual stimuli movements increase the experience of motion sickness symptoms (e.g., Bubka et al., 2006; Tamada & Seno, 2015; Keshavarz et al., 2019; Lo & So, 2000). Sharp right turns due to rapid changes in the viewpoint and the speed of optic flow can increase the experience of motion sickness (Koenderink, 1986; Stoner et al., 2011; Bertin et al., 2005). Successfully, the redesign of the routes led to fewer motion sickness-related dropouts. Other researchers can consider using wide turns, if applicable, in the design of the future navigation experiments.

Limitation and future directions

Adverse side effects of simulator sickness are not only disturbing to participants and their efficiency; they can financially affect the study due to participants' drop-out. The design of the virtual town in the present study was restricted (e.g., a small town with a limited number of driving routes) to avoid inducing motion sickness. Redesigning the routes to include only left turns led to fewer dropouts of older adults due to motion sickness. Compared to other similar driving simulator studies (e.g., Keshavarz et al., 2018; Fricke & Bock, 2018), the present study had fewer reports of motion sickness. One reason could be the different age group categorization. In contrast to the studies mentioned above (e.g., Keshavarz et al., 2018; Fricke & Bock 2018), we did not have older adults (e.g., 66 to 80), which could be a reason for having lower sickness reports. Older age (66 and over) has been associated with higher rates of simulator sickness (e.g., Kawano et al., 2012; Brooks et al., 2010; Keshavarz et al., 2018; Fricke & Bock, 2018; Kennedy et al., 2010). It would be highly informative if we were able to test the effectiveness of optic flow deceleration in wider turns on this group. Future studies can consider examining this approach with larger sample sizes with old adults included.

Another limitation to this study is concerning landmark types. Distal landmarks and proximal landmarks are beneficial for allocentric and egocentric navigation, respectively (Jansen-Osmann & Fuchs, 2006; Waller & Lippa, 2007; Wiener et al., 2009; De Condappa, 2016; Livingstone-Lee et al., 2011; Mueller et al., 2008; Hurlebaus et al., 2008; Ruddle et al., 2011; Steck & Mallot, 2000). In the present study, we used both proximal and distal landmarks; however, we did not differentiate the allocentric and egocentric trials based on the type of available landmarks at intersections. Future studies can explore the effect of age on egocentric and allocentric spatial processing depending on the type of landmarks.

Conclusion

In the present study, we assessed the association between age and the development of spatial representations in a driving task. The development of egocentric spatial representation was preserved with age. However, an age-related deficit was observed when the spatial representations were retrieved from an allocentric frame of reference. Testing participants in routes with wider visual turns rather than sharp turns led to a lower ratio of simulator sickness dropouts. We observed a significant effect of training on the development of allocentric navigation. It has been shown that navigation training has the potential to make a significant improvement in both young and older adults' navigation skills (Lovden et al., 2012). Potentially, interventions like providing allocentric navigation training for older drivers would be an excellent way to keep them safely on the road for longer.

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CHAPTER 6: Individual Differences in Navigation and GPS Use: Mental Health, Working Memory, and Spatial Skills

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Preface

Chapter 6 presents the results of an online experiment in which the relationship between mental health factors such as depression, anxiety, and stress and dependency on GPS were examined. Furthermore, the effect of different types of GPS instruction (e.g., instructions with or without landmark names included) on route learning was studied. The results showed that greater self-reports of depression, stress, and anxiety were associated with poorer memory for learned routes. Interestingly, while increased anxiety and stress were correlated with increases in the GPS dependency of drivers, increased depression was associated with decreases in GPS dependency.

Abstract

Use of a Global Positioning System (GPS) for navigation decreases the engagement of drivers with the environment. Long-term use of GPS may hinder spatial learning. Cognitive abilities such as working memory and spatial skills, as well as mental health conditions, can significantly influence navigational performance and GPS dependency. We conducted an online study on young adults to assess relationships between self-reported mental health, working memory, and navigation skills, including dependency and reliance on GPS navigation aids. The questionnaires included the McGill GPS Questionnaire, Santa Barbara Sense of Direction Scale, Depression, Anxiety, and Stress scale (DASS-42), Spatial Anxiety Questionnaire (SAQ), and Adult Executive Functioning Inventory (ADEXI). These measures were correlated with performance on a route learning navigation task, which tested different landmark-based navigation instructions and egocentric/allocentric strategies. In particular, the navigation task examined the effect of incorporating landmarks into GPS-like instructions to increase spatial awareness. Overall, measures of depression and anxiety, spatial anxiety, working memory span, and self-reported navigation skills were highly associated with route learning accuracy and GPS use.

Keywords: GPS dependency, Landmarks, Navigation, Mental Health conditions, spatial Anxiety, Working memory, Egocentric navigation, Allocentric navigation, GPS

1. Introduction

1.1. Landmark-based GPS

Global Positioning Systems (GPS) in cars and smartphones are becoming a convenient navigation aid for drivers. Navigation requires drivers to use cognitive resources such as attention, visuospatial processing, and executive function systems (Ruddle & Lessels, 2006; Ekstrom, 2015). Using GPS reduces the cognitive load of navigation while driving and has important beneficial outcomes, such as finding alternative routes and reducing the likelihood of getting lost in new environments. However, it may also be associated with reduced spatial awareness and drivers' lack of engagement with the environment may result in less attention to the navigational cues along the route (Dahmani & Bohbot, 2020; Ishikawa, 2019; Ishikawa et al., 2008; Gardony et al., 2015; Willis et al., 2009; Münzer et al., 2006; Parush et al., 2007). Long-term outsourcing of spatial abilities to GPS may result in limited spatial skills, including poor spatial memory, disrupted mental rotation and perspective-taking abilities in novel environments, and less accurate distance estimation (Ishikawa et al., 2008; 2019; Ruginski et al., 2019; Dahmani & Bohbot, 2020). Clearly, there is a cost-benefit relationship with GPS use that should be considered.

Efficient navigation requires strong spatial awareness of the environment. Wayfinding demands proper encoding, retrieval, and manipulation of navigational information to apply various navigation strategies (e.g., Gras et al., 2013; Boccia et al., 2017; Kato & Takeuchi, 2003; Wolbers & Hegarty, 2010; Tascon et al. 2017; Lawton, 1994; Pazzaglia & De Beni, 2006; Meneghetti, et al., 2011). Two common navigation strategies involve egocentric and allocentric approaches. Egocentric navigation uses route knowledge which takes advantage of the sequential connections between a series of landmarks and route direction instructions (e.g., turn left at the church) (e.g., Zhong & Kozhevnikov, 2016; O'Keefe & Nadal, 1978; Siegel & White, 1975; Arleo & Rondi-Reig, 2007; Ekstrom & Isham, 2017). In contrast, allocentric navigation uses survey knowledge involving a more flexible, map-like representation of the environment and landmarks (e.g., the school is north of the church) (e.g., O'Keefe & Nadel, 1978; Siegel & White, 1975; Zhong & Kozhevnikov, 2016; Arleo & Rondi-Reig, 2007; Ekstrom & Isham, 2017).

Our navigation skills are also highly affected by the availability and type of navigational cues in the environment. Landmarks can increase our navigation accuracy (Jabbari et al., 2021; 2022; Chan et al., 2012; Hamburger & Roser, 2014; Meneghetti et al., 2021; Steck & Mallott, 2000; Ruddle et al., 2011; Hurlebaus et al., 2008). When traveling a route, associating proximal landmarks (local nearby objects) to the sequence of the route and turning directions improves encoding of the spatial information (Krukar et al., 2020; Padmanaban & Krukar, 2017). Survey knowledge can also be improved when distal landmarks (global distant objects) are used to make map-like references (Driscoll, et al, 2005; Ruddle et al., 2011; Chan et al., 2012; Steck & Mallot, 2000; Jabbari et al., 2022).

One debated modification to current GPS systems is incorporating landmarks into GPS instructions. When compared to traditional GPS instruction, incorporating landmark information has been shown to improve navigational skills (Krukar et al., 2020; Gramann et al., 2017; Schwering et al., 2017; Lowen et al., 2019). Traditional GPS systems may hinder spatial abilities by reducing the engagement of navigators with the environment (Ruginski et al., 2019; Dahmani & Bohbot, 2020). As a result, incorporating landmark information into GPS instructions may improve spatial knowledge by increasing engagement with the environment.

The first goal of this study was to assess the effect of landmark-based GPS instructions on the application of egocentric and allocentric route learning in drivers. Even though the effect of landmark-based GPS instructions on navigation has been investigated recently (Krukar et al., 2020; Gramann et al., 2017; Schwering et al., 2017; Lowen et al., 2019), it has not been assessed on different navigation strategies. Other research has shown that turn-by-turn GPS instructions from an egocentric point of view improved route memory at the expense of survey knowledge (Munzer et al., 2012). Thus, we expected landmark-based GPS instructions to strengthen egocentric route learning more than the allocentric route learning.

1.2. Self-reported Mental health conditions & GPS dependency

Mental health conditions can influence spatial memory through their adverse effects on hippocampus functionality (MacMaster & Kusumakar, 2004; Sheline et al., 2003; Videbech & Ravnkilde, 2004; Brown et al., 2020). The hippocampus plays a critical role in spatial abilities and navigation (Addis et al., 2011; Kim et al., 2015; O'Keefe and Nadel, 1978; Ekstrom et al., 2003). Clinical mood disorders such as depression correlate with reductions in hippocampal volume and low spatial memory skills (Cornwell et al., 2010; Gould et al., 2007; Hickie et al., 2005). Similarly, studies have shown an adverse effect of anxiety on spatial navigation in children (Mueller et al., 2009) and on the structure of the hippocampus in animals (Herrero et al., 2006; Engin & Treit, 2007). Stress has also been found to induce changes within hippocampal functions and consequently disrupt navigation abilities (Brown et al., 2020; Magariños et al., 1997).

Furthermore, there is a domain-specific form of anxiety called "spatial anxiety," which refers to fear and apprehension related to spatial processing tasks (Lyons et al., 2018). Spatial anxiety may prevent an individual from engaging in situations requiring spatial navigation and spatial memory skills, which can further enhance spatial anxiety.

Thus, the second goal of this study was to assess the effect of mental health conditions like depression, stress, and anxiety on navigational performance and GPS dependency. Despite established relationships between mood disorders and hippocampal function and the well-known role of the hippocampus in navigation, there is little research on the relationship between these mental health factors, navigation abilities and GPS use (Levita et al., 2014;

Lyons et al., 2018). We hypothesized that increased symptoms (from self-report questionnaires) of depression, anxiety, and stress would be adversely related to spatial navigation skills and thus, would be positively correlated to GPS dependency.

1.3. Working memory, self-reported navigation skills & GPS dependency

Individual differences in working memory capacity may correlate with navigational abilities. Visuo-spatial processes (e.g., landmarks) and verbal working memory processes (e.g., street names, landmark names) play a critical role in the encoding and retrieval of spatial information (Wen et al., 2011; Gras et al., 2013; Weisberg & Newcombe, 2016; Meneghetti et al., 2021). For example, Weisberg and Newcombe (2015) found that individuals with lower working memory scores demonstrated poorer performance in learning landmark names and images compared to those with greater working memory scores.

Furthermore, individuals with working memory deficits (e.g., ADHD) struggle with navigation tasks that rely heavily on temporary storage and maintenance of information. Due to a lower attention span, these individuals have more difficulty forming associations between the landmarks and their relative positions (Robaey et al., 2016).

To the best of our knowledge, no study has evaluated the relationship between working memory abilities and GPS dependency. Therefore, the third goal of this study was to assess the effect of working memory span on GPS use and navigation skills. We looked at the relationship of self-reported navigation skills with navigation performance, working memory score, mental health factors, and GPS use. We expected to observe a higher GPS dependency and lower route-learning accuracy in individuals with poorer working memory scores and lower self-reported navigation skills.

2. Method

2.1. Participants

Ninety-five McMaster undergraduate students with an age range of 18 - 26 years old (Mean age= 18.63, SD=1.25) participated in this online study and received course credit for their participation. All participants were required to have a valid G2/G driver's license or equivalent. The study protocol was approved by the McMaster Research Ethics Board. Each participant completed a set of questionnaires followed by a spatial navigation task, as described below.

2.2. Questionnaires

We used the McMaster LimeSurvey online platform to create and administer the questionnaires. Participants completed the questionnaires in the following order: 1) a general demographic questionnaire, 2) McGill GPS questionnaire, 3) Adult Executive Functioning Inventory (ADEXI), 4) the Spatial Anxiety Questionnaire (SAQ), 5) the Depression, Anxiety, and Stress Scale (DASS-42); and 6) the Santa Barbara Sense of Direction Questionnaire (SBSOD). Questionnaires can be found in the Github repository linked in section 3.1.

The demographic questionnaire asked about gender, age, video gaming experience, and driving frequency. The McGill GPS questionnaire measured GPS reliance and dependency of individuals in 20 items in a 5-point Likert scale. It included items which asked about frequency of GPS use (e.g., “How often do you try to find a new route, without a GPS, to a previously visited destination?”) and the extent of GPS dependency (e.g., I can only find my way using a GPS) (Dahmani & Bohbot, 2020).

To assess the mental health factors, we used the DASS-42 (Antony et al., 1998; Crawford & Henry, 2003). The DASS-42 consisted of three subscales which measured depression, anxiety, and stress. This questionnaire included 42 items in a 4-Likert scale. The

SAQ is the other questionnaire we used to assess spatial anxiety (Lyons et al., 2018). It measured anxiety experienced performing spatial tasks such as mental rotation or wayfinding. Participants predicted their level of anxiety in certain situations (e.g., “Asked to imagine and mentally rotate a 3-dimensional figure”). The SAQ consisted of three subscales which measured imagination, mental manipulation, and navigation-related anxiety. This questionnaire included 24 items in a 5-point Likert scale format. The ADEXI questionnaire measured working memory and inhibitory control through nine, 5-point Likert scale items (e.g., “When someone asks me to do several things, I sometimes remember only the first or last.”) (Holst & Thorell, 2018). The last questionnaire we used was the SBSOD, which is a standardized self-report scale that measures wayfinding skills. It includes 15 items in a 7-point Likert scale (e.g., “I am very good at giving directions.”) (Hegarty et al., 2002).

2.3. Spatial navigation task

Following the completion of questionnaires on LimeSurvey, participants were directed to a virtual navigation task, hosted on the Pavlovia online platform (https://pavlovia.org/). The navigation task was programmed in Psychopy v2021.2.3. There were two independent variables: the Landmark condition was a between-subjects variable (Landmark vs. No Landmark condition), and the Viewpoint condition was a within-subject variable (Egocentric vs. Allocentric viewpoint). Participants were randomly assigned to the Landmark vs. No Landmark condition at the outset of the experiment. The dependent variables were response time (ms) and accuracy in the test phase.

2.3.1. Stimuli

Ninety-six city intersection images were created by recording screenshots, at 1920x1080 resolution, from the Street View perspective within Google Maps and Google Earth Pro 7.3.4.8248 (https://www.google.com/earth/versions/). Each image portrayed, as closely as possible, the viewpoint from a car approaching the intersection (e.g., Figure 1), with constraints that (1) it was possible to proceed straight or turn left or right, (2) a salient, nameable landmark was visible on one of the intersection corners (e.g. museum, church, post office), and (3) each landmark was distinct from all other landmarks used in the stimulus set. There were 6 unique intersections for each of the 8 routes (48 images), and 2 versions of each intersection (total 96 images) to create an egocentric perspective (e.g., same viewpoint at learning and at test) and an allocentric perspective (e.g., different viewpoint at test).

2.3.2. Procedure

Participants learned to navigate 8 routes along city streets, each leading to a different destination and each defined by turning directions at 6 intersections along the route. Each route consisted of a learning phase followed immediately by a test phase. Participants were allowed to take a break after each route, if desired. The duration of the navigation task was approximately 30 minutes.

The stimuli (described above) were pictures of the intersections at street level, viewed from the perspective of a driver approaching the intersection. During the learning phase for each route, the intersections were encountered in sequence along with GPS-like instructions printed below the image indicating whether to turn left, turn right, or proceed straight through the intersection on the way to the destination. The instructions differed depending on which landmark condition the participant was assigned. For example, the instructions might read “Turn right to reach the hospital” (No Landmark condition) or “Turn right at the gas station to reach the hospital” (Landmark condition). Participants were instructed to remember the direction they took at each intersection, and to respond by pressing the associated left, right, or up arrows on the computer keyboard.

The learning phase of each route was followed immediately by a testing phase which tested memory for the correct turn at each intersection (Figure 1). Images of the 6 intersections were presented in random order. The instructions printed below each image were the same for both Landmark conditions (e.g., "Which direction do you need to take at this intersection to reach the hospital?"). Three of the 6 intersections presented exactly the same image, with the same viewpoint, as was seen in the learning phase (*egocentric* condition), thus the correct response would be the same direction (left, right, or straight) as the response in the learning phase. The other 3 intersection images were taken from a different point of view, as would be seen if the driver were approaching the same intersection from a different direction (*allocentric* condition), thus the correct response would differ from the learning phase. Each route had an equal number of egocentric (n = 3) and allocentric (n = 3) intersection images in the testing phase. Responses were not time-limited in either the learning or test phases. Response times were measured as the time between the onset of the image to detection of the keypress response.

Figure 1: An illustration of a stimulus example used in the navigation study: each intersection image contained a salient landmark (e.g., Cineplex). **In the training phase**, in the Landmark condition, participants received landmark-based GPS turning instructions, and in the No landmark condition, they received traditional GPS turning instructions that did not mention the landmark. **In the testing phase**, in the egocentric condition, they received the same intersection image in the same orientation that was shown in training. In the allocentric condition, the intersection image was shown from a different orientation, simulating approaching the intersection from a different direction.

3.Results

3.1. Statistical analysis

A regression analysis was run on the data to check for linear and nonlinear associations between variables. In particular, we were interested in evaluating whether: 1) mood disorder factors (depression, anxiety, and stress) measured by DASS-42 and SAQ; 2) working memory span measured by ADEXI; and 3) self-reported navigation skills measured by SBSOD could predict: 1) GPS dependency and reliance measured by the McGill GPS questionnaire; and 2) response times and navigation accuracy in egocentric and allocentric trials assessed by the online navigation task. The data and R code for the regression analysis can be found here: https://github.com/Jabbariy/Ch6_YJ.

Further, we ran a 2 x 2 mixed ANOVA on accuracy and reaction time data from the online navigation task using Jamovi software (2.2.5.0). The independent variables were the between-subjects variable Landmark condition (Landmarks vs. No landmarks provided in the GPS directions during the learning phase) and the within-subjects variable of Viewpoint (Egocentric vs. Allocentric images during the test phase). The dependent variables were reaction time and accuracy score of the test trials. Only the reaction time of the correct trials were included in the analysis.

We assessed relationships between these dependent variables and demographics, including age, gender, frequency and hours of driving in an average week, hours of playing video games in an average week, as well as the years of driving experience. Only driving frequency was significantly correlated with the accuracy score of the egocentric trials (r = 0.258, p = 0.001). Therefore, we controlled for this variable in the regressions and ANOVA analysis that we ran on the accuracy scores.

3.2. Regression analysis

In this section, we reported statistically significant associations only. For a full report on all the associations, please refer to the Github repository mentioned in section 3.1.

3.2.1. McGill GPS

We observed that McGill GPS score was significantly associated with the navigation subscale of the SAQ (β = 63.552, p < .001) and all three subscales of DASS including anxiety (β = 42.975, p = .016), depression (β = - 55.426, p = 0.0007) and stress (β = 36.129, p = .042). This finding indicated that depression, stress, and anxiety, as a mood disorder or at the spatial level in performing spatial navigation tasks, can predict dependence and reliance on using GPS. While stress and anxiety predicted an increase in self-reported GPS use, depression related to a decrease in self-reported GPS use. Similarly, higher self-reported wayfinding skills (SBSOD) predicted lower GPS use (β = -69.872, p < .0001). Working memory score (ADEXI) had a nonlinear relationship with McGill GPS score indicating a higher use of GPS for low memory span and an opposite trend for high memory span (β = -22.642, p =.039) (see Table 1 for more details).

Table 1: Associations of **McGill GPS score** with **SAQ**, **DASS**, **SBSOD**, and **ADEXI** questionnaires.

Predictors		β	**SE**	***t* value**	***p* value**
SAQ	*Intercept*	64.179	1.019	62.98	< .0001
	SAQ Navigation	63.552	10.91	5.825	< .0001
DASS	*Intercept*	64.179	1.11	57.833	< .0001
	Anxiety	42.975	17.662	2.433	0.0169
	Depression	-55.426	15.839	-3.499	0.0007
	Stress	36.129	17.509	2.063	0.0420
ADEXI	*Intercept*	64.179	1.115	57.575	< .0001

	Working Memory	-22.642	10.865	-2.084	0.0399
SBSOD	*Intercept*	64.178	0.967	66.34	< .0001
	SBSOD	-69.872	9.429	-7.41	< .0001

3.2.2. Egocentric and allocentric accuracy and reaction time

We observed a significant relationship between accuracy of the egocentric trials and spatial anxiety in performing mental rotation tasks measured by SAQ (β = - 0.578, p = 0.005) and anxiety, in general, measured by DASS (β = -0.821, p = 0.009). These negative associations indicated a lower accuracy score for high levels of reported anxiety. Furthermore, the reaction time of the egocentric trials was related to the spatial anxiety measured by SAQ (β = 6.432, p = 0.0004), indicating that a faster reaction time corresponded to a higher level of reported anxiety. No other significant relationships were observed between the egocentric trial accuracy and the rest of the questionnaires. We did not find any significant associations between self-reported measurements and the accuracy scores of allocentric trials (see Table 2 & 3 for more details).

Table 2: Associations of **egocentric trials accuracy score** with **SAQ** and **DASS** questionnaires. Driving frequency was a controlled covariance variable because it associated with accuracy scores.

Predictors		***β***	**SE**	***t* value**	***p* value**
SAQ	*Intercept*	0.585	0.059	9.815	< .0001
	SAQ_Mental Manipulation	-0.578	0.202	-2.867	0.0052
	Driving frequency	0.038	0.016	2.342	0.0215
DASS	*Intercept*	0.556	0.058	9.529	< .0001
	Anxiety	-0.821	0.308	-2.669	0.009
	Driving frequency	0.047	0.016	2.979	0.0037

Table 3: Associations of **egocentric trials reaction time** with **SAQ** questionnaire.

Predictors		***β***	**SE**	***t* value**	***p* value**
SAQ	*Intercept*	3.098	0.166	18.702	< .0001
	SAQ Navigation	6.432	1.755	3.665	0.0004

We also looked for any links between self-reported navigation skills, mental health, and working memory factors. A high score in subjective sense of direction measured by SBSOD was significantly associated with a high working memory score ($\beta = 4.229$, $p < .0001$), and low spatial anxiety in performing navigational tasks ($\beta = -5.726$, $p < .0001$). The anxiety subscale of DASS was marginally related to a low self-reported sense of direction ($\beta = -2.950$, $p = 0.086$). No other significant association was observed (see Table 4).

Table 4: Associations of **SBSOD** with **SAQ**, **DASS** and **ADEXI** measures.

Predictors		***β***	**SE**	***t* value**	***p* value**
SAQ	*Intercept*	3.6315	0.088	41.032	< .0001
	SAQ_Navigation	-5.7262	0.947	-6.043	< .0001
DASS	*Intercept*	3.6316	0.1069	33.957	< .0001
	Anxiety	-2.9506	1.7021	-1.733	0.0865
ADEXI	*Intercept*	3.6316	0.1002	36.251	0.0037
	ADEXI	4.2298	0.9764	4.332	< .0001

3.3. Landmark-based GPS design

3.3.1. 2 x 2 Mixed ANOVA - Accuracy

There was a significant main effect of point of view (egocentric vs allocentric) on accuracy, $F(1, 90) = 11.253$, $p = 0.001$. Post hoc tests with *Tukey* correction showed that accuracy of the egocentric trials was significantly higher than the allocentric trials, $t(90) =$

14.146, $p < .0001$ (see Table 5). We did not observe a significant main effect of landmark condition on accuracy, $F(1, 90) = 0.224$, $p = 0.636$, nor an interaction between landmark condition and accuracy of egocentric and allocentric trials, $F(1, 90) = 0.005$, $p = 0.940$ (see Table 6 for post hoc comparisons).

Table 5: Descriptive statistics: **Mean** and **Standard Error** of **Accuracy** and **Reaction Time (sec)** of **Egocentric** and **Allocentric** trials for the two GPS instruction conditions **(Landmark vs. No landmark)**

Variable	Point of view	Condition	N	Mean	SE
	Egocentric	*Landmark*	44	0.732	0.027
Accuracy		*No Landmark*	49	0.712	0.030
	Allocentric	*Landmark*	44	0.456	0.026
		No Landmark	49	0.437	0.024
	Egocentric	*Landmark*	44	3.529	0.313
Reaction Time		*No Landmark*	49	2.747	0.190
	Allocentric	*Landmark*	44	6.567	0.872
		No Landmark	49	5.576	0.818

Table 6: Post Hoc Comparisons - **Accuracy** of **Egocentric** and **Allocentric** trials x **Landmark Condition.**

Comparison								
Point of views & Landmark conditions				**Mean Diff**	**SE**	**df**	***t value***	p_{tukey}
Egocentric	Landmark	Egocentric	No Landmark	0.013	0.040	90	0.3480	0.98542
		Allocentric	Landmark	0.273	0.028	90	9.6825	< .00001
		Allocentric	No Landmark	0.290	0.037	90	7.6432	< .00001
	No Landmark	Allocentric	Landmark	0.259	0.037	90	6.8763	< .00001
		Allocentric	No Landmark	0.276	0.026	90	10.327	< .00001
Allocentric	Landmark	Allocentric	No Landmark	0.016	0.035	90	0.4743	0.964

3.3.2. 2 x 2 Mixed ANOVA - Reaction Time

We observed a significant main effect of point of view (egocentric vs. allocentric) on reaction time, $F(1, 91) = 32.918$, $p < .0001$. Post hoc test with Tukey correction showed that reaction time of the egocentric trials was significantly faster than the allocentric trials, t (91) = -5.737, p <.0001 (see Table 5 for descriptive statistics). Neither the main effect of landmark condition, F (1, 91) = 1.518, p = 0.220, nor the interaction between landmark condition and reaction times of egocentric and allocentric trials were significant, F (1, 91) = 0.042, p = 0.837 (see Table 7 for post hoc comparisons).

Table 7: Post Hoc Comparisons - **Reaction time** of **Egocentric** and **Allocentric** trials x **Landmark Condition**.

Comparison								
Point of views & Landmark conditions				**Mean Diff**	**SE**	**df**	***t value***	p_{tukey}
Egocentric	Landmark	Egocentric	No Landmark	0.781	0.358	90	2.1785	0.14
		Allocentric	Landmark	-3.038	0.742	90	-4.093	0.001
		Allocentric	No Landmark	-2.047	0.862	90	-2.372	0.09
	No Landmark	Allocentric	Landmark	-3.820	0.902	90	-4.234	0.001
		Allocentric	No Landmark	-2.828	0.703	90	-4.021	0.001
Allocentric	Landmark	Allocentric	No Landmark	0.9916	1.195	90	0.8294	0.84

4. Discussion

We conducted an online study to examine relationships among self-reported measures of mental health conditions (depression, anxiety, and stress), working memory abilities, navigation abilities, GPS dependance and reliance. We also examined the relationships between these survey measures and performance on an online navigation task, which further tested the effects of different landmark-based GPS-like instructions on egocentric and allocentric route learning.

4.1. Landmark-based GPS

One of the aims of this study was to assess whether incorporating landmark information into GPS instructions improves driver navigation. Participants in the training trials reached a destination by following directional instruction at intersections that either included a landmark (e.g., turn right at the movie theater to reach the school) or did not include a landmark (e.g., turn right to reach the school). Later, they were tested on their memory for the route they followed at each of the intersections, either from the same point of view as they saw in the training (egocentric trials) or a different point of view (allocentric trials). In contrast to our hypothesis, we did not observe an improvement in route learning accuracy when the landmark-based GPS instructions were provided. This held true for both egocentric and allocentric trials.

In this study, we used salient visible landmarks at intersections. Salient objects at decision points are more likely to be considered landmarks than objects at non-decision points (Janzen, 2006; Green et al., 1995; May & Ross, 2006). One possibility for not observing a significant effect of landmark-based GPS instruction could be due to the type of landmarks that we used. In both the landmark and no landmark conditions, the landmarks that we used were the same visually strong and memorable cues; the only difference was that the landmark was explicitly named in the landmark condition. Therefore, participants may have associated turns with landmarks regardless of whether the landmarks were explicitly named or not. Another reason could be the structure of the GPS instructions. We did not provide verbal instructions like most GPS systems. The written instructions might emphasize the visual attention of participants to the image and better encode the landmarks in both conditions. Future studies should investigate the effect of landmark-based GPS instructions delivered verbally.

Furthermore, the effect of landmark-based GPS instructions may not have been detectable in an online image-based navigation task. A more ecologically valid test setting would increase the involvement of various cognitive factors in navigators since they are engaged in multiple tasks in tandem, such as driving, monitoring the environment, and perceiving the GPS instructions. As a result, incorporating landmarks into GPS instructions might have a different effect on navigation accuracy in a more ecologically valid setting, such as a driving simulator. Lastly, the between-subject design of the study may also have had an effect on the observed results.

4.2. Self-reported Mental health factors: Anxiety & Stress

It has been demonstrated that mental health disorders can significantly affect our spatial abilities by affecting the encoding and retrieval processes of information (e.g., Brown et al., 2020). In this study, we observed that anxiety and stress were associated with an increase in GPS use, a decrease in egocentric navigation accuracy, and lower self-reported wayfinding skills. These observations are in line with the literature findings on mental health factors and spatial skills, showing anxiety and stress reduce navigational performance (Mueller et al., 2009; Gardony et al., 2011). Specifically, He and Hegarty (2020) found that higher levels of spatial anxiety limit environmental exploration and result in a greater reliance on navigation aid systems. The release of stress hormones has been shown to disrupt the performance of the hippocampus and, consequently, can affect the navigator's preference in applying navigation strategies. When under stress, navigators are less likely to apply a cognitively demanding strategy such as the allocentric navigation strategy. In contrast, they prefer a simpler stimulus-response strategy such as an egocentric navigation strategy to guide their performance (Gardony et al., 2011; Schwabe et al., 2008; Schwabe & Wolf, 2013; Oei et al., 2007).

4.3. Self-reported Mental health factors: Depression

Depression and antidepressants have been shown to have a negative effect on driving frequency and spatial navigation (Cornwell et al., 2010). To the best of our knowledge, no studies have assessed the relationship between depression and GPS use. Our results suggest that depression is linked with a lower use of GPS. This could be due to a variety of factors. For example, depression is associated with a decline in driving tendencies (Babulal et al., 2018) and consequently lower use of GPS. Following up on this finding, we ran a correlation test on the self-reported frequency and hours of driving in an average week and the depression score. However, no significant negative relationship was found. This might suggest that our participants who scored high on the depression scale have not experienced a decline in weekly driving hours or frequency, but often drove locally, which normally does not require GPS. A future study could address this question by asking about frequency of driving in local, familiar environments versus extended, unfamiliar environments.

4.4. Working memory & self-reported navigation skills

In this study, we observed that a higher working memory span was associated with lower GPS use and a higher self-reported sense of direction. Working memory plays a significant role in encoding spatial information (Cornoldi & Vecchi, 2004; Meneghetti et al., 2016; 2021; Gras et al., 2013). Therefore, individuals with a lower working memory span may struggle with encoding and retrieving spatial cues, and this may increase GPS dependency and reliance. To the best of our knowledge, no studies have evaluated the relationship between working memory abilities and GPS use. However, some studies have explored the influence of working memory on navigation performance, indicating greater working memory skills improve performance in navigation tasks (e.g., Gras et al., 2013). For instance, Weisberg and Newcombe (2015) found that participants with lower accuracy in a pointing task had a lower working memory score and a poor sense of direction. These participants also showed difficulty in learning landmark names and images, whereas the opposite trend was observed for participants with high working memory scores.

We also observed that individuals with a higher self-reported sense of direction reported lower GPS use. Similar findings in the literature indicate that the greater self-reported spatial skills, the lower the GPS use (He & Hegarty, 2020; Dahmani & Bohbot, 2020). Hejtmánek et al. (2018) also found that subjective evaluation of one's own navigation skills was associated with a higher use of maps for route learning instead of reliance on GPS.

4.5. Limitations

Existing studies on the relationship between mental health factors and spatial navigation are limited and have mainly been conducted on clinical populations (Cornwell et al., 2010; Mueller et al., 2009). However, in this study, we used self-reported measures of mental health conditions, which might not be a strong diagnostic of mental health conditions.

Due to the online nature of the study, we designed an image-based navigation task that allowed us to use high-detail real-life stimuli, but our design lacked the auditory and proprioceptive cues that participants could receive if they were tested in a driving simulator using steering, gas, and brake pedals. Using written GPS instructions as opposed to verbal instructions might have placed an additional load on the visual sensory systems of participants and consequently affected the encoding process of the spatial information.

Furthermore, it would have been useful to administer a landmark recognition test in both conditions to detect whether the insignificant effect of landmark-based GPS design is not due to poor landmark recognition. Finally, this study was conducted online and, accordingly, had its own types of restrictions, such as possible environmental distractions and different administration times and conditions based on the participants' location. Future studies can test our hypothesis in a controlled laboratory setup using a driving simulator.

4.6. Conclusion

Overall, our results support the hypothesis that cognitive spatial skills can be significantly affected by mental health factors (e.g., stress, depression, and anxiety) and other cognitive elements such as working memory abilities. These factors affect reliance on navigation aid systems such as GPS for wayfinding. In recent years, the ease of wayfinding granted by GPS technologies readily available in vehicles and smartphones has made it the dominant form of navigation assistance. It is an interesting ongoing question whether overuse of GPS navigation aids may negatively impact spatial learning abilities. Future studies can explore strategies for navigation aid design that would offer both cognitive offloading and effective engagement with surroundings to support spatial and navigation skills.

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CHAPTER 7: General Discussion

The focus of this final chapter is to situate the main findings of the studies presented in this thesis into the broader scope of literature. The experiments included in this thesis assessed the spatial memory and wayfinding abilities of drivers in different situations in an effort to expand our understanding of various cognitive and environmental factors that affect drivers' navigation abilities. This thesis stands apart from earlier published works in the field of spatial cognition due to its focus on evaluating wayfinding in a variety of experimental and correlational settings within the ecologically valid context of driving and navigating. To the best knowledge of the author, no other thesis has addressed several interrelated topics that affect drivers' spatial representations using such a wide variety of measures and conditions as the present thesis offers. In the following paragraph you will find the important points discussed in each chapter succinctly summarized.

In Chapter 2, the effect of different classes of environmental landmarks on route knowledge of drivers and the transfer of route to survey knowledge was examined. In Chapter 3 we evaluated the effect of vestibular cues on wayfinding of drivers in different landmark-based environments by assessing the integration of landmark cues with vestibular cues. In Chapter 4 the association of a range of individual differences factors in cognitive abilities such as visual-spatial and self-reported navigation skills (e.g., mental rotation abilities, spatial working memory span, spatial pointing skills, & self-reported sense of direction) was assessed with route learning of drivers in the presence of different classes of landmarks. We then examined the effect of an important individual difference factor, “age”, on route learning of drivers in more detail in Chapter 5. Eventually, in Chapter 6, we examined the association of certain self-reported mental health factors (e.g., depression, anxiety & stress) on navigational skills and GPS dependency of drivers as well as the effect of incorporating landmarks into the GPS instructions on route learning. Below we discuss the distinct aspects and importance of the findings reported in this thesis compared to the literature.

Ecologically-valid experimental setup-Immersive driving simulator

The relationship between sensory systems in desktop virtual tasks differs from that in motion simulators and this matter can affect route learning of navigators (e.g., Bowman, et al., 2002; Chance, et al., 1998). In all the experiments provided in this thesis, excluding chapter 6 which was an online study, participants experienced the virtual driving tasks in an immersive motion simulator and benefited from receiving idiothetic cues from the simulator during driving (Chapters 3 and 5). Idiothetic cues (e.g., vestibular cues, proprioceptive cues) are an important source of self-motion information, vital for keeping track of the traveled distances and the magnitude of body rotations (e.g., Smith, 2017; Loomis et al., 1993; Mittelstaedt & Mittelstaedt, 1980; Wallace et al., 2002; for a review see Cullen & Taube, 2017; Chrastil & Warren, 2012). Unfortunately, virtual desktop driving tasks fail to provide appropriate idiothetic cues to participants (e.g., Tan et al., 2006; Ruddle & Lessels, 2006; 2009; Chance et al., 1998).

Simulators are highly reliable and practical in driving and safety research. They enable risk-free replication of extremely hazardous driving circumstances and allow for the precise control of the situations that drivers are exposed to (e.g., Walker & Trick 2018; 2019; Van Benthem & Herdman, 2021; Beninger, et al., 2020). The motion simulator that we used to simulate different driving contexts enabled participants to physically turn their head to orient in the environment, rather than virtually turn and translate using joystick or keyboard keys. The vestibular system is influenced by head and neck rotation (Beisel et al., 2005; Chance et al., 1998; Zheng et al., 2009; Yoder & Taube 2014; Laurens & Angelaki, 2018). The large field of view provided in the simulator resulted in drivers' head movements to look around in the virtual environment which would provide a more realistic driving experiment different from the navigation studies that do not require active driving or use a small field view.

Aim and Scope

Most of our travels, if not all, necessitate navigation to a specific destination. Navigating while driving requires monitoring multiple actions simultaneously (e.g., Mueller & Trick, 2012; Trick et al., 2004) such as controlling the vehicle speed, steering movements, accelerator and brake pedals, determining the heading direction, and watching and accounting for the movement of other vehicles and pedestrians. While keeping track of these actions, it is necessary to avoid undesirable situations like accidents. Successfully doing so adds a significant load to the attention and spatial memory span needed for navigation. Undoubtedly, multiple action monitoring tasks, such as driving and navigating are cognitively demanding tasks that require mental effort from drivers (e.g., Scholl, 2009; Trick et al., 2004). As a result, it is not surprising that drivers increasingly outsource/offload their spatial abilities to the external navigational aid systems. Nowadays with improvements in technology drivers can obtain simple and precise navigational information from navigation aid systems such as a GPS. Moreover, development of autonomous vehicles is advancing rapidly in both research and industry. Even though there are some advantages to autonomous vehicles such as improving mobility for certain populations, and elimination of human error in detecting hazards (Othman, 2020; 2021a,b), the studies on safety of autonomous vehicles are still in early stages and there are many potential safety drawbacks to the behavior of autonomous vehicles (Krisher, 2018; Sivak & Schoettle, Othman, 2015a,b).

Despite their many benefits, there are disadvantages to cognitive offloading and over reliance on either GPS or autonomous vehicles. Offloading the task of wayfinding to GPS and driving to autonomous vehicles may be strongly associated with offloading spatial cognitive abilities and driving skills. Over reliance on GPS systems may lead to deterioration of spatial skills (Ishikawa et al., 2008; Ishikawa, 2019; Ruginski et al., 2019; Dahmani & Bohbot, 2020). Some research suggests that over reliance may result in less activity in the brain's hippocampal area responsible for spatial learning (Javadi et al., 2017). Furthermore, offloading driving abilities to autonomous vehicles may result in poor memory of driving skills (Friedland, 2019) and attentional issues in crisis situations where the driver must take control of the car (Endsley, 2019; Brown & Laurier, 2017).

In addition, similar to situations in which navigation guidance provided by passengers can be distracting, GPS instructions can be distracting for drivers and potentially increase the crash risk (Trick et al., 2004; Toxopeus, et al., 2011; McPhee et al., 2004). Sometimes the suggested route by GPS systems is not an optimal preferred route for the navigators (e.g. high speed routes). Moreover, if drivers rely only on the visual display instructions and avoid the verbal instructions, the risk of getting distracted and misled increases compared to when they rely only on the verbal instructions or a combination of both visual and verbal instructions (Liu, 2001).

Accordingly, knowledge about the importance and performance of various navigational cues (e.g., landmark cues, vestibular cues), cognitive spatial skills (e.g., mental rotation abilities, working memory span) and individual differences such as mental health factors (e.g., anxiety, depression) is crucial for understanding what contributes to effective navigation. The experiments presented in this thesis sought to increase understanding of the mechanisms underlying spatial navigation so as to help drivers better manage their everyday wayfinding tasks. We hope that the findings reported in this thesis on spatial skills and navigational cues will broaden the navigation literature and suggest avenues for future research on designing better GPS application and affordance in vehicles. Ultimately, we hope our findings help navigators effectively find their way in various environments and lessen the difficulties they may encounter navigating while driving. Below, we situate the important main findings of each chapter with respect to the literature.

Visual Cues, Route, and Survey Knowledge

In the experiments presented in Chapters 2, 3, and 4 participants were trained with guiding arrows on different routes leading to a target destination in a virtual town with the presence of either proximal landmarks (nearby structures), distal landmarks (distant structures), both proximal and distal landmarks, or no landmarks. Later they were tasked to find the target destination without the help of guiding arrows. Results showed that proximal landmarks were the most reliable cues for effective route learning (e.g., Jabbari et al., 2022; Hurlebaus et al., 2008; Ruddle et al., 2011). When proximal landmarks were present, drivers were able to retrace the exact training routes and reach the target destinations quickly and accurately. Distal cues were not as helpful as proximal cues, and participants demonstrated the least accurate route knowledge when they attempted navigation in the no landmark environment (Jabbari et al., 2022).

The experiments provided in Chapter 2 further examined how route knowledge can be transferred to survey knowledge. Participants who were trained to find the target destination with the proximal/distal landmark conditions mentioned earlier were later exposed to the same virtual town, but this time without any landmarks available to them. We were interested to see how previous exposure to various types of landmarks would help drivers to find the target location in a landmark-free environment. Even though route learning was more effective in the presence of proximal landmarks, in the transfer condition participants who were previously trained to find the target destination with the help of the navigational information of the distal landmarks had the highest transfer effect. This showed that during route learning in the presence of distal cues, drivers generated better cognitive maps of the environment which further improved their survey knowledge and assisted them to locate the target when there were no landmarks in the environment. It can be concluded that map-like spatial representations built in the presence of distal landmarks were helpful to drivers when the navigational resources in the environment were restricted.

Proximal and distal cues differences

In the simulated environments of the experiments described in this thesis, distal landmarks could occasionally change into proximal landmarks during the training trials, depending on the proximity of drivers to them. This raises the question as to why navigational information of distal landmarks were not as easy to use for route learning as the proximal landmarks were. Similarly, it can be asked as to why it was challenging for drivers to create cognitive maps when proximal landmarks were present. Below we discuss this matter in detail.

Distal and proximal cues offer distinct navigational information. While distal cues provide compass-like orientational and heading information, proximal landmarks act more like a global tracking system (GPS), providing positional information useful for self-localization. However, the information from the cues, even though distinct, is sometimes challenging to dissociate. To successfully solve a navigational challenge, navigators use the cues that are most beneficial to the navigational issues that they encounter. For instance, in the Morris Water Maze task, rodents have been seen to use distal cues to determine their heading and use proximal cues to determine their location to reach a hidden platform (Hamilton et al., 2007; Knierim & Hamilton, 2011).

A driver's spatial perspective is highly variable when navigating an environment with proximal landmarks since there is a substantial change in the spatial view of the navigator with small locational movements (e.g., Knierim & Hamilton, 2011). In such a case, obtaining allocentric information (e.g., distant information) from proximal landmarks is indeed challenging (e.g., O'Keefe & Nadel, 1978; Benhamou & Poucet, 1998; Save & Poucet, 2000). This matter has been further confirmed in neuroimaging studies where proximal landmarks, in contrast to distal landmarks, were not able to activate the hippocampus place cells that are required for cognitive mapping (Lenck-Santini et al., 2005; Save et a.,1998; Cressant et al.,1999; Save & Poucet, 2000; Barry et al., 2006). Overall, Chapter 2 indicated the importance of proximal landmarks over distal landmarks to route learning and supports a hypothesis that there is parallel formation of cognitive maps and route knowledge in the presence of distal landmarks.

Effectiveness of Combined Visual and Vestibular Cues

Previous studies have demonstrated that the combination of self-motion perception and landmark cue processing can reduce response variance and improve navigation (Nardini et al., 2008; Zhao & Warren, 2015; Sjolund et al., 2018). Rodent studies have demonstrated that in the absence of vestibular cues, landmarks are necessary for successful navigation (Stackman & Herbert, 2002; Youngstrom & Strowbridge, 2012). However, no existing studies have tested how vestibular cues interact with landmarks in humans. The goal of chapter 3 was to find direct experimental evidence for possible facilitation of route-based navigation in drivers when vestibular cues were available. We used a motion simulator to examine the contribution of physical self-motion cues on memory under three landmark conditions: proximal, distal, and no landmarks.

Similar to the findings of chapter 2 and 4, we found that route memory was improved in the presence of landmarks. What we observed about the effect of vestibular cues on route learning across landmark conditions ruled out two potential hypotheses. Vestibular cues were not independent from visual cues and therefore did not have a uniform effect on route navigation. Furthermore, the relative contribution of vestibular cues did not differ when less reliable landmarks for route learning were present (distal landmarks), or when there were no landmarks. In contrast, we observed that vestibular cues were most effective when combined with landmarks that promote body-based (egocentric) navigation strategies, such as proximal landmarks. Vestibular cues were less effective when combined with landmarks that promoted an external frame of reference, such as distal landmarks. Our results suggested that vestibular cues result in the greatest improvement on human spatial navigation when they coincide with proximal cues, potentially because vestibular cues evoke episodic memories that integrate better with proximal landmarks. Accordingly, it can be concluded that physical cues to self-motion are integrated by associating the physical movement with nearby landmarks.

Visual spatial and self-reported navigational skills

Depending on our viewpoint, environmental objects can have an allocentric position with regards to the position of other objects (e.g., the pharmacy is on the east side of the gas station) or can have an egocentric position with regards to our body location (e.g., the pharmacy is in front of me) (e.g., Moraresku & Vlcek, 2020; O'Keefe & Nadel 1978, Klatzky 1998). During driving, egocentric or allocentric positions of environmental objects constantly shift relative to the driver's viewpoint. For instance, egocentric location of buildings or allocentric location of other vehicles change with respect to the driver or a fixed reference landmark. As a result, navigating while driving requires constant updating of the driver's spatial representation pertaining to an egocentric and allocentric frame of reference. Good navigators can reduce the cost of constant egocentric updating by developing an allocentric representation of the environment which would decrease the working memory resources' demand for constantly updating the driver's location egocentrically (Hegarty et al., 2006, Miyake et al., 2001, Shah & Miyake, 1996). However, not everyone is able to easily switch from egocentric to allocentric spatial strategy or even develop an allocentric representation. Moreover, presence of landmarks highly affect this ability and navigation strategy preference of navigators (e.g., Wolbers & Hegarty, 2010; Ishikawa & Montello, 2006).

The goal of chapter 4 was to identify different spatial and navigational skills that increase spatial awareness of drivers by enhancing the effective application of different navigation strategies in different landmark-based environments. Through the administration of various cognitive and self-reported assessments it was revealed that the importance of visual spatial and navigational skills would be altered in the presence of different classes of landmarks and under additional cognitive load of driving. For instance, we found that spatial skills like mental rotation abilities are important for using directional information that distal landmarks provide.

Working memory is one of the important cognitive mechanisms that plays a significant role in better sustainment of spatial information and greater ability to recall routes (e.g., Gras et al., 2013; Meneghetti et al., 2016, 2021; Bosco et al., 2004; Coluccia, 2008). The monitoring of the positions of several objects as they move around other identical objects in a visual display is known as multiple-object tracking (Pylyshyn & Storm, 1988), a task similar to driving on a highway. The study done by Trick et al., (2012) revealed that some of the individual differences in performance on the multiple-object tracking task were predicted by spatial working memory tests like the Corsi Span Test. In the experiment presented in chapter 4, we used various visual-spatial tasks and working memory tasks to see if they could predict the navigation performance of participants and whether it depended on the type of landmarks available in the environment. We found that the role of spatial (Corsi Span Test) and verbal (Digit Span Test) working memory in route learning might be more identifiable in a route-based navigation task in the presence of proximal landmarks rather than in a map-based navigation task in the presence of distal landmarks. However, as suggested in Chapter 4, to be confident about this hypothesis a dual task paradigm with a visual-spatial or verbal working memory interference task is needed while drivers are engaged in a route learning task. Other visual spatial tasks, such as the Mental Rotation Test, predicted successful target localization in situations where mental rotation is required, such as driving in the presence of distal landmarks.

Moreover, testing the navigation performance of drivers in various landmark conditions allowed us to observe that self-reported landmark-based navigational skills were highly correlated with the navigation performance of drivers in different landmark-based environments. Drivers who reported a high dependence on landmarks and visual memory for wayfinding were less accurate in locating the target destination when they were navigating in a landmark-free environment and more accurate when both distal and proximal landmarks were provided to them. Overall, corroborating with the findings of literature, the results presented in Chapter 4 revealed that how drivers orient themselves in unfamiliar environments and learn new routes depends on a wide variety of individual factors (e.g., Zhong & Kozhevnikov, 2016; Gras et al., 2013; Boccia et al., 2017; Malinowski, 2001). Furthermore, we revealed that the association of visual-spatial and self-reported navigational abilities with route learning while driving varies based on the availability and type of environmental landmarks.

Aging and Navigational Skills

Unfortunately, aging can be associated with noticeable shortfalls in visual-spatial perception and navigation (e.g., Bird & Burgess, 2008). Research has shown a contrast in the navigational performance of young and older adults (e.g., Zhong & Moffat, 2018; Burns, 1999). This contrast has been seen in terms of preferred types of landmark and wayfinding strategies (e.g., Schuck et al., 2015; Glockner, et al., 2021; De Condappa, 2016). Frequently, proximal landmarks (nearby objects) and simple stimulus-response navigation strategies (aka egocentric navigation strategy) are the choices of older adults, in contrast to distal landmarks (distant objects) and map-based cognitively demanding strategies (aka allocentric navigation strategy), which are the choices of young adults (Rodgers et al., 2012; Moffat & Resnick, 2002; Driscoll et al., 2005).

The ability to properly navigate in the environment is vital for older adults' safety, independence, and lifestyle. Unfortunately, older adults with diminished spatial abilities are more likely to rely on caregivers or avoid unfamiliar environments due to the potential navigational challenges (e.g., Lawton & Brody, 1969). Aging can also affect selective attention and situational awareness of drivers. During driving, we receive a huge amount of dynamic information, far greater than what working memory can easily handle. To drive safely, we constantly need to select the relevant amount of information and decide which activities to undertake corresponding with the information (e.g., Dehmani & Bohobot, 2020; Trick et al., 2004; Toxopeus, et al., 2011). The failure to select the proper stimulus to attend to (e.g., a potential hazard: a pedestrian who is about to jump into the street) or the proper action to undertake based on the stimulus (e.g., changing lanes or pressing the brake) is the cause of most reported crashes (e.g., Hakamies-Blomqvist et al., 2004; Romoser & Fisher, 2009a; Romoser et al., 2005; Romoser, 2013; Pradhan et al., 2011; 2006; Pollatsek et al., 2006a,b; McGwin et al., 1998; 2000).

Working memory and attention span are the base of "*situation awareness*". *Situation awareness* enables drivers to predict what aspects of the situation they should be aware of and attend to while navigating (e.g., Romoser, 2013; Pradhan et al., 2006; Pollatsek, et al., 2006a, b; McGwin, et al., 1998; Finnigan et al., 2011; Bolstad & Hess, 2000). Age-related cognitive decline can restrict the amount of information that can be processed in working memory and affects the effectiveness of retrieval processes which can in turn impair the development of *situation awareness* and increase the crash risk (Bolstad & Hess, 2000; Munzer et al., 2006; Parush et al., 2007). Similarly, numerous aircraft-reported accidents attribute loss of situation awareness in pilots as a contributing factor (Bolstad et al., 2010; Brightman, et al., 2021).

The study covered in Chapter 5 sought to increase our knowledge of how aging affects spatial navigation to help us master challenging navigational situations as we age. Chapter 5's findings extended the existing literature on the relationship of age and spatial representations of environment, as it provided an ecologically valid experimental setup to test the spatial representations of three different age groups of young (18 - 30), early middle-age (30 - 45), and late middle-age (45 - 66) while driving. We observed that all participants performed similarly well developing an egocentric spatial representation of the routes they traveled during driving. However, compared to young and early middle-age adults, late middle-age adults performed less satisfactorily when they were tasked to develop allocentric spatial representation of the routes.

The literature on the age-resiliency of egocentric spatial representation has been inconsistent. While some research indicated age-related impairment effects on the development of egocentric representation (e.g., Fernandez-Baizan, et al., 2019; 2020; Ruggiero, et al., 2016), others indicated an age-resiliency effect (e.g., Rodgers et al., 2012; Gazova et al., 2013; Moffat & Resnick, 2002; Iaria et al., 2009). The study provided in Chapter 5 indicated that egocentric navigation representation of the environment stayed intact until the late sixties, in contrast to allocentric navigation representations that decreased with age. This study only included the three age groups of young, early, and late middle-age adults. Future studies can explore further by including an older adult group (66 and above).

Another important finding of Chapter 5 was the effect of training on developing allocentric representations. Research has previously shown a positive effect of training on older adults' driving performance, situation and self-awareness (Romoser & Fisher, 2009a, b; Romoser, 2013; Pollatsek, et al., 2006a,b). Chapter 5 results showed that with training, older adults can overcome challenges involved with spatial allocentric tasks. Allocentric training might be emphasized at retirement homes, rehabilitation facilities, or hospitals that focus on the cognitive rehabilitation of older adults.

Landmark-based GPS and Navigation

Navigational aid systems such as GPS, can compensate for our inadequate spatial knowledge when driving; however, a long term reliance on GPS can degrade our spatial abilities through divided attention, which detaches the drivers' full attention from the environment and leads to less involvement of working memory, which degrades drivers' spatial memory for the environment (Munzer et al., 2006; Parush et al., 2007; von Stülpnagel & Steffens, 2012; Fenech et al., 2010; Gardony et al., 2013; 2015; Hejtmánek et al., 2018; Willis et al., 2009). These side effects can impair drivers' situational awareness and vigilance toward hazards and consequently increase the crash risk (von Stülpnagel & Steffens, 2012; Munzer et al., 2006; Parush et al., 2007). In an effort to lessen the adverse effects of current GPS systems on spatial skills, modified GPS designs have been suggested. Suggested modifications are around the type of the information that GPS instructions would provide (e.g., Krukal et al., 2022). Research has shown that GPS instructions that visualize proximal and distal landmarks affect route vs survey knowledge, differently. For instance, highlighting proximal landmarks in GPS instructions or using turn-by-turn instructions would improve route knowledge (aka egocentric navigation performance) while highlighting distal landmarks or providing map-like information would improve survey knowledge (aka allocentric navigation performance) (Lowen et al., 2019; Münzer et al., 2012).

In a study done by Krukal et al. (2020) the effect of three types of GPS instructions on route learning and memorability of instructions were assessed. The given instructions differed in the type and amount of information that they provided. The instructions were *Turn by turn*, which provided routes described as a sequence of turns and metric information (e.g., Turn right at Main street west and drive for 500 m), *Spatial chunking*, which provided chunked local route information and sometimes landmarks located at decision points, a similar design to the experiment presented in Chapter 6 (e.g., Turn left at the second intersection), or *Orientation*, which provided more integrated information by including survey information (e.g., Go towards the shopping mall, passing the gas station on your right. Turn left before the post office). Krukal et al. (2020) found that the orientation instructions resulted in both better route knowledge and better survey knowledge. Of the other two conditions, the spatial chunking GPS instructions led to better route knowledge, but both groups demonstrated poor survey knowledge compared to the orientation instructions.

One of the key aspects studied in chapter 6 was whether incorporating proximal landmarks in GPS instructions improves route learning of drivers. We used an online navigation task to assess egocentric and allocentric representations associated with route learning. In accordance with previous findings in the literature, higher accuracy and faster reaction times were seen in egocentric trials compared to allocentric trials. Surprisingly we did not find a beneficial effect of landmark-incorporated GPS instructions in egocentric or allocentric trials, which argues against the findings of some published studies (e.g., Krukar et al., 2020; Gramann et al., 2017; Schwering et al., 2017; Lowen et al., 2019). One plausible hypothesis that could be drawn from our results is that the visual configurations we used as landmarks were noticeable enough that they were used as an associative cue by the participants even in the condition that did not explicitly provide the name of the landmark in the GPS instructions. Another hypothesis is that the simple landmark-based instructions in our image-based study (e.g., Turn right at the gas station to reach the museum), were not as effective as they would have been with descriptive instructional details as seen in other studies (e.g., Kukar, et al, 2020). Moreover, research has shown that drivers prefer the auditory GPS verbal instructions over using the visual instructions as it might cause confusion for them at some points (Noel et al., 2005). As an extension to the experiment presented in Chapter 6, future studies should test the effect of lessening the visual load on route learning by providing auditory verbal instructions.

Mental health factors and Navigation

The experiments described in chapter 6 also assessed associations of the self-reported mental health factors with the GPS use and navigation performance. This was a combined online study and the participants were the same people who contributed the data described in the Landmark-based GPS and Navigation section above. We found that stress and anxiety (general anxiety and anxiety at performing spatial tasks such as mental rotation) was associated with an increase in GPS dependency whereas depression decreased this dependence. Depression and anxiety are significantly detrimental to driving performance and spatial skills through the adverse effect that they impose on hippocampus functionality (Herrero et al., 2006; Engin & Treit, 2007; Cornwell et al., 2010; Gould et al., 2007; Hickie et al., 2005). We hypothesized that depression might increase the tendency of drivers to drive locally and as a result decrease the need for GPS. However, anxiety can increase the stress of getting lost and as a result increases the GPS dependency (e.g., He & Hegarty, 2020). Moreover, we observed that anxiety may have been associated with the navigation performance in the egocentric trials as evidenced by a notable decrease in the accuracy of these trials (Mueller et al., 2009; Gardony & Taylor, 2011). The results of our survey study were consistent with the clinical findings in the literature on the relationship between mental health disorders and navigation ability (e.g., Cornwell et al., 2010; Mueller et al., 2009). We also expanded the existing findings by demonstrating a negative relationship between GPS dependency and depression, in particular.

Future directions and limitation

Time-based trial

It is worth noting that the trials in the experiments presented in Chapter 2, 3, and 4 were time-based which can induce stress in drivers. Time pressure and stress can alter decision making, restrict processing of the available information in the environment, and induce performance decrements (e.g., Maule et al., 2000; Schwabe & Wolf, 2013; Gagnon & Wagner, 2016). The time pressure in trying to reach the target destination before the "Time out" message could change driver's wayfinding strategies and the landmark preference. A greater focus on proximal cues over distal cues (Brunyé, et al., 2017; Gardony & Taylor, 2011) and a tendency to use egocentric navigation strategies over allocentric strategies to minimize cognitive effort has been observed (e.g., Schwabe & Wolf, 2013), which can be a suboptimal wayfinding strategy at some points in the task. Future studies can examine whether the importance of landmarks and navigation strategies differs without a time pressure during driving.

Proprioceptive cues

Aside from vestibular input, there are other sensory cues that are unique to drivers such as proprioceptive cues. For example, pressing gas and brake pedals, moving the steering wheel, and neck activate proprioceptive receptors in the corresponding joints and muscles. The proprioceptive cues can be important for making episodic memories during route learning (reviewed in Chrastil & Warren, 2012). We were not able to control the proprioceptive cues in the presented experiments; however, future studies can consider controlling these cues in addition to vestibular cues.

Motion Sickness

Participants' drop-out due to motion sickness can be harmful to any research project, budget-wise. Furthermore, in cases participants do not dropout, and complete the task while being sick, their performance will be negatively affected. Motion sickness symptoms occur when there is an increased peripheral optic flow and an incongruence between visual and vestibular cues and are more prevalent among older adults than young adults (e.g., Classen et al., 2011). The experiments we presented in this thesis (except Chapter 6) required an active drive in the virtual towns, which involved frequent turns and changes in the heading direction. In order to decrease the risk of motion sickness, we allocated a small layout to the virtual towns and designed short and time-based trials to avoid participants wandering in the virtual town. This design was quite helpful as we had a very low rate of dropout among young adults in the Chapter 2, 3 and 4 experiments. Similarly, Huygelier and colleagues (2019) in a flight simulation study demonstrated that the short duration of the virtual reality test trials and brief breaks between tasks reduced the sickness symptoms, especially in older adults. Furthermore, in Chapter 5, we demonstrated that designing routes with wide left turns, instead of sharp right turns, reduced the risk of sickness among older adults. Designing larger towns could have lifted many of our design restrictions, such as placing more landmarks, or assigning multiple target destinations in the towns. Future studies can look for a way to design larger virtual towns with consideration of the risk of motion sickness to reassess the importance of different types of landmarks.

Eye tracking

In chapter 6 we reported the results of an online study on the effect of the landmark-based GPS instructions using an image-based route learning experiment. A group of participants received traditional GPS instructions without landmark names included in the instruction, but the other group received a modified GPS instruction that included the name of a salient, noticeable landmark at intersection. We did not observe a positive effect of landmark-based instructions on route learning. Using an eye tracker, we could check if the group receiving the traditional GPS instruction were noticing the landmarks even when they were not highlighted by the GPS instructions. It is possible that the presence of noticeable landmarks at intersections in an image-based design precluded the beneficial effect of landmark-based GPS directions.

Clinical population

In Chapter 6, we proposed a new hypothesis suggesting that depression is connected with a decreased reliance on GPS, which may be brought on by more local driving that is GPS-independent. Future research can test this hypothesis using a clinical sample diagnosed with depression instead of relying on self-reported information about the mental health conditions of participants.

Dissertation Conclusions

In this thesis, we studied various factors and skills that can improve the wayfinding of drivers. Wayfinding and driving are two cognitively demanding tasks that can be affected by various external and internal factors. We scientifically examined the effect of environmental cues such as various types of landmarks (proximal/distal) on the route learning of drivers. We observed that self-motion cues such as vestibular cues and visual spatial skills such as mental rotation improved route learning depending on the available landmarks in the environment.

The age-resistant effect of egocentric navigation was observed; in contrast, there was an age-related, less optimal performance in allocentric navigation. Mental health factors, such as depression, anxiety, and stress, were associated with navigation performance and a change in the dependency of drivers on GPS. The findings of this study can be incorporated into the everyday navigation performance of drivers and improve their wayfinding abilities in unfamiliar environments, situations where GPS is not available, or navigational information resources are limited. According to the observed results in this thesis, drivers are more successful in navigation in unfamiliar environments when they (1) pay attention to the landmarks along their routes, (2) flexibly implement various navigation strategies, (3) use navigational information from various types of cues, and (4) implement visual-spatial skills such as mental rotation when needed.

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