Charting the path towards rehabilitation: a compensatory approach to navigation impairments
Kuil, M.N.A. van der

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Compensatie als aanpak voor navigatieproblemen

Milan Nicolaas Anthonie van der Kuil

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Charting the path towards rehabilitation: a compensatory approach to navigation impairments

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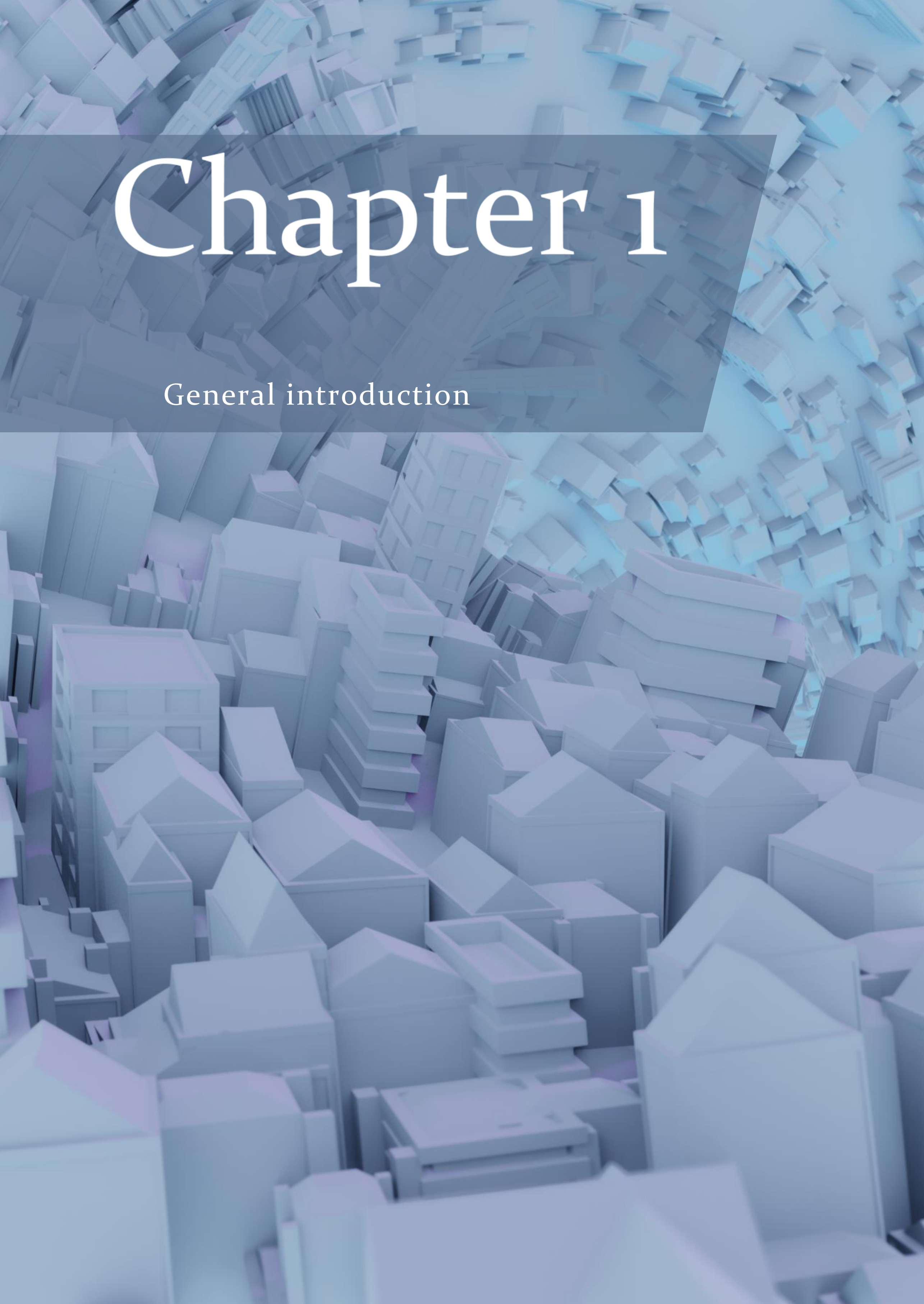

Chapter 1

General introduction

Spatial Navigation

Spatial navigation can be defined as the process by which organisms use multiple cues such as landmarks, path integration and beacons to determine a route to a goal and travel that route (Brodbeck & Tanninen, 2012). The term navigation conjures up images of long journeys to novel and faraway places. While navigation plays an important role in exploration and journeying, the same cognitive processes are involved in more mundane tasks, such as commuting to work or doing groceries. To account for the wide array of spatial challenges humans are confronted with every day, evolution has favoured highly flexible, adaptive and reliable cognitive functions that make up navigation ability (Clint, Sober, Garland Jr, & Rhodes, 2012). However, our navigational abilities are far from perfect. Most people have experienced being lost at some point in their lives. Being unable to determine one's location or having lost one's sense of direction can be a fearful experience (Hill, 1998). Once one has lost one's orientation, anchor points in the environment seem harder to select, distances are more difficult to judge and the environments can look similar. Finding your way back to a known location involves taking risks, such as attempting to backtrack, sampling a route or heading along a direction which should point you on your way home. However, making a wrong decision, might take you further from your intended path. People who get lost experience increasing levels of self-doubt, frustration and anxiety when disoriented (Lawton, 1994; Lynch, 1964; Oliver, Wildschut, Parker, Wood, & Redhead, 2022). This stress response upon disorientation is deeply ingrained in the human psyche. Throughout human evolution, people had to be able to navigate in order to effectively forage for food and return to places of shelter. As such, losing one's orientation can threaten survival.

While most people get lost a few times during their lifetime, for others this is a daily reality. People with brain afflictions such as acquired brain injuries, neurodegenerative diseases and neurological afflictions frequently report difficulties during navigation (Cushman, Stein, & Duffy, 2008; Němá et al., 2021; van der Ham, Kant, Postma, & Visser-Meily, 2013). Such navigation problems are often diverse and complex. Consider the following account by a patient with acquired brain injury after a motorcycle accident.

"I first noticed [that I had navigation impairments] when I still was at the rehabilitation centre. They [therapists] tried to cycle with me through Utrecht. While we were cycling, I told my physiotherapist: "I used to work in Utrecht, in the Nachtegaalstraat. I was store manager of

a computer hardware store". She then replied: "Now that is interesting, we currently are in the Nachtegaalstraat"." I had no idea."

Similar accounts are hardly unique. Over the last decades, there have been numerous neuropsychological case studies in which patients with similar problems are described.

One well-known case is that of a London taxi driver who suffered bilateral hippocampal lesions (Maguire, Nannery, & Spiers, 2006). London taxi drivers are famously required to obtain 'The Knowledge' by following a thorough training program in which the layout of over 25000 streets and thousands of points of interest are studied, before receiving an operating licence. The patient had passed all examinations in the past and had been operating as a taxi driver for 40 years before he suffered a lesion in the hippocampal area. After the injury the patient reported problems when navigating the city he was once very familiar with. Upon investigation, the patient seemed to be able to navigate along the main roads of the city and remembered the landmarks of the city and the spatial relation between them. However, after the lesion, the patient became lost when deviating from the main roads and was required to take the small and irregular side roads he once knew.

Other cases that illustrate the complexity of navigation impairments are those of patients AC and WJ, described by van der Ham et al. (2010). Both patients had suffered damage to the parieto-occipital right hemisphere and reported problems when navigating routes. Further investigation showed that both patients had impaired route-following abilities, but the nature of these problems was vastly different. One patient had problems in remembering the order of important landmarks and scenes along a route, while the other patient had problems remembering what action to take at each decision point along the route. As such, while both patients report similar daily problems, one patient's problem stemmed from temporal route impairments while the other's stemmed from spatial route impairments.

Goals

The goal of this dissertation is to conceive a first, standardized rehabilitation therapy for patients with navigation impairments resulting from acquired brain injuries. The treatment's concept will draw heavily from the existing spatial cognition literature, advances in game technology and best practices in cognitive rehabilitation. As such, a personalized, automated, blended-care treatment will be developed. In this introduction, I will describe the current perspective on the neurocognitive structure of navigation abilities. Furthermore, I will provide a brief overview of earlier attempts to treat navigation problems in patients with acquired brain injuries. Lastly, I will discuss what approach will be taken in the development of the rehabilitation therapy and how recent technological innovations can be utilized to make the treatment accessible to all patients.

Neurocognitive architecture of navigation abilities

Cognitive maps

Over the last century, spatial learning and navigation have been studied intensely in different fields of psychology. Uncovering the mechanisms by which organisms learn about the environment has been of great interest to behaviourist psychologist as it lay at the core of a debate between psychologists adhering to reinforcement and non-reinforcement theories (Jensen, 2006). At the time, researchers such as Hull and Skinner argued that all learning was part of a stimulus-response reinforcement (Delprato & Midgley, 1992), while researchers such as Tolman argued that organisms can learn information without direct reinforcement or motivation, latent learning (Tolman, 1949). To support his theory, Tolman studied navigation and spatial learning in rats. Navigation and spatial learning are ideal functions to study in relation to latent learning as obtaining spatial knowledge itself does not generate immediate rewards, but is necessary to survival. In 1948 Tolman published the iconic article 'Cognitive Maps in Rats and Men' in which he formally introduced the concept of a cognitive map (Tolman, 1948). Tolman proposed that organisms, when given enough exposure to an environment, form a mental representation, analogous to a cartographic map. This cognitive map contains Cartesian elements such as places, distances and angles between locations. As such, the cognitive map contains a representation of the environment, regardless of the current perspective or location of the organism. Given the nature of the ongoing debate between behaviourist psychologists, the cognitive map theory was received with mixed reactions (Skinner, 1950).

Years later, works of O'Keefe and Nadel reinvigorated the cognitive map theory as they provided neurobiological support for the concept of a cognitive map with the discovery of place cells in the rat brain (O'Keefe & Nadel, 1978). Place cells, found in the hippocampus area, correspond to a spatial receptive field and fire whenever a rat is in a specific location in a given environment. Further support for the cognitive map theory was provided with the discovery of additional types of neurons that are involved in spatial mapping such as grid cells and boundary cells (Barry et al., 2006; Hafting, Fyhn, Molden, Moser, & Moser, 2005). The discovery of these neurons in the hippocampus regions provide support for a Cartesian cognitive map and helps us understand how the brain organizes space. Moreover, analogous neuron formations are found in the human brain suggesting that humans form cognitive maps of the environment in a similar fashion (O'Keefe, Burgess, Donnett, Jeffery, & Maguire, 1998).

Landmark, route, survey knowledge

In parallel to the animal studies of O'Keef and Nadel, navigation and spatial learning was studied in the fields of developmental and cognitive psychology. One of the most influential contribution to those fields was the landmark-route-survey model described by Siegel and White (1975). This model placed spatial learning in a clear constructivist framework, proposing that spatial knowledge is obtained in successive stages. First, landmark knowledge is acquired, representing knowledge of the identity of prominent objects or features of the environment that serve as beacons, anchor points and signals at key intersection points. Second, route knowledge arises, as organisms learn fixed paths that connect locations to each other. Finally, survey knowledge is formed. This map-like representation of the environment allows navigators to estimate distances and judge angles between locations and to take short cuts. As such, survey knowledge describes a cognitive map of the environment.

The concepts of landmark, route and survey knowledge are still useful in categorizing the type of spatial information that is obtained. However, the hierarchical nature of the model has been abandoned by most researchers as studies have shown that survey knowledge, can be formed after initial exposure an environment.

Allocentric & egocentric representation in navigation

Organisms rely on spatial reference frames whenever spatial information is encoded, updated or processed (Roberta L Klatzky, 1998). An important functional and neuroanatomical distinction exists between allocentric and egocentric reference frames. The allocentric reference frame, sometimes referred to as the exocentric or geocentric reference frame, is comprised of spatial relations between objects in an environment (**Fig 1.1**). These object-to-object relations are represented independent of the perceiver's position or perspective (Vogeley & Fink, 2003). Conversely, egocentric reference frames constitute spatial relations between the agent and objects in the environment (Fig 1.2). As such, the egocentric reference frame is strongly dependent on a first-person perspective.

All spatial tasks are depended on the allocentric and egocentric reference frames of the agent. For some spatial tasks, the reliance on allocentric and egocentric reference frames are obvious. For example, the allocentric reference frame is used when drawing a map of the environment, when determining one's place in the environment based on distances and angles from prominent objects in the environment or when taking novel shortcuts through an environment. The egocentric reference frame is involved in following a beacon (i.e. 'move towards a visible object in the environment') and when learning a route via stimulus-action associations (e.g. 'go left at the red building'). There are however, more complex instances in which there is an interaction between allocentric and egocentric reference frames. For example, a navigator can encode a route, consisting of a sequence of turns (e.g. left, right, right), into an egocentric reference frame. When the same route is retraced from end to start, the navigator is required to abstract view-dependent (egocentric) information and processes it in an allocentric reference frame (J. Wiener, Kmecova, & de Condappa, 2012).

In most situations, there are multiple ways in which spatial goals can be reached. The approach an agent takes in order to reach a spatial goal when placed in a particular situation can be defined as one's navigation strategy (Hok, Poucet, Duvelle, Save, & Sargolini, 2016). The type of spatial information that is encoded and the manner in which it is processed indicates whether an egocentric or allocentric navigation strategy is employed. In naturalistic environments, it is often hard to measure what strategy is being used. However, Igloi, Zaoui, Berthoz, and Rondi-Reig (2009) have converted animal study paradigms to virtual reality tasks in order to investigate navigation strategy used by humans.

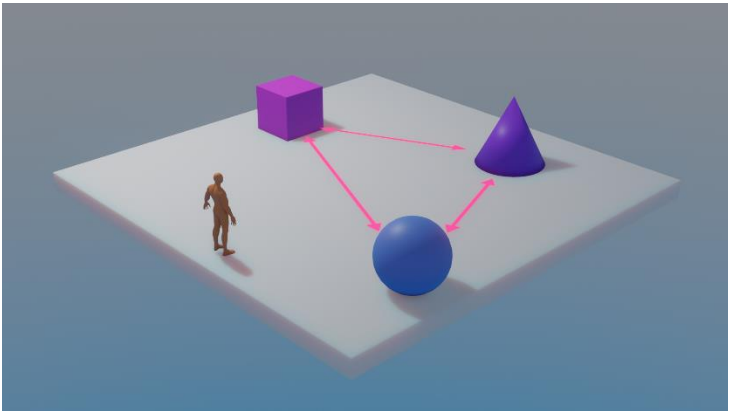

Fig 1.1 Allocentric reference frame

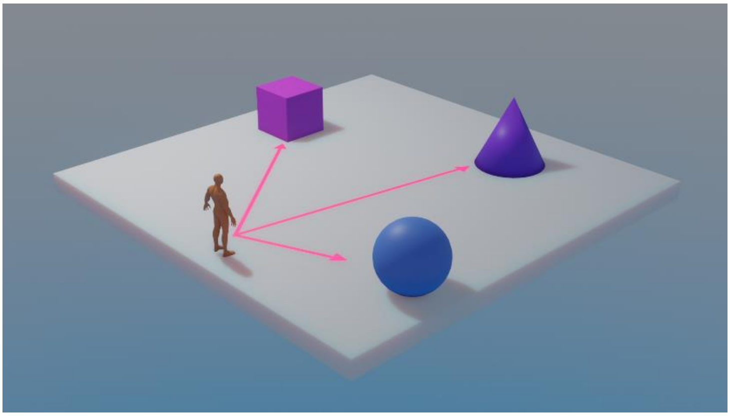

Fig 1.2 Egocentric reference frame

This study shows that humans are able to use egocentric, allocentric or mixed navigation strategies interchangeably. However, most people seem to prefer a strategy. Importantly, both allocentric and egocentric strategies can be observed even after initial exposure to an environment.

The distinction between egocentric and allocentric reference frames is also evident on a neuroanatomical level. Research has shown both overlapping and specific neural correlates involved in egocentric and allocentric encoding and processing. Functional MRI studies have shown overlapping neural correlates for allocentric and egocentric processes in the precuneus, cuneus, superior frontal lobe bilaterally, lingual gyrus, superior posterior parietal lobe and superior occipital gyri (Boccia, Nemmi, & Guariglia, 2014; Zaehle et al., 2007). Both bilateral hippocampal and parahippocampal activation is specifically associated with allocentric memory encoding (Parslow et al., 2004). Another fMRI study in which a non-visual encoding was examined, indicated that allocentric encoding activated the bilateral hippocampal gyri, bilateral inferior temporal gyri, the right inferior and superior frontal gyrus, and of the right inferior and superior parietal lobe whereas egocentric references frames are uniquely encoded in the medial superior parietal cortex (precuneus) (Zaehle et al., 2007).

Taxonomy of navigation impairments

The complex, multifaceted nature of our navigation abilities and the large-scale recruitment of the brain during spatial tasks insinuates its susceptibility to brain injuries. A large variety of navigation problems have been observed in patients with a variety of brain afflictions such as dementia (Cushman et al., 2008; Delpolyi, Rankin, Mucke, Miller, & Gorno-Tempini, 2007), Korsakov (Oudman et al., 2016), multiple sclerosis (Němá et al., 2021) and acquired brain injuries (Livingstone & Skelton, 2007; van Asselen et al., 2006). A taxonomy of navigation problems first appeared in an influential paper by Aguirre and D' Esposito (Aguirre & D'Esposito, 1999). In this paper, navigation problems are referred to as topographic disorientation. Within this taxonomy, four types of impairments were distinguished. Egocentric disorientation, describing the problems patients might have with representing the location of objects with respect to the self. Heading disorientation, which describes the inability to represent the direction of orientation in relation to the environment. Landmark agnosia, describing the inability of patients to represent landmarks, and anterograde agnosia, describing problems patients might have in creating novel representations of the environment. While this taxonomy has been of great use for over two decades, the model lacked a solid neurocognitive bases for its taxonomic division of impairment categories. Recently, the model has been updated by Claessen and van der Ham (2017). This updated model has a more thorough basis with regards to the neuroanatomical substrates associated with navigation impairments and contemporary models in the spatial cognition literature. The model distinguished three domains of navigation impairments: landmark impairments, location-based impairment and path-based impairments.

Patients impaired in the landmark domain have problems recalling or recognising previously known or famous landmarks, or have problems encoding unfamiliar landmarks.

Areas of the brain associated with landmark impairments include lesions in the right temporal and occipital lobes, right hippocampus and right parahippocampal areas.

Patients with location-based impairments have difficulties processing egocentric or allocentric location information. This includes the patients' ability to make spatial judgments (either categorically or co-ordinately), egocentric updating, understanding the interrelation of landmark locations. Areas of the brain associated with location-based impairments include the right temporal lobe, the right parietal lobe, the right retrosplenial lobe and the right occipital lobe.

Finally, patients with path-based impairments report difficulties with regards to the paths that connect locations with each other. Areas of the brain associated with path-based impairments include the right occipital lobe, the right temporal lobe and the right parietal lobe.

Earlier Treatments

Over the past decades, there have been several attempts to treat navigation problems resulting from brain afflictions. Many of these studies concern a single patient with specific navigation problems. Bouwmeester, van de Wege, Haaxma, and Snoek (2015) describe a patient with landmark (unfamiliar landmarks) and location-based navigation impairments who successfully learned to navigate specific routes in his direct environment after repeated exposure to them and training how to utilize a booklet. S. J. C. Davis (1999) describes a treatment for a patient with location-based navigation impairments, who was taught mnemonic techniques to remember specific names and locations of streets in her hometown, allowing her to navigate this part of town. Rivest, Svoboda, McCarthy, and Moscovitch (2018) describe a patient with landmark, location and path navigation impairments who was taught to adopt an errorless learning protocol allowing her to use a smartphone to find routes accurately and reliably. Incoccia, Magnotti, Iaria, Piccardi, and Guariglia (2009) report a patient who never learned to navigate due to complications after congenital hydrocephalus shortly after birth. A training was developed in which the patient was taught to carefully explore the environments and use language-based strategies, resulting in her adopting several cognitive strategies that allowed her to navigate alone.

Kober et al (2013) studied the effects of a navigation training in multiple patients. In this study, patients were trained to learn a route in virtual reality using an errorless learning approach. An increase in general spatial abilities was observed after the training. A more generalizable approach was taken by Claessen, van der Ham, Jagersma, and Visser-Meily (2016). In this study, 6 stroke patients with widely different navigation problems (ranging from landmark-based to path-based impairments) participated. A thorough diagnostic process would take place in which a large number of navigation abilities would be assessed. Depending on the domain of navigation problems, a compensatory navigation strategy would be constructed that focussed on the patient's intact navigation abilities. As such, the compensation component was not determined by the use of tools, mnemonic techniques or specific routes, but rather by the application of a novel navigation strategy. Patients were trained to use this strategy by performing exercises in virtual environments.

While these therapies certainly yielded positive results for the patients, they have not led to a comprehensive treatment that could be employed in clinical settings. There are several reasons for this. The treatments were highly individualized and focussed on specific impairments of the individual in question. As such, these training modules will be of little use to patients with slightly different patterns of impairments. Most studies train patients how to navigate in a specific environment relevant to them. As such, these training modules require substantial adjustments to the training content depending on the locality of a patient. Moreover, it is unclear to what degree training in predetermined environments will allow for transfer of abilities when navigating in different areas. Lastly, most training programmes involved extensive, time consuming face-to-face therapy. While this is admittedly a practical consideration, a blended form of therapy, in which patients receive both face-to-face and online care, might enhance clinical feasibility of a therapy.

Current direction

The previous studies on navigation rehabilitation prove to be an excellent starting point for the development of a novel treatment. In developing the current treatment, we intent to follow a set of core principles.

First, the treatment should be based on the principle of compensation. The complexity and multifaceted nature of navigation, allows for ample opportunity to select strategies that are beneficial to the navigator. In most situations, there are multiple ways to reach a goal location. When patients are aware of their intact navigational abilities and are able to identify which strategy can be applied, patients might be able to navigate in novel environments. This approach is supported by the general rehabilitation literature. Compensatory strategy training has been recommended as standard practice for treatment of memory impairments following brain injury (Cicerone et al., 2019; Cicerone et al., 2011). In addition, two earlier studies have successfully applied a compensation approach in their treatment (Claessen, van der Ham, et al., 2016; Incoccia et al., 2009).

The treatment's underlying concepts should be theory-driven and should be grounded in the neurocognitive literature on spatial navigation. Many earlier treatments have been developed to help a single patient navigate his or her direct environment (Bouwmeester et al., 2015; S. J. C. Davis, 1999). These therapies typically narrow their focus towards an individual and do not take full advantage of the wealth of knowledge available in the field of spatial cognition. Over the past decade, fMRI, lesion and experimental studies have provided a us with a solid understanding regarding the different neuroanatomical and functional dissociations of navigation abilities. These models can be used to systematically diagnose navigation problems and identify intact abilities. Using these models, multiple treatment options can be constructed, allowing for the range of impairments that is to be expected.

The second principle is to develop a treatment with standardization and generalizability in mind. The treatment should be appropriate for patients with a wide variety of navigational problems and varying levels of cognitive functioning. In the context of the content of the training, the compensatory approach should allow us to train beneficial strategies as long as components of navigational abilities are intact. Instead of patient-tailored reconstructed environments, we aim to further increase the generalizability by constructing non-specific, modular environments for the training to take place in. With regard to the interaction with the treatment, we should ensure a high level of usability, suitable for people with severe cognitive impairments. We aim to minimize the complexity of the instructions while the difficulty of the exercises should be adapted to the performance levels of the patient.

As a third principle, we aim to investigate the degree to which innovative technology can be used in rehabilitation therapies. Game technology and virtual reality techniques have seen a rapid development over the past years. Realistic and ecologically valid virtual environments can now be used on most consumer devices (e.g. computers and smartphones). Virtual environments can potentially be of great benefit for diagnostic and treatment purposes for patients with brain injuries (Faria, Andrade, Soares, & i Badia, 2016; Maggio et al., 2019; Spreij, Visser-Meily, Sibbel, Gosselt, & Nijboer, 2020). In the case of navigation strategy training, several aspects of virtual environments seem desirable. Patients require practise to master novel navigation strategies. However, patients with navigation problems often rapport spatial anxiety (van der Ham et al., 2013). As such, practising outside might pose a barrier for these patients. Virtual environments can offer a safe, easily accessible environment to experiment with novel strategies. Furthermore, physical and mental fatigue is a common phenomenon in patients with stroke or traumatic brain injuries and typically hinders recovery and rehabilitation (Belmont, Agar, Hugeron, Gallais, & Azouvi, 2006; De Groot, Phillips, & Eskes, 2003; Schepers, Visser-Meily, Ketelaar, & Lindeman, 2006; Winward, Sackley, Metha, & Rothwell, 2009). Performing exercises in virtual environments might be less exhausting compared to real-life training, which might enhance rehabilitation effectiveness. Over-stimulation is a related phenomenon common in people with brain injuries (Donker-Cools, Schouten, Wind, & Frings-Dresen, 2018; Killington et al., 2015). Many patients experience sensory overload when exposed to crowded environment with loud noises, mixed conversations and flashing lights. As such, training novel strategies in controlled, calm, virtual environments might be more effective compared to real-world environments. Finally, it should be stressed that spatial challenges can often be solved with a variety of approaches in real- world environments. In order to entice patients to adopt a beneficial strategy (and disregard reliance on an old strategy), environments can be constructed in a manner that favours the use of the target strategy.

Lastly, the use of a blended-care paradigm should be a core component of the treatment. The past decade has seen an increase in successfully applied digital health programs. Blended-care programs have several advantages over solely face-to-face therapy. Digital health tools can be designed to closely fit to a patient's needs and preferences. It can increase a patient's access to care, might raise effectiveness of regular interventions and reduce the treatment time of therapists (Kip, Bouman, Kelders, & van Gemert-Pijnen, 2018). In addition, Blended-care interventions can reduce the number of visits to a clinic and might thereby increase treatment adherence. For therapists, such an approach might reduce the working load, increasing the feasibility of the therapy.

Dissertation Outline

The general objective of this dissertation was to introduce a rehabilitation training for patients with navigation impairments as a result of acquired brain injury. This thesis was subdivided into three parts: the problem assessment, the developmental process and the evaluation of the intervention (Fig 1.3).

Part I: Problem assessment

The first aim of the thesis was to identify the prevalence and severity of navigation impairments within the patient population.

Part II: Treatment development

The second goal was to formulate a conceptual framework for the intervention. In this part, we will determine whether the concept of a dissociated spatial representation holds when information is presented from different perspectives. Furthermore, we will determine what the requirements are om terms of usability of a home-based training for the ABI population. Finally, we will assess the views and levels of acceptance of blended-care compensation training interventions from the viewpoint of therapists in the field.

Part III: Treatment evaluation

The third goal of the thesis was to evaluate the effectiveness of the intervention. First, the concept of navigation strategy training will be tested in the healthy population. Second, we will assess the effectiveness of the intervention in the patient population.

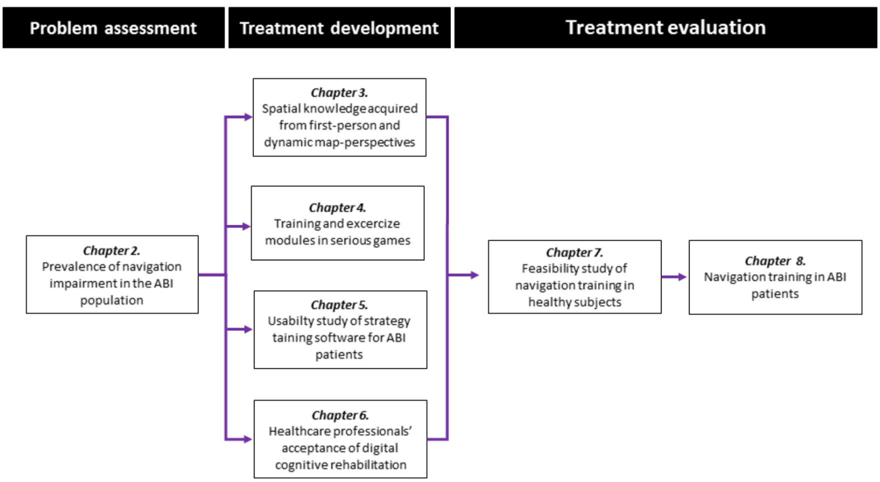

Fig 1.3 Outline of this dissertation.

Chapter 2

Navigation ability in patients with acquired brain injury: A population-wide online study

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Abstract

The ability to travel independently is a vital part of an autonomous life. It is important to investigate to what degree people with acquired brain injuries (ABI) suffer from navigation impairments. The aim of this study was to investigate the prevalence and characteristics of objective and subjective navigation impairments in the population of ABI patients. A large-scale online navigation study was conducted with 435 ABI patients and 7474 healthy controls. Participants studied a route through a virtual environment and completed 5 navigation tasks that assessed distinct functional components of navigation ability. Subjective navigation abilities were assessed using the Wayfinding questionnaire. Patients were matched to controls using propensity score matching. Overall, performance on objective navigation tasks was significantly lower in the ABI population compared to the healthy controls. The landmark recognition, route continuation and allocentric location knowledge tasks were most vulnerable to brain injury. The prevalence of subjective navigation impairments was higher in the ABI population compared to the healthy controls. In conclusion, a substantial proportion (39.1%) of the ABI population reports navigation impairments. We advocate the evaluation of objective and subjective navigation ability in neuropsychological assessments of ABI patients.

Introduction

Acquired brain injury (ABI) refers to brain injury following rapid onset damage to the brain after birth that is not caused by hereditary, congenital or degenerative events (Tibaek, Kammersgaard, Johnsen, Dehlendorff, & Forchhammer, 2019; Turner-Strokes, 2003). The most common types of ABIs result from cerebrovascular accidents (CVA), traumatic brain Injury (TBI) and brain tumours, whereas less common causes of ABIs include hypoxia, intoxication, and infection (Turner-Strokes, 2003). In the Netherlands, a country with 17.2 million inhabitants, approximately 645,900 people (38 out of 1000) suffer from an acquired brain injury (RIVM, 2016).

ABI can have a profound impact on a patient's life. Patients often report cognitive impairments (e.g., working memory, executive functioning, attention) (Rees et al., 2007) in addition to social, emotional and behavioural problems (Cattelani, Zettin, & Zoccolotti, 2010; Milders, Fuchs, & Crawford, 2003). These impairments typically carry over to activities of daily living such as returning to work, doing groceries or maintaining a social network (Haggstrom & Larsson, 2008; Schipper, Visser-Meily, Hendrikx, & Abma, 2011; van Velzen, van Bennekom, Edelaar, Sluiter, & Frings-Dresen, 2009; Wade et al., 2018).

Professional occupation, running a household and attending social events, often require us to travel between locations. As such, the ability to navigate plays a key role in maintaining an independent life (Sohlberg, Todis, Fickas, Hung, & Lemoncello, 2005). The impact of navigation impairments on daily life has been shown to be substantial. In a sample of mild stroke patients, 29% of the participants reported navigation problems. The levels of reported impairments correlate strongly with psychosocial quality of life, stressing the importance of independent navigation for activities of daily living (van der Ham et al., 2013).

Navigation impairments are not limited to stroke patients. Neuropsychological case studies report navigation problems in TBI patients (Rosenbaum et al., 2000), brain tumour patients (van der Ham et al., 2010) and patients with brain injury as a result of hypoxia (Herdman, Calarco, Moscovitch, Hirshhorn, & Rosenbaum, 2015), infections (Hirayama, Taguchi, Sato, & Tsukamoto, 2003; Maguire et al., 2006) and intoxication (Turriziani, Carlesimo, Perri, Tomaiuolo, & Caltagirone, 2003). However, the prevalence of these problems among the ABI population at large is currently unknown. There is reason to expect that navigation impairments are common in patients with multiple types of ABI. Spatial navigation is a high level cognitive ability that is supported by a range of cognitive functions and brain networks (Boccia et al., 2014; Wolbers & Hegarty, 2010). As such, navigation ability should not be regarded as a singular cognitive function, but rather, as a synergy of distinct cognitive processes. Disruption of these systems as a result of brain injury can lead to a wide variety of difficulties when navigating in an environment.

To understand the nature of the navigation problems reported after ABI, it is important to investigate what component of navigation ability is afflicted in a patient. There have been several attempts to capture the components of navigation into a model. Siegel and White (1975) proposed an influential framework in which spatial knowledge is subdivided in landmark, route and survey knowledge (L–R–S framework). According to this framework, spatial knowledge is acquired sequentially. First, fine-grained knowledge about landmarks in the environment is obtained. Then, spatial and temporal relations of landmarks along routes are learned. Finally, survey knowledge is formed, resembling a cognitive map of the environment, allowing navigators to take shortcuts or sketch maps of the environment. While the subdivision of knowledge types has not been disputed, later studies demonstrate that the spatial knowledge is not necessarily obtained in a sequential fashion, nor does extensive route knowledge always lead to survey knowledge (Ishikawa & Montello, 2006). Furthermore, several important aspects of navigation ability are not taken into account in this model, such as perspective taking and spatial updating (Blajenkova, Motes, & Kozhevnikov, 2005; Zhong & Kozhevnikov, 2016).

A different line of research has focussed on the formation and use of spatial memory. Core concepts to these studies include egocentric (self-centred) and allocentric (world-centred) representations (Roberta L Klatzky, 1998). Egocentric and allocentric representations determine how people orientate themselves in an environment, how locations and places are memorized and what spatial strategies are used during navigation (Bullens, Igloi, Berthoz, Postma, & Rondi-Reig, 2010; Burgess, 2006; Wen, Ishikawa, & Sato, 2013). Importantly, these studies show that egocentric and allocentric representations are constructed in parallel (Igloi et al., 2009). This suggests that a map-like understanding of the environment (allocentric representation) can be formed during initial exposure to an environment.

More recently, Claessen and van der Ham (2017)have proposed a classification of navigation impairments based on the functional properties of navigation impairment found in neuropsychological case studies reported in the literature. This model combines elements from both the L–R–S framework and research on spatial memory. This classification entails three distinct functional domains of navigation ability that are particularly relevant for understanding navigation impairment: knowledge of landmarks, locations, and paths.

Landmarks serve as beacons and reference points in the environment, marking important decision points and allowing navigators to maintain oriented along a route (Chan, Baumann, Bellgrove, & Mattingley, 2012; Sorrows & Hirde, 1999). Landmark based navigation impairments concern a defect in the ability to encode, retrieve or recognize salient objects (e.g., a statue or building) in an environment. The main neural correlates involved in landmark processing are the parahippocampal place area, and the retrosplenial complex and the prefrontal cortex (R. A. Epstein, 2008; Janzen & Jansen, 2010). In addition, lesions to the right medial occipitotemporal lobe are often associated with landmark impairments (R. Epstein, DeYoe, Press, Rosen, & Kanwisher, 2001; Landis, Cummings, Benson, & Palmer, 1986; Mendez & Cherrier, 2003; Takahashi & Kawamura, 2002; van der Ham et al., 2010).

Location-based navigation impairments describe problems in remembering, processing and updating the locations of landmarks in an environment (Burgess, 2006). In order to understand the location of objects in an environment, one constructs a mental representation of space. Impairments occur in the construction of egocentric representations (understanding where objects are in relation to your own location) and allocentric representations (understanding the configuration of objects in the environment regardless of your own location) (Roberta L Klatzky, 1998). The parietal cortex is the key neural correlate involved in processing egocentric references frames while the hippocampus, parahippocampal gyrus and thalamus are typically involved processing allocentric representations during navigation (Colombo et al., 2017; Johnson & Davis, 1998).

Path–based navigation impairments describe difficulties in understanding how locations in the environment are connected to each other. This includes the use and formation of route knowledge (Siegel & White, 1975). For example, understanding the order in which landmarks are encountered along a route or remembering what direction one should take at intersections to continue along a route. Path-based navigation impairments also describe survey knowledge; the ability to form and utilize a map-like understanding of an environment (Siegel & White, 1975). This allows navigators to take shortcuts, find novel routes, estimate the direction and distance between locations. The hippocampus is involved in both route and survey knowledge. In addition, route knowledge is supported by the medial temporal lobe whereas survey knowledge-based navigation is further supported by the inferior temporal cortex and the posterior superior parietal cortex (Brown, Hasselmo, & Stern, 2014; Shelton & Gabrieli, 2002).

Currently, navigation impairments receive relatively little attention in clinical practise. Common tests employed during patient intake, such as the MMSE (Zwecker et al., 2002), the MOCA (Nasreddine et al., 2005) and CLCE-24 (C. van Heugten, Rasquin, Winkens, Beusmans, & Verhey, 2007) typically do not assess navigation ability. Moreover, navigation ability is not accounted for in elaborate testing batteries (e.g., WAIS (D Wechsler & Scale—Revised, 1987), BADS (Wilson, Evans, Alderman, Burgess, & Emslie, 1997)) employed in more comprehensive neuropsychological assessments. As a result, few healthcare centres inventory navigation ability among ABI patients. In order to determine whether navigation impairments require more attention in healthcare centres, we aimed to provide an overview of the prevalence and characteristics of navigation impairments among the ABI patient population. To this end, three goals have been formulated.

The first goal of the current study was to assess the occurrence of objective and subjective navigation impairments in the population of patients with ABI. In order to investigate the effects of ABI on navigation abilities, objective and subjective measures of navigation ability were compared between a group of ABI patients and a group of healthy controls. The second goal of this study was to determine what component of navigation ability is most often impaired in the ABI population. We will examine what domains of navigation abilities, landmark, location or path, are most vulnerable to brain injury. The third goal of this study was to investigate the prevalence of the different types of navigation impairments and to what degree these depend on ABI type and the location (hemisphere) of the lesion.

Providing a clear understanding of the scope and severity of navigation impairments amongst the ABI population will aid healthcare professionals in detecting and understanding problems that patients might experience in daily life. Additionally, results might provide insight with regard to the most common navigation impairments that a therapist might encounter, as well as the type of patient that is at risk of suffering from navigation problems. Finally, information on the prevalence of the impairment might help decide whether navigation assessment should be part of patient intake procedures.

Methods

Recruitment

The experiment was hosted online on the websites "navigerenkunjeleren.nl" and "weekendvandewetenschap.nl". Participants were invited to participate in the study through national, local and social media, organized by The Weekend of Science. This is a Dutch annual event organized by the Secretary of Education, Science and Culture, with the goal of promoting science to the general public. Additionally, "hersenonderzoek.nl" an online platform that promotes research to an interested audience, was used to invite people to participate in the study. Two versions of the experiment were available online: a version for healthy participants (van der Ham et al., 2020) and a version for people with ABI (the current experiment). Inclusion criteria for the ABI participants were (1) older than 16 years old, (2) acquired brain injury and (3) access to stable internet connection. Psychiatric disorders were exclusion criteria for participation. Due to the open nature of the experiment, no official medical records were obtained. As such, adherence of the in- and exclusion criteria was not verified. The study was approved by the local ethical committee at Leiden University, and conducted in accordance with the declaration of Helsinki (2013). Each participant provided informed consent prior to participation.

Tasks

The design of the experiment paradigm was similar to that described by van der Ham, Claessen, Evers, and van der Kuil (2020). The experiment consisted of a general questionnaire, an objective navigation assessment and a questionnaire that was used to assess subjective navigation ability.

General questionnaire

The experiment started with a general questionnaire in which participants provided demographic information, including age, gender, education level (scores ranging from 1, lowest, to 7, highest (Verhage, 1964)) and the province (within the Netherlands) they lived in. Additionally, participants provided information about their spatial experience (How often do you travel to places you have not visited before?), with response options ("never", "several times a year", "several times a month", "weekly or more"), and the residence type (urban or rural). This was followed by three questions about the nature of their brain injury: type of brain injury, location of brain injury and onset of acquired brain injury.

Subjective navigation assessment

Subjective navigational ability was assessed using the Wayfinding questionnaire (Claessen, Visser-Meily, de Rooij, Postma, & van der Ham, 2016b). The Wayfinding questionnaire consists of 22 items that are rated on a 7-point Likert scale. The Wayfinding questionnaire contains 3 sub-scales of navigation ability: navigation & orientation (11 items), distance estimation (3 items) and spatial anxiety (8 items). Cut-off values for the three sub-scales have been determined to indicate an impaired score (navigation & orientation =< 32, distance estimation =< 6, spatial anxiety =>44).

Objective navigation assessment

The objective navigation assessment was identical to the experimental design described in van der Ham et al. (2020). Participants watched a 69-s movie in which a virtual environment was explored. In the video, a path through a fictitious forest was traversed from a first-person perspective on normal walking speed. The environment consisted out of 8 intersection points (5 two-way intersections, 3 three-way intersections). The stroke of land alongside the path was filled with vegetation and dunes, making it impossible to see previous and upcoming components of the path. Along the path, participants would encounter 8 distinct landmarks (oil barrels, spaceship, science fiction crate, rowboat, car, container, buoy and a formation of crystals) (Fig 2.1).

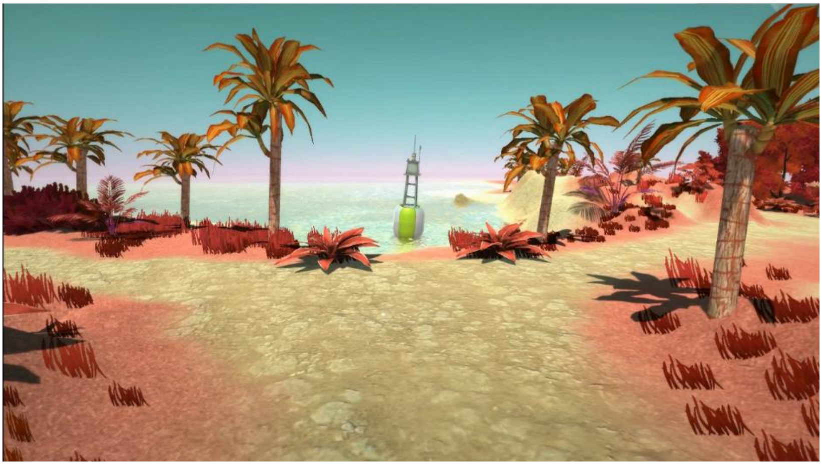

Fig 2.1 A screenshot of the navigation task indicating one of the eight landmarks in the environment.

Following the demonstration route, participants completed five navigation tasks, each assessing a component of navigational ability: landmark recognition, allocentric location knowledge, egocentric location knowledge, route-based path knowledge, survey-based path knowledge.

In the landmark recognition task, participants were presented with eight images of landmarks and had to indicate whether the landmark was encountered along the route. Half of the landmarks that were shown to participants were not present in the environment. In the allocentric location task, participants were presented with a map of the environment. Participants were shown a landmark and had to indicate where on the map (location A, B, C or D) the landmark was encountered. In the egocentric location task, participants were presented with an image of an intersection point (including the landmark) shown from a first-person perspective. Six arrows were shown pointing to different directions with an interval of 60 degrees. Participants had to select which arrow pointed towards the ending location of the route. In the route-based path knowledge task, participant were shown an image of an intersection point (including the landmark), depicted from a first-person perspective. Participant had to indicate the direction of the route at each intersection point (left, right or straight). In the survey-based path knowledge task, participants were shown three landmarks. Participants had to indicate which two landmarks were closest to each other (beeline). A total score of 8 could be obtained in the landmark recognition tasks. In all other tasks, a score of 4 could be obtained. Scores were calculated separately for each of the five navigation tasks.

Procedure

Participants visited the website to partake in the experiment. First, an information letter and consent form was presented. Participants gave consent to participating in the experiment by checking a box indicating that they read the information, and a box stating that they agreed to participate. All data was gathered anonymously.

The experiment started with the general questionnaire, followed by the objective navigation assessment. During the objective navigation test, participants watched the video and completed the landmark recognition task. The order of the remaining four navigation tasks was randomized. The objective navigation assessment was followed by the Wayfinding questionnaire. After completing this part, participants received feedback on the objective navigation score in the form of a graph, indicating their performance on the landmark task, relative to the route knowledge path + egocentric location and the survey knowledge path + allocentric location tasks. Additionally, participants received general information about navigation strategy and tips to improve their navigation ability.

Statistics

Matching procedure

In order to investigate the effects of ABI on navigation abilities, objective and subjective measures of navigation ability were compared between the ABI group and a group of healthy controls. The sample size and demographics of the healthy participants (*n* = 7474) and ABI patients (*n* = 435) varied considerably (**Table 2.1**). To account for the differences between the two samples, a propensity score matching procedure was conducted using the “IBM SPSS Statistics Essentials for R” package and “SPSS PS Matching” plugin (Thoemmes, 2012). Propensity score matching allowed us to match individuals from the healthy control sample to the patients’ sample on the basis of a set of selected covariates, whilst minimizing selection bias.

Before starting the matching procedure, the sample of healthy participants was trimmed based on participant age. The minimal age required for participation in the ABI population was 16, while the sample of healthy participants included participants younger than 16. As such, healthy participants younger than 16 were not included the analysis.

A propensity score was calculated by performing a logistic regression using a set of matching variables as predictors. The matching covariates used were age, gender, education, residence type and spatial experience.

Age and gender were included as matching variables as these variables are well known individual factors influencing navigation ability (Castelli, Corazzini, & Geminiani, 2008; Gron, Wunderlich, Spitzer, Tomczak, & Riepe, 2000; Moffat, Zonderman, & Resnick, 2001). Education level has been included as matching variable as there was a clear discrepancy between education levels in the healthy sample compared to the sample with ABI patients. Residence type has been included as matching variable as there are differences in navigation abilities and strategies that can be employed in dense urban environments compared to open rural environments (Juliani, Bies, Boydston, Taylor, & Sereno, 2016). For example, global landmarks might be more present in rural environments whereas navigation in dense urban towns might favour the use of local landmarks (Steck & Mallot, 2000). Spatial experience, measured by how often people visit novel environments, was included as matching variables in order to account for ABI patients that do not venture outside their residence too often (Logan et al., 2004; W. Q. Qiu et al., 2010).

The propensity scores of healthy participants and ABI patients were matched using a 1-to-1 nearest neighbour matching algorithm without replacement. To limit inaccurate matching, a calliper with a width equal to 0.2 of the standard deviation of the logit of the propensity score was used (Austin, 2011a). The resulting matches were assessed for overall imbalance using Hansen and Bowers (2008) imbalance test and the relative multivariate imbalance L1 test (Iacus, King, & Porro, 2009).

Table 2.1 Demographics of ABI patients and sample of pre and post-matched healthy controls.

Variable	ABI (*N*=435)	Control (matched) (*N* = 435)	Control (unmatched) (*N*=7474)
Gender (% female)	71.7	71.5	65.2
Age , years, *M* (*SD*)	54.62 (12.48)	54.56 (16.39)	51.11 (17.52)
Education*, *M* (*SD*)	5.68 (0.84)	5.7 (0.83)	6.05 (0.80)
Residence type (% Urban)	63.4	67.1	70.4
Spatial experience, *M* (*SD*)	2.12 (0.63)	2.08 (0.49)	2.28 (0.59)

* Education was measured on the Verhage Scale (range 1-7), a Dutch categorization of education level, with higher scores reflecting higher education levels (Verhage, 1964).

Subjective navigational ability

Since healthy participants and ABI patients were matched using the propensity score matching procedure, the data was treated as paired for the main effects analysis. A repeated measures MANOVA analysis was performed with the scores on the three scales of the Wayfinding Questionnaire (navigation & orientation, distance estimation and spatial anxiety) as dependent variables and group (healthy *vs*. ABI) as within subject factor. The proportion of participants that reported impaired levels of subjective navigation ability on the Wayfinding questionnaire were calculated following the cut-off values described in Claessen, Visser-Meily, et al. (2016b). The proportions of impaired individuals in the ABI group and the healthy controls were compared using the McNemar test.

To investigate the effect of ABI type and ABI location on self-reported navigation impairments, a (non-paired) MANOVA was conducted with the scores on the three scales of the Wayfinding Questionnaire (navigation & orientation, distance estimation and spatial anxiety) as dependent variables and ABI type as within-subject factor. Gender, education and age were included as covariates. The effect of ABI location was investigated using a sub-set of participants with ABI types that typically concern localized lesions: stroke, brain tumour, epilepsy. Only participants that knew the location of their lesion were included in this analysis. A (non-paired) MANOVA was performed with the scores of the WQ as depend variables and ABI location (left, right and bilateral) as between subject factor. Specifically, in a post-hoc analysis, performance differences between patients with left *vs*. right hemispherical damage were assessed.

Objective navigation ability

Since healthy participants and ABI patients were matched using the propensity score matching procedure, the data was treated as paired for the main effects analysis. To assess the differences in objective navigation ability between healthy participants and ABI patients, a repeated measures MANOVA analysis was performed with the 5 navigation tasks (landmark recognition, egocentric location knowledge, allocentric location knowledge, route-based path knowledge and survey-based path knowledge) as dependent variables and group (healthy *vs*. ABI) as within subject factor.

To assess the effect of ABI type and location on navigation ability, a (nonpaired) MANCOVA was performed with the 5 navigation tasks scores as depend variables and ABI type as between subject factor and gender, age and education as covariates. To investigate an effect of ABI location, a sample of ABI participants with localized damage (stroke, brain tumour and epilepsy) was selected. Participants who did not know the location of their ABI were excluded from this analysis. A (non-paired) MANCOVA was performed with the 5 navigation task scores as dependent variables, ABI location as between subject factor and age, gender and education as covariates. Specifically, in a post-hoc analysis, performance differences between patients with left *vs*. right hemispherical damage was assessed.

Results

Participants

A total of 485 ABI patients completed both the Wayfinding questionnaire and all 5 navigation tasks. Out of this sample, 50 participants were excluded from analysis because they reported neurological, congenital, psychiatric or otherwise unclear medical conditions instead of ABIs (e.g., ADHD, Alzheimer's disease, focal cortical dysplasia, tremors). One participant was excluded as the reported gender was unclear. In total, 435 participants with ABI were included in the analysis (**Table 2.1**). A variety of ABI types were reported by the ABI patients (**Table 2.2**). The largest proportion of ABI patients in this sample had experienced a stroke (45.1%) or traumatic brain injury (23.0%). Other types of ABI were reported less frequently (<10%). The locations of brain injuries were equally divided between the left and right hemispheres, although roughly a third of the ABI patients were unable to report the location of the lesion (37.7%). Most of the ABI patients in this sample were in the chronic stage of brain injury (86.9%), as the onset time of the injury was more than 12 months ago. The sample of healthy controls that completed the 5 navigation tasks, the Wayfinding questionnaire and were 16 years or older, consisted of 7474 participants (Table 2.1).

Propensity score matching

Prior to the matching procedure, MANOVA analysis revealed significant differences (F (3, 7905) = 34.39; $p < .001$; $\eta^2 = .013$) between the ABI and control group for the variables age (F (1, 7907) = 16.99; $p < .001$; $\eta^2 = .002$), education (F (1, 7907) = 85.79; $p < .001$; $\eta^2 = .011$), and spatial experience (F (1, 7907) = 27.27; $p < .001$; $\eta^2 = .003$). Chi-squared tests show significant differences in gender (χ^2 (1) = 7.66, $p = .006$) and residence type (χ^2 (1) = 9.39, $p = .002$) between the two samples. Using propensity score matching, 435 healthy controls were matched to the ABI patient sample. Post matching balance checks revealed an increase in overall balance. Standardized mean differences (Cohen's *d*) was lower than 0.1 after matching, indicating that none of the covariates exhibited a large unbalance after matching (Austin, 2011b). This was confirmed by subsequent balance assessments: the overall χ^2 balance test was not significant, χ^2 (5) = 3.08, $p = .69$, the relative multivariate imbalance L1 was larger in the unmatched sample (.46) than in the matched sample (.45). After the propensity score matching procedure, the ABI sample and the matched healthy controls were comparable in terms of age, education, gender, spatial experience, and residence type (Table 2.1).

Table 2.2 Overview of subjective navigation impairments within subcategories of the ABI population.

ABI patient Characteristics (N = 435)	%	% Impaired*	% Impaired on separate WQ scales**		
			NO	DE	SA
ABI Type					
Stroke	45.1	42.9	21.4	24	21.9
Traumatic	23.0	36.0	19	22.0	16
Brain Tumour	6.9	26.7	16.7	16.7	16.7
Intoxication	1.8	62.5	25	12.5	37.5
Infection	4.8	42.9	9.5	19.0	33.5
Epilepsy	5.1	31.8	22.7	18.2	18.2
MS	4.1	27.8	11.1	22.2	11.1
Hypoxia	3.2	57.1	28.6	35.7	50
Other/Unknown	6	30.8	7.7	15.4	23.1
ABI afflicted hemisphere					
Left	26	40.7	22.1	24.8	13
Right	21.8	41.1	20	22.1	10.9
Bilateral	14.5	34.9	20.6	22.2	7.2
Unknown	37.7	38.4	15.9	20.1	18.9
ABI onset					
Acute phase (0-12 months)	7.4	40.6	15.6	18.8	25
Chronic phase (> 12 moths)	86.9	40.2	20.6	23.5	21.4
Unknown	5.7	20.0	0	4	16

* impaired on at least one of the Wayfinding questionnaire scales

** NO: Navigation & orientation scale, DE: Distance estimation scale, SA: Spatial anxiety scale.

Subjective navigation impairments

Overall, 39.1% of the ABI participants were impaired on any of the subscales of the Wayfinding questionnaire, compared to 19.3% in the control group. Proportional analysis using the McNemar tests revealed a significantly higher percentage of self-reported impairments in the ABI compared to the control group for the navigation & orientation (19.1% *vs.* 8.7%, $p < .001$), distance estimation (21.1% *vs.* 11.3%, $p < .001$) and spatial anxiety subscales (21.4% *vs.* 7.1%, $p < .001$).

Analysis of subscale scores on the Wayfinding Questionnaire using a paired MANOVA (repeated measures) revealed a main effect of group (control *vs.* ABI) on self-reported navigation ability (F (3, 432) = 24.11; $p < 0.001$; $\eta_p^2 = .14$). Univariate tests indicated a significant effect of group on navigation & orientation (F (1, 434) = 42.35; $p < 0.001$; $\eta_p^2 = .09$), distance estimation (F (1, 434) = 25.63; $p < 0.001$; $\eta_p^2 = .06$) and spatial anxiety (F (1, 434) = 65.36; $p < 0.001$; $\eta_p^2 = .13$) (**Fig 2.2**). Post-hoc paired *t*-test showed that the control group scored significantly higher on navigation & orientation ($p < .001$) and distance estimation ($p < .001$) (higher scores on these scales referred to higher self-reported spatial ability), whereas the ABI group scored higher on the spatial anxiety subscale ($p < .001$) (higher score referred to higher levels of spatial anxiety).

Exploratory analyses were conducted to determine whether there was an effect of type and location of ABI on self-reported navigation abilities. A MANOVA revealed a main effect of ABI type (F (27, 2571) = 3.931; $p < 0.001$; $\eta_p^2 = 0.40$) on subjective navigation performance. Post-hoc pairwise comparison revealed that compared to the control group, stroke and TBI scored significantly lower on navigation & orientation and distance estimation subscales. Patients with stroke, TBI, hypoxia and intoxication scored significantly higher on spatial anxiety compared to the control group. No effect of ABI location was found on subjective navigation abilities.

Table 2.3 Comparison of objective navigation impairment between the control and ABI population

Navigation	Max. score	Chance level score	ABI	Control (matched)	Contrasts		
			M (SD)	*M (SD)*	*F*	*df*	*p*
Landmark Recognition	8	4	6.68 (1.15)	6.84 (1.06)	4.33	1, 434	.038*
Egocentric Location	4	0.67	1.18 (0.89)	1.23 (0.93)	0.65	1, 434	.421
Allocentric Location	4	1	1.77 (1.08)	1.92 (1.09)	4.41	1, 434	.036*
Path Route knowledge	4	1.75	2.38 (1.02)	2.56 (0.93)	7.35	1, 434	.007*
Path Survey knowledge	4	1.33	2.31 (1.08)	2.40 (1.03)	1.67	1, 434	.197

* Indicates significant difference between the control and ABI populations.

Objective navigation impairments

A paired MANOVA (repeated measures) revealed a main effect of group (control *vs.* ABI) on objective navigation ability (F (5, 430) = 2.53; p = 0.029; η_p^2 = .03). Univariate tests showed a significant effect of group on performance on the landmark recognition task (F (1, 434) = 4.33; p = 0.038; η_p^2 = .01), allocentric location knowledge task (F (1, 434) = 4.41; p = 0.036; η_p^2 = .01) and route-based path knowledge task (F (1, 434) = 7.35; p = 0.007; η_p^2 = .01). Post-hoc analysis showed that ABI patient scored significantly lower on landmark recognition, allocentric location knowledge and route-based path knowledge compared to the control group (Table 2.3).

Exploratory analyses were performed to assess the effect of ABI type and ABI location on objective navigation ability (Table 2.4). While the group analysis revealed a differences between the control and ABI group, no specific effects of ABI type were found (F (45, 4285) = 1.166, p = .209, η_p^2 = .012). The analysis of ABI location demonstrated a trend-level effect of ABI location on objective navigation performance (F (15, 1836) = 1.589, p = .069, η_p^2 = .013). Further investigation of this trend suggested that this effect was specifically present in the landmark recognition task (F (3, 621) = 4.2, p = .01, η_p^2 = .018), in which patients with right hemisphere ABIs scored significantly lower compared to controls (p = 0.01) and patients with left hemisphere lesion (p = .029).

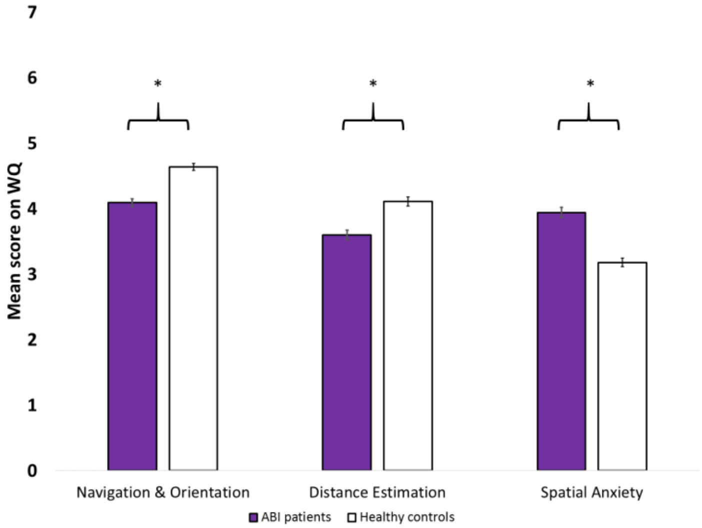

Fig 2.2 Scores on the subscales of the Wayfinding questionnaire. Error bars represent standard error of the mean. * Indicates a significant difference between the control and ABI populations.

Table 2.4 Overview of objective navigation score for the 5 subtasks per brain injury type, onset time and location of brain injury.

Participant characteristics		Navigation subtasks*				
Description	% (ABI group)	Landmark Recognition	Location: Egocentric	Location: Allocentric	Path: Routes	Path: Survey
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Healthy Control	-	6.84 (1.05)	1.23 (0.93)	1.92 (1.09)	2.56 (0.93)	2.40 (1.03)
ABI Type						
Stroke	45.1	6.68 (1.15)	1.12 (0.93)	1.69 (1.04)	2.34 (1.01)	2.25 (1.12)
Traumatic	23	6.73 (1.20)	1.12 (0.95)	1.89 (1.02)	2.37 (1.09)	2.36 (1.02)
Brain Tumour	6.9	6.63 (1.07)	1.30 (0.75)	2.20 (0.99)	2.33 (1.09)	2.47 (0.94)
Intoxication	1.8	6.00 (1.95)	1.25 (0.87)	1.75 (1.04)	2.25 (1.04)	1.75 (1.39)
nfection	4.8	6.81 (0.93)	1.05 (0.67)	1.57 (1.12)	2.33 (0.97)	2.48 (1.29)
Epilepsy	5.1	6.77 (1.19)	1.55 (0.86)	1.91 (1.23)	2.41 (0.91)	2.55 (0.80)
MS	4.1	7.11 (0.96)	1.44 (0.92)	2.06 (1.11)	2.61 (0.98)	2.44 (1.19)
Hypoxia	3.2	6.43 (1.09)	1.14 (0.53)	1.50 (1.40)	2.21 (0.97)	2.21 (0.89)
Other/Unknown	6	5.89 (1.24)	1.38 (0.94)	1.46 (1.17)	2.85 (0.97)	2.15 (1.16)
ABI afflicted hemisphere						
Left	26	6.81 (1.00)	1.29 (0.89)	1.82 (1.09)	2.43 (1.03)	2.46 (0.99)
Right	21.8	6.43 (1.25)	1.08 (0.91)	1.84 (1.08)	2.39 (1.03)	2.27 (1.23)
Bilateral	14.5	6.91 (1.17)	1.02 (0.92)	1.75 (1.06)	2.35 (1.05)	2.27 (1.09)
Unknown	37.7	6.64 (1.15)	1.23 (0.88)	1.71 (1.08)	2.36 (1.01)	2.24 (1.05)
ABI onset						
Acute phase (<12 months)	7.4	6.88 (1.24)	1.34 (0.91)	1.72 (1.14)	2.25 (1.02)	2.25 (1.11)
Chronic phase (>12 months)	86.9	6.66 (1.14)	1.17 (0.91)	1.79 (1.06)	2.37 (1.03)	2.33 (1.08)
Unknown	5.7	6.72 (1.14)	1.20 (0.87)	1.44 (1.16)	2.72 (1.02)	2.04 (1.09)

*The maximum and chance level scores for each subtask is presented in **Table 2.3.**

Discussion

Little is known about the prevalence of navigation impairments among patients with ABI. The aim of this study was to provide an overview of navigation impairments in this population to inform rehabilitation specialist about prevalence and characteristics of navigation problems. Results can help clinicians to make informed decision about whether or not to adopt navigation ability assessment in clinical intake procedures.

The first goal of this study was to determine the occurrence of subjective and objective navigation impairments in ABI patients compared to a group of healthy participants that were matched in terms of gender, age, education, resident type (urban or rural) and spatial experience. Compared to the control group, ABI patients scored significantly lower on self-reported navigation ability and objective navigation ability. ABI patients are 2.03 times more likely to report subjective navigation impairments compared to healthy participants. In the current sample, 39.1% of the patients had an impaired score on at least one scale of the Wayfinding questionnaire (compared to 19.3% in the control group). The percentage of self-reported navigation impairments is substantially higher than the proportion found in previous research with solely mild stroke patients (29%) (van der Ham et al., 2013). We expect that the higher level of impairments found in the current study is the result of the relatively loose inclusion criteria for ABI patients. In the current study, all ABI patients were allowed to participate whereas van der Ham et al. (2013) included only patients that scored high on independent living indexes. The self-reported impairments were reflected in the lowered performance on the objective navigation assessments. The increased impairment levels are not as high (31% to 86%, depending on the location of the lesion), as reported earlier studies that included relatively large samples of ABI patients (Barrash, Damasio, Adolphs, & Tranel, 2000). Barrash et al. (2000) investigated route learning in a real environment, using an 8 min route and used 3 consecutive trials to assess route knowledge. In contrast, the current study was concerned with a more general assessment of navigation ability spanning over 5 domains. Furthermore, this study consisted of a shorter route (69 s) and did not include repetition of tasks. As such, we suspect that the proportion of impaired ABI patients in the current study reflects a conservative number.

The second goal of the study was to explore what domain of navigation ability (landmark, location or path) was most vulnerable to acquired brain injury (Claessen & van der Ham, 2017). The results show that ABI patients scored lower on the landmark recognition task, allocentric location task and the route-based path knowledge task compared to the control group.

The ability to encode and recognize landmarks can be regarded as one of the most fundamental components of navigation ability. Landmarks serve as beacons, associative and directional cues (Chan et al., 2012). As such, other components of navigation ability, location and path, partially rely on intact landmark memory. Because of its importance to navigation, the human brain is highly effective at detecting and encoding objects at key decision points in the environment to the point that this occurs independent of attention to the object (Janzen & van Turennout, 2004). As such, impairments in the ability to recognize landmarks can have detrimental effects on navigation. It should be noted that the landmark recognition task used in the current paradigm only reflects one component of landmark knowledge: the encoding and recall of novel landmarks. Different subcategories of landmark impairments, such as the ability to recognize familiar and famous landmarks or the ability to recognize scenes rather than specific objects, were not assessed in this task.

ABI patients scored lower on the route-based path knowledge task. Here, we assessed the ability to remember what direction to take when standing at an intersection point, in order to replicate a route. Route continuation ability allows navigators to form an understanding of paths between important locations in an environment. Route continuation is a prominent navigation ability that arises early during development and is relatively well preserved with regard to aging (Nys, Hickmann, & Gyselinck, 2018; Wiener et al., 2020). While route continuation appears to be a stable and enduring ability, the current study shows it is vulnerable to acquired brain injury. This result supports earlier findings on the vulnerability of route learning after ABI (Barrash et al., 2000).

Lower scores on the allocentric location task show that ABI patients in general have more difficulty remembering where landmarks were located when presented with a map. This task required participants to convert knowledge obtained egocentrically, to an allocentric reference frame. It is well known that the switch between perspectives is difficult. Furthermore, increased difficulty with perspective switching is observed after aging and in patients with neurodegenerative diseases such as Alzheimer's disease and patients with mild cognitive impairments (Colombo et al., 2017). These difficulties are also observed in the ABI population.

Lastly, we assessed whether the type of ABI and location (hemisphere) of the injury would affect the occurrence of objective and subjective navigation impairments. Earlier research has established that subjective navigation impairments are often reported by stroke patients (van der Ham et al., 2013). Importantly, our results show that navigation impairments are not limited to stroke patients, but are also reported by people with traumatic brain injury, intoxication and hypoxia. No effect of hemispherical location of the brain injury on subjective navigation impairments was found.

Furthermore, no effect of ABI type was found on the objective navigation impairments. However, a trend effect of brain injury location was observed. ABI patients with right hemispherical damage scored lower on the landmark recognition task compared to the controls and patients with left hemispherical damage. This result is in line with a wealth of fMRI and lesion studies that have shown that networks in the right hemisphere are of particular importance for navigation and spatial memory (A. D. Ekstrom et al., 2003; Gramann, Muller, Schonebeck, & Debus, 2006; Iaria, Chen, Guariglia, Ptito, & Petrides, 2007; Jacobs et al., 2010; Maguire, Frackowiak, & Frith, 1997).

Of note are the relatively large differences between ABI patients and controls on the mean scores of the subjective (self-reported) task and the small differences between the means of the objective navigation scores. This discrepancy suggests a limited selectivity of the objective assessment. This can in part be explained by the design of the study, which was constrained to be short and accessible online, rather than a complete diagnostic assessment (Claessen et al., 2017). A more thorough assessment of each domain is likely to raise the selectivity to impairments in each task. However, the discrepancy between self-reported and objectively measured cognitive problems is a well-known phenomenon in neuropsychological assessments of ABI patients. Many studies fail to find a clear relation between self-reported cognitive complaints and objective performance (Aben et al., 2011; Duits, Munnecom, van Heugten, & van Oostenbrugge, 2008; Lamb, Anderson, Saling, & Dewey, 2013; Spencer, Drag, Walker, & Bieliauskas, 2010; Stulemeijer, Vos, Bleijenberg, & van der Werf, 2007; Winkens, Van Heugten, Fasotti, & Wade, 2009). Cognitive problems experienced in daily life are often influenced by subtle factors such as fatigue, reduced mental effort capacity and personal factors (e.g., emotional functioning), that are often not registered by neuropsychological assessments (Borgaro, Baker, Wethe, Prigatano, & Kwasnica, 2005; Riese et al., 1999).

Overall, our results show that almost half of the patients with ABI reported navigation impairments. Subjective impairments occur roughly two times more often in the ABI population. Furthermore, navigation impairments are prominent in all types of ABI and can be observed in patients with left, right and bilateral brain injuries. Specific components of navigation ability, landmark recognition, route continuation and allocentric location knowledge are most vulnerable to brain injury. Therefore, we strongly recommend that screening and treatment of navigation impairments are included in clinical practice guidelines at rehabilitation treatment centres. Awareness and recognition of patient's daily navigation problems is an important step in starting potential treatment. We encourage healthcare professionals to discuss potential difficulties in spatial navigation a patient might experience following brain injury. Practitioners could ask about a patient's ability to remember landmarks, describe a route or ask patients to use a map. In case of complaints, a patient can be asked to fill in the Wayfinding questionnaire to determine the presence of subjective navigation complains. Finally, the domain of navigation impairment should be assessed. The navigation test used here provides a suitable solution for a standardized diagnostic tool to provide an objective measure of such complaints, as a specific reference group can be constructed from the large control group.

While large-scale online assessments have many advantages, several important limitations should be noted. First, participants performed the experiment unsupervised. This will have introduced a level of uncertainty and noise in the dataset. For example, participants might not have understood all questions or might have had a bad internet connection. Second, because this study was part of a public science event, an open web link to the experiment was used rather than a unique personalized code that could be traced back to an individual. It was therefore impossible to verify the characteristics of the participants in this study. Consequently, we did not obtain medical records, nor were we able to inspect any underlying cognitive processes that might have contributed to the reported navigation problems. As such, we relied on self-identification of acquired brain injury. While a large proportion of patients were able to provide detailed information on their brain injury (94%), this could not be validated. Third, the online availability of the study might have attracted a population of participants that are not necessarily representative of the ABI population as a whole. Patients who experienced difficulties during navigation might have been more inclined to participate in the experiment. As such, the level of self-reported impairments might have been slightly biased towards higher levels of navigation impairments. Additionally, seeking out and performing this online study requires a certain degree of cognitive functioning, posing a potential bias towards ABI patients with sufficiently intact cognitive abilities. However, it is likely that the impact of this bias is diminished by the large number of participants in this study. We also identified limitation of a more methodological nature, as the experiment was short and broad (focussing on a variety of domains). Most components of the objective navigation assessment contained only 4 multiple choice questions. This allowed us to investigate the general effect of ABI types on all components of navigation in a single test. The disadvantage of this approach was that the differences between groups are only apparent on group levels, as no cut-off threshold for task specific impairment levels could be formulated. Lastly, the current navigation task utilized a video from which a route was learned instead of real-world route that was traversed. Several studies show that movement information (e.g., vestibular and proprioceptive signals) obtained during real-world navigation contributes to the formation of spatial knowledge. Loss of movement information negatively affects egocentric navigation, the formation of survey knowledge and knowledge about route order (Chrastil & Warren, 2013; Sorita et al., 2013; Xie et al., 2017). As such, the current assessment of navigation ability is likely to underestimate the performance of participants when compared to real-life navigation. However, as the purpose of the study was to compare the performance of ABI patients to healthy controls, this limitation is not likely to effect the current results. It should be noted that this approach has advantages: the environment is novel to all participants, disrupting factors are removed (e.g., traffic, whether conditions) and exposure of the environment is kept constant amongst participants. Furthermore, there are studies that suggest that navigation performance in real and virtual environments is highly comparable (Lloyd, Persaud, & Powell, 2009; Richardson, Montello, & Hegarty, 1999) and that transfer of information between real and virtual environments is possible (Peruch, Belingard, & Thinus-Blanc, 2000).

When placing all results in context, we conclude that navigation impairments are common amongst patients with all types of acquired brain injuries. Neurologists, rehabilitation specialists, neuropsychologists, occupational therapists, and general practitioners are encouraged to ask all ABI patients about potential changes in their navigation abilities after the incident. Especially participants with right hemispherical damage should be inspected. Patients with self-reported navigation impairments should be referred to neuropsychologists for further diagnosis of the type of impairment and develop suitable treatments for these patients.

Chapter 3

Spatial knowledge acquired from first-person and dynamic map perspectives

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Abstract

As we become familiar with an environment through navigation and map study, spatial information is encoded into a mental representation of space. It is currently unclear to what degree mental representations of space are determined by the perspective in which spatial information is acquired. The overlapping model of spatial knowledge argues that spatial information is encoded into a common spatial representation independent of learning perspective, whereas the partially independent model argues for dissociated spatial representations specific to the learning perspective. The goal of this study was to provide insight into this debate by investigating the cognitive functions underlying the formation of spatial knowledge obtained through different learning perspectives. Hundred participants studied an ecologically valid virtual environment via a first-person and map perspective. The map employed in the study was dynamic, allowing for the disentanglement of learning perspective and sequential information presentation. Spatial knowledge was examined using an array of navigation tasks that assessed both route and survey knowledge. Results show that distinct visuospatial abilities predict route knowledge depending on whether an environment is learned via a first-person or map perspective. Both shared and distinct visuospatial abilities predicted the formation of survey knowledge in the two perspective learning conditions. Additionally, sequential presentation of map information diminishes the perspective dependent performance differences on spatial tasks reported in earlier studies. Overall, the results provide further evidence for the partially dissociated model of spatial knowledge, as the perspective from which an environment is learned influences the spatial representation that is formed.

Introduction

Whenever we learn about the spatial characteristics of an environment, information is encoded into a mental representation of space (O'Keefe & Nadel, 1978; Tolman, 1949) Research has shown that the nature of a mental representation depends on a variety of factors, such as the navigator's goal (T. T. Brunyé & Taylor, 2009; Taylor, Naylor, & Chechile, 1999), preferred spatial strategy (F. Pazzaglia & De Beni, 2001) and visuospatial abilities (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). One factor that is believed to be of particular influence on the characteristics of a mental representation of space is the spatial perspective from which the environment is learned (Richardson et al., 1999; Shelton & Gabrieli, 2002; Thorndyke & Hayes-Roth, 1982; Torok, Nguyen, Kolozsvari, Buchanan, & Nadasdy, 2014). The most common method of spatial knowledge acquisition is through direct exploration of an environment. Acquiring spatial information from a first-person perspective tailors to the development of route knowledge (Siegel & White, 1975). Navigators encode spatial information regarding the trajectories between locations in the environment, including sequences of turns, order of landmarks along paths, and landmark–action associations (O'Malley, Innes, & Wiener, 2018). However, we often acquire spatial information from studying indirect sources of information such as cartographic maps. Acquiring spatial information by studying maps directly tailors to the development of survey knowledge of an environment, as cartographic maps depict configurational, layout, and metric information about the relations between landmarks in the environments (Munzer, Zimmer, Schwalm, Baus, & Aslan, 2006).

Although spatial information can be obtained from different perspectives, the emerging mental representations of space go beyond the modality of the learning perspective. Many studies have shown that navigators are able to draw maps of the environment after learning a route from a first-person perspective (Chrastil & Warren, 2012; Coluccia, Bosco, & Brandimonte, 2007; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Muffato, Meneghetti, & De Beni, 2019) Additionally, navigators are able to find shortcuts and use place strategies after learning an environment from a first-person perspective, demonstrating configurational knowledge of an environment (Labate, Pazzaglia, & Hegarty, 2014; Wiener, de Condappa, Harris, & Wolbers, 2013). Configurational knowledge of an environment can be obtained even after the initial exposure to an environment (Igloi et al., 2009 & Rondi-Reig, 2009). Conversely, people are able to effectively navigate through an environment and point towards specific locations from a first-person perspective after studying an environment using a map (Allison & Head, 2017; Zhang, Zherdeva, & Ekstrom, 2014).

As such, the consensus is that both route and survey knowledge can be acquired from different learning perspectives. However, there is debate about the cognitive characteristics of mental representations of space acquired via different spatial perspectives (Zhang et al., 2014). One line of evidence suggests that spatial knowledge obtained from different learning perspectives is encoded into a common cognitive representation of space, while the other studies suggests that spatial knowledge obtained from first-person and map perspectives is represented independently. Zhang et al. (2014) classified these different views into a partially independent model and an overlapping model.

The partially independent model is supported by behavioral studies that have shown an advantage for the recall of information congruent with the learning perspective. Spatial knowledge related to routes and trajectories such as route descriptions and route distances are recalled more effective when learned from a first-person perspective compared to a map perspective (Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). Conversely, map learning leads to higher performance on map sketching and Euclidean distance estimation tasks (Muffato et al., 2019; Taylor et al., 1999). As such, spatial representations constructed through first-person navigation are anchored towards the trajectories that have been traversed, whereas representations obtained through maps are more focused towards the configuration of landmarks in the environment (Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982).

The overlapping model proposes that spatial knowledge is encoded into a common representational structure, regardless of the perspective from which an environment is learned. This model is supported by studies that reveal that both first-person and map perspective encoding of spatial information is anchored towards an orientation dependent vector (Shelton & McNamara, 2004).

More recently, the neural mechanisms underlying spatial learning from different perspectives have been studied using neuroimaging techniques. Evidence provided by these studies does not conclusively support one model over the other. Neuroimaging studies report a common neural substrate that is involved in map and first-person perspective learning as well as regions that are distinct for each learning perspective. Some researchers argue that this common neural substrate indicates that spatial information is processed in a mixed or common spatial representation (L. Latini-Corazzini et al., 2010; Shelton & Gabrieli, 2002). However, other researchers have focused on the distinct neural substrates, and argue that the existence of different substrates indicates a partially distinct representation of space (Zhang, Copara, & Ekstrom, 2012).

This debate has focused largely on differences between first-person navigation and cartographic map study in terms of perspective modalities. Yet, a fundamental difference between first-person learning and map study is the pacing in which information is presented in both modalities. An inherent property of first-person navigation is that spatial information is presented in a dynamic, sequential fashion. Understanding paths that make up the environment requires navigators to combine and order a set of landmarks and locations. In contrast, during cartographic map study, a complete environment is shown statically. This raises the question whether the differences in mental representations that are observed can be attributed to learning perspectives or to the static and dynamic differences of information presentation. Navigational aids used in cars and mobile devices utilize interactive maps that combine progressive information presentation and map perspectives. These dynamic maps present cartographic information in a route-like fashion and can, thus, serve as a more comparable medium to first-person navigation when studying the effects of perspective learning (Tad T. Brunyé, Mahoney, & Taylor, 2013).

A few studies have contrasted spatial knowledge acquired through first-person and dynamic map perspectives (Shelton & Gabrieli, 2002; Shelton & McNamara, 2004; Shelton & Pippitt, 2007; Yamamoto & DeGirolamo, 2012). In these studies, spatial representation obtained from different perspective was contrasted after extensive learning of a relatively simple environment. Furthermore, these studies use a limited number of tasks that assess spatial knowledge in each condition.

Insight to this debate might be provided by assessing not only the quality of the spatial knowledge obtained through different learning perspectives, but also by investigating the cognitive mechanisms that underlie spatial learning from different perspectives. Much research has already been directed at determining the contribution of a variety of cognitive functions and visuospatial abilities to first-person and static map study. Most notably, visuospatial working memory, verbal working memory, perspective -taking ability, and mental rotation ability have repeatedly been shown to be involved in navigation (Coluccia et al., 2007; Gras, Gyselinck, Perrussel, Orriols, & Piolino, 2013; Hegarty et al., 2006; Meneghetti, Fiore, Borella, & De Beni, 2011). However, how these functions contribute to spatial knowledge acquisition via different perspectives has yet to be studied systematically.

One study contrasted the cognitive mechanisms underlying first-person and dynamic map perspective learning using judgement of relative direction tasks (Fields & Shelton, 2006). This study revealed distinct patterns of visuospatial abilities predicting spatial orientation ability after first-person and dynamic map learning, hinting at a partially dissociated representation. However, to gain more insight into the cognitive mechanism underlying the development of route and survey knowledge from different perspectives, it is important to assess the relationships between visuospatial abilities and a broader array of navigation tasks.

The aim of the current study was to determine to what degree mental representations of space are dependent on learning perspective. We assessed whether overlapping or distinct cognitive functions contribute to performance on a broad range of navigation tasks after first-person and dynamic map learning. to account for the sequential information presentation inherent to first-person navigation, a dynamic map was used to provide spatial information from a map perspective. Spatial knowledge was assessed after a single run through an ecologically valid virtual environment, reflecting a realistic navigation situation in which no overlearning takes place. The Previous research provides evidence for both an overlapping and a partially dissociated representation of space after learning from different spatial perspectives. As such, we will examine two hypotheses. If the same set of visuospatial abilities predict performance on the route and survey knowledge tasks regardless of learning perspective, the results support the overlapping model of spatial representation. Conversely, if perspective dependent visuospatial abilities predict performance on route and survey knowledge, we accept the partially independent model. Additionally, we investigated route and survey knowledge obtained through different learning perspectives as the previous studies have interpreted perspective specific advantages as evidence for distinct mental representations of space (Thorndyke & Hayes-Roth, 1982). Following the models of spatial representation, finding a significant advantage of perspective on performance would favor the partially dissociated hypotheses, whereas similar performance would support the overlapping model of spatial representation.

Methods

Participants

One hundred participants (63 females) participated in this experiment. Participants were between 18 and 35 years of age (*M* = 22.18, *SD* = 0.28), finished or attended college or university level education. Participants with a history of neurological, psychiatric, and psychological disorders were screened from the experiment (e.g., anxiety disorder, major depression, etc.). All participants signed an informed consent form and were compensated for participation in participant hour credits or with a small monetary reward of 6 euro per hour. The Leiden University's local ethics committee for psychological research approved this study.

Materials

The study consisted of two questionnaires, two spatial navigation assessments, and four standardized neuropsychological tests. All computerized components of the study ran on an HP Elite Book 8770 w, with a Core i7-3840QM processor (2.8 GHz) and 16 GB RAM.

Questionnaires

All participants completed a screening questionnaire in which demographic characteristics such as age, gender, handedness, level of education, and gaming experience was acquired. Furthermore, screening information about a history of psychiatric or neurological disorders was obtained. Subjective navigation complaints were assessed using the Wayfinding Questionnaire (de Rooij, Claessen, van der Ham, Post, & Visser-Meily, 2019). The Wayfinding Questionnaire contains 22 items in 3 subscales: navigation and orientation (11 items), distance estimation (3 items), and spatial anxiety (8 items). All items were rated on a seven-point Likert scale.

Spatial navigation assessment

Objective navigation ability was assessed using an adapted version of the Virtual Tübingen task (Claessen, Visser-Meily, de Rooij, Postma, & van der Ham, 2016a). A virtual model of the city center of Tübingen was used as the testing environment (van Veen, Distler, Braun, & Bulthoff, 1998). Four similar routes through Virtual Tübingen were constructed (Fig 3.1.A). A comparable distance was traversed in each route (A route: 393 m, B route: 338 m, C route: 371 m, and D route: 367 m). Each route contained eight intersection points. At intersection points, the routes could turn left, right, or go straight ahead. Each route was composed of six unique corridors (paths between intersections) and three common corridors shared with other routes. Common corridors were never visited in the same heading direction in any of the routes.

Each route through the environment could be shown from two perspectives: first-person perspective (Fig 3.1.B) and dynamic map perspective (Fig 3.1.C). In the first-person perspective variation, participants observed the route from a camera placed at a height of 1.70 m. At each intersection, the camera would stop and turn in the direction of each corridor before continuing along the route. In the dynamic map perspective variation, a red arrow was shown on the map that traversed the environment. This arrow was shown from an aerial, bird’s-eye view (38 m high), using a camera locked onto the position of the arrow. The camera was always aligned towards the north and did not rotate. An orthographic lens was used, revealing the walls of the buildings of corridors in the environment. Eight black and white icons were placed above buildings to indicate a buildings’ function (e.g., theatre, library, etc.). During the learning phase, participants were instructed to memorize as much as possible about the spatial characteristics of the environment.

Navigation Tasks

After learning the environment (from either first-person or dynamic map perspective), participants completed six recall tasks in which navigation abilities were assessed. The first two tasks, *Route Sequence* and *Route Continuation*, assessed route knowledge. The remaining four tasks, *Point to Start location*, *Point to End location*, *Distance Comparison*, and *Locations on Map*, measured survey knowledge.

Directly after observing the video, a Route Sequence task was conducted. Participants indicated what action was taken at each of the eight intersections. Options were left-turn, right-turn, or straight ahead. No images of the intersections were shown. Numbers 1–8 were listed and participants selected the arrow icon indicating the response options. This task required an egocentric reference frame as a number of bodily turns were requested regarding the navigator in the environment. In the map-perspective condition, an orientation switch was required, as the turn direction was based on the orientation of the red arrow that moved along the route. A participant’s score was the sum of correct responses (ranging from 1 to 8).

Then, the Route Continuation task was performed. Participants were presented with eight images of the intersections in random order. Participants had to indicate whether they turned left, right, or went straight ahead at each decision point by pressing the arrow keys left, right, or up, respectively. In the map-perspective condition, an orientation switch was required, as the turn direction was based on the orientation of the red arrow that moved along the route. A participant's score was the sum of correct responses (ranging from 1 to 8).

Participants then performed the Point to Start and Point to End tasks. Participants were shown eight scenes taken along the route in random order. Participants were asked to indicate where the start or end locations of the route were using a rotational device. In the first-person perspective variation, the rotational device was placed horizontally on the desk in front of the participants. Participants were asked to point from the perspective shown in the image. In the map perspective version, the rotational device was placed vertically on the desk next to the monitor. Participants had to indicate the start/ending location on the map, relative to the red arrow icon the camera was following. The perspective from which the items of the task were presented corresponded to the perspective in which the environment was learned (no perspective switch was enforced). As such, the spatial orientation tasks assess survey knowledge in both learning perspectives (Ekstrom, Arnold, & Iaria, 2014). Scoring was based on the mean pointing deviation angle for each trial, ranging from 0 to 180 degrees deviation.

In the Distance Comparison task, participants completed eight trials in random order. In each trial, a target image and two response images were shown. In the first-person perspective version, the images were scenes along the route. In the map perspective version, the images were landmarks encountered along the route. Participants had to indicate which of the two response locations was closest to the target location (crow's flight distance). This task required an allocentric reference frame to complete as metric, configurational knowledge of the environment was assessed. Scoring was based on the number of correct responses (ranging from 1 to 8).

The final task participants performed was Locations on Map. Participants were shown a schematic city map including icons indicating starting and ending locations. In the first-person perspective version, participants were shown images of eight scenes along the route in random order. Participants had to indicate the correct location on the city map using the mouse. In the map perspective version, participants had to indicate where landmarks were located on the city map. Scoring was based on the mean distance deviation from the correct location (pixels) for each trial.

Neuropsychological Assessment

Four neuropsychological tests were performed to assess visuospatial abilities. The forward and backwards Corsi block -tapping tasks were used to assess visuospatial working memory (R. P. C. Kessels, van den Berg, Ruis, & Brands, 2008; Roy P. C. Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000). Product score (span x item score) was calculated and used as outcome measure.

The WAIS-IV Digit Span test was used to assess verbal attention span and working memory (David Wechsler, 2008). Product score (span × item score) was calculated and used as outcome measure.

Fig 3.1 Overview of the environment and the perspectives used in the spatial navigation assessment. Schematic map of the environment. The red, green, blue, and purple lines illustrate the four routes. The arrows indicate the route directions. b View of the environment as presented from the first-person perspective. c View of the environment as presented from the dynamic map perspective.

A computerized version of the Mental Rotation task was used assess higher level visuospatial processing (Shepard & Metzler, 1971). The version of the mental rotation tasks contained 48 trials. Half of the trials contained pairs of images that depicted the same object,

whereas the other trials contained mirrored pairs. The rotation used for the objects were 0, 45, 90, and 180 degrees mental rotation over either the horizontal or vertical axes. Total correct answers (accuracy) were
taken as outcome variable. Reaction time slope and intercept for correct answers were calculated
using the “least squares” method to calculate a straight line over the reaction times for the different degrees of mental rotation. Note that eight participants did not have a correct answer on all of the stimuli categories. For these cases, a line was fitted on the available data.

The Santa Barbara Object Perspective -Taking Tests were used to measure perspective -taking ability. The task contained 12 items. Average pointing deviation in degrees was calculated as main outcome variable for this task (Hegarty & Waller, 2004).

Procedure

All participants read the study’s information letter and signed an informed consent form prior to the experimental session in concordance with the Declaration of Helsinki (2013). The session started by filling in the screening questionnaire, followed by the Wayfinding Questionnaire. Participants then completed the navigation tasks. Two of the four available routes were assigned to each participant in a counter balanced procedure based on enrolment order (eight possible combinations of routes). For each route, a map perspective and a first-person perspective version was available. Participants would observe the two routes from different learning perspectives. Half of the participants would start with the dynamic map perspective, while the other half started with the first-person perspective. Participants observed the demo route and completed the subtests in the following order: Route Sequence, Route Continuation, Distance Comparison, Point to Start, Point to End, and Location on Map. This order of tasks was maintained to minimize the transfer of knowledge obtained through questions (e.g., the Route Continuation task contained information beneficial for the Route Sequence task). After the first demo video and tasks were completed, the procedure with the alternative perspective was performed. A 15-min break was introduced after which participants completed the visuospatial tests in the following order: Corsi Block Tapping, Digit Span, Santa Barbara perspective taking, and the Mental Rotation task.

Statistical Analysis

The mean scores on the neuropsychological tests (Corsi Block Tapping, Digit Span, Mental Rotation, and Perspective Taking) and the navigation tasks (Route Sequence, Route Continuation, Point to Start, Point to End, Distance Comparison, and Locations on Map) were calculated. Then, the relationship between neuropsychological abilities and performance on navigational tasks was investigated for both perspectives. First, a Pearson correlation analyses was performed to explore the relationship between all variables. This was followed by exploratory backward stepwise linear regression analyses that included (1) gender, (2) perspective -taking task score, the product score of (3) forward and (4) backward Corsi Block Tapping task, the product score of (5) forward and (6) backward Digit Span product scores, (7) Mental Rotation accuracy, (8) slope, and (9) reaction time, as independent variables. Performance on the 12 navigation tasks was used as dependent variables. The elimination criteria for these regression models were set to $p < 0.1$. All assumptions of multiple regression were assessed and met.

Performance differences on navigation tasks between different learning perspectives were assessed using a mixed model MANCOVA analysis, with learning perspective (first-person *vs*. dynamic map) as within-subject factor. Gender was included as a between subject factor. The scores of the neuropsychological tests were included as covariates.

Responses in the navigation tasks with a reaction time faster than 200 ms were negated. Average scores for each task were calculated without these trials. This occurred in 10/4800 trials (0.2%). Due to technical difficulties, the data of two participants were missing for the Route Sequence task (dynamic map perspective). to minimize the effects of extreme values in the regression analyses, Point to Start and Point to End (dynamic map perspective) were transformed using a 10-log transformation. Point to Start and Point to End (first-person perspective) were transformed using a square -root transformation.

Results

Demographic data and an overview of neuropsychological test performance are presented in Table 3.1. Overall performance scores on the navigation subtasks for both the first-person and dynamic map perspectives are displayed in Table 3.2. The results of the exploratory Pearson correlation analysis are presented in Supplementary Table 3.1. Diagnostics of the multiple regression assumption tests are displayed in Supplementary Tables 3.2 and 3.3.

Table 3.1 Demographics and scores on neuropsychological tests

Variable	M	SD
Demographic		
Age	22.18	2.81
Gender (% male)	37	
Education*	6.62	.49
Neuropsycholigcal assessment		
Perspective Taking test (deviation)	24.10	14.91
Corsi Span, Forward (span)	6.43	0.95
Corsi Span, Forward (product)	64.22	19.44
Corsi Span, Backward (span)	6.57	0.83
Corsi Span, Backward (product)	67.63	17.58
Digit Span, Forward (span)	6.41	1.33
Digit Span, Forward (product)	64.93	26.96
Digit Span, Backward (span)	5.37	1.13
Digit Span, Backward (product)	52.70	21.24
Mental Rotation, accuracy (%)	76.73	11.51
Mental Rotation, reaction time (ms)	5309.24	3591.95
Mental Rotation, slope (ms/degree)	20.83	15.23

*Education measured using the Verhage scale, a classification of education according to the Dutch education system. Ranging from 1-7, with 7 being the highest education level.

Table 3.2 Performance scores on navigation subtasks for both the dynamic map perspective and first-person perspective conditions.

Virtual Tübingen tasks	Dynamic map perspective		First-person perspective		MANCOVA			Post-Hoc contrast
	M	SD	M	SD	DF	F	p	p
Route knowledge					2, 87	.102	.903	
Route sequence (% correct)	65.69	24.57	61.13	28.81				-
Route continuation (% correct)	82.14	16.76	69.75	19.48				-
Survey knowledge					2, 89	0.089	.915	
Distance comparison (% correct)	66.75	17.15	65.13	20.59				-
Location on map (deviation in pixels)	120.98	69.09	142.72	73.52				-
Survey knowledge (orientation tasks)					*	*	*	
Point to start-location (deviation in degrees)	24.58	25.21	49.29	20.56				<.001
Point to end-location (deviation in degrees)	28.18	15.24	51.78	23.12				<.001

* Data did not meet assumptions for MANCOVA analysis; post-hoc contrast calculated using a Signed-Rank t-test.

Regression and performance analysis

Route knowledge tasks

Multiple regressions were calculated to determine whether similar of different small-scale spatial abilities predicted performance on the *Route Sequence* and *Route Continuation* tasks after learning a route from a dynamic map and first-person perspective (**Table 3.3**).

Route Sequence

A significant model was found for Route Sequence (first-person perspective), *F* (2, 97) = 7.75, $p < 0.001$, with a R^2 of 0.14. Corsi forward product score significantly predicted Route

Sequence score in the first-person learning condition (p < 0.001). Participant's Route Sequence score increased score by 0.51 for each increment of Corsi forward product score. As the variable elimination criteria were set to p < 0.1, the model included a trend-level interaction between Mental Rotation (slope) and Route Sequence score (p = 0.061).

A significant regression equation was found for Route Sequence (dynamic map perspective), F (2, 95) = 5.25, p < 0.01 with a R^2 of 0.10. Perspective -taking score significantly predicted Route Sequence score in the map learning condition (p < 0.05). Participant's Route Sequence score decreased by 0.39 for each degree of deviation in the perspective-taking task. None of the other variables significantly predicted Route Sequence score. The model included a trend -level interaction between Corsi forward product score and Route Sequence score (p = 0.073).

Route Continuation

A significant regression model was found for Route Continuation (first-person perspective), F (2, 97) = 7.28, p < 0.01 with a R^2 of 0.13. Corsi forward product significantly predicted Route Continuation score in the first-person learning condition (p < 0.01). Participant's Route Continuation score increased by 0.29 for each increment of Corsi forward product score. None of the other variables significantly predicted Route Continuation (first-person learning). The model included a trend level interaction between Perspective taking and Route Continuation score (p = 0.081).

A significant regression model was found for Route Continuation (dynamic map perspective), F (2, 97) = 10.81, p < 0.001 with a R^2 of 0.18. Perspective -taking score significantly predicted Route Sequence score in the map perspective condition (p < 0.001). Participant's Route Continuation score decreased by 0.39 for each degree of deviation in the perspective-taking task. None of the other variables significantly predicted Route Continuation (dynamic map perspective). The model included a trend-level interaction between Mental rotation accuracy and Route Continuation score (p = 0.069).

A mixed model MANCOVA was performed to assess the effect of learning perspective on performance of the route knowledge tasks. The MANCOVA did not reveal a main effect for learning perspective on performance in the tasks (p > 0.05) (**Table 3.2**). A significant interaction effect was found for learning perspective * Corsi Forward Product, F (2, 87) = 5.95, p < 0.01 partial η^2 = 0.12. Univariate tests showed a significant interaction effect of perspective and Corsi Forward product score on the Route Continuation performance, $F(1,88) = 10.13$, $p < 0.01$ partial $\eta^2 = 0.10$.

Survey knowledge tasks

Multiple regressions were calculated to determine whether similar of different small-scale spatial abilities predicted performance on the Distance Estimation, Location on Map, Point to Start, and Point to End tasks after learning a route from a dynamic map and first-person perspective (Table 3.4)

Distance Comparison

No significant predictors were found for performance on the Distance Comparison task in the first-person learning perspective. The backward elimination procedure removed all independent variables with a p score larger than 0.10. Similarly, no significant predictors of Distance Comparison were found after learning from a dynamic map perspective. A model with trend-level significance resulted from the backwards elimination procedure $F(1, 98) = 3.83$, $p = 0.053$ with a R2 of 0.03. The Corsi Backward product score predicted Distance Estimation at trend level ($p = 0.053$).

Table 3.3 Results of stepwise multiple regression analyses of factors predicting performance on route knowledge tasks after learning a route from first-person and dynamic map perspectives.

Nav. Task	Predictors	*t*	*p*	*B (SE)*	*β*	*F*	*p*	R^2
First-person perspective								
Route Sequence	Overall model					7.75	<.01	.14
	Corsi forward (Product)	3.63	<.01	.51 (.14)	.34			
	Mental rotation (Slope)	1.89	<.1	.34 (.18)	.18			
Route Continuation	Overall model					7.28	<.01	.13
	Perspective taking	-1.76	< .1	-.22 (.13)	-.17			
	Corsi forward (Product)	3.05	< .01	.29 (.09)	.29			
Dynamic map perspective								
Route Sequence	Overall model					5.25	<.01	.10
	Perspective taking	-2.39	<.05	-.39 (.16)	-.24			
	Corsi forward (Product)	1.81	<.1	.23 (.13)	.18			
Route Continuation	Overall model					10.81	<.01	.18
	Perspective taking	-3.63	<.01	-.39 (.11)	-.35			
	Mental rotation (Accuracy)	1.84	<.1	.26 (.14)	.18			

Location on Map

A significant regression model was found for the Location on Map task (first-person learning), *F* (3, 96) = 6.32, $p < 0.01$ with a R^2 of 0.17. Corsi forward product significantly predicted Location on Map score in the first-person learning condition ($p < 0.01$). Participant's Location on Map accuracy (measured in pixel deviation) increased by 1.35 for each increment of Corsi forward product score. None of the other variables significantly predicted Location on Map (first-person learning). The model included two trend-level relations with Location on Map score: Gender ($p = 0.056$) and Mental Rotation (slope) ($p = 0.09$).

A significant regression model was found for the *Location on Map* task (dynamic map perspective), *F* (1, 98) = 4.60, $p < 0.05$ with a R^2 of 0.05. Corsi Backward product score significantly predicted *Location on Map* score in the map perspective condition ($p < 0.05$). Participant's Location on Map accuracy (measured in pixel deviation) increased by 0.83 for each increment of Corsi backward product score. The regression models reveal that visuospatial working memory, as measured in the Corsi Forward and Backward block - tapping task, predicted performance in survey tasks after learning from both the first-person and dynamic map perspectives.

A mixed model MANCOVA was performed to assess the effect of learning perspective on performance on Distance Estimation and Location on Map. The MANCOVA did not reveal a main effect for learning perspective on performance in both tasks ($p > 0.05$) (Table 3.2).

Pointing to Start Location

A significant regression model was found for Point to Start (first-person perspective), F (3, 95) = 7.5, $p < 0.001$ with a R^2 of 0.24. Perspective taking ($p < 0.01$), Gender ($p < 0.01$), and Corsi Forward product score ($p < 0.01$) significantly predicted Point to Start score after first-person learning. Square -root transformed pointing deviation increased by 0.03 degrees for each degree of pointing deviation in the perspective-taking task. Square root transformed Pointing deviation decreased by 0.02 degrees for each increment of Corsi forward product score.

A significant regression model was found for Point to Start (dynamic map perspective), F (1, 98) = 30.69, $p < 0.001$ with a R^2 of 0.24. Perspective taking significantly predicted Point to Start score in the map perspective condition ($p < 0.001$). Log transformed pointing deviation increased by 0.01 degrees for each degree of pointing deviation in the perspective-taking task. None of the other variables significantly predicted Point to Start.

Table 3.4 Results of stepwise multiple regression analyses of factors predicting performance on survey knowledge tasks after learning a route from first-person and dynamic map perspectives.

Nav. Task	Predictors	*t*	*p*	*B (SE)*	*β*	*F*	*p*	R^2
First-person perspective								
Distance Estimation	Overall model					-	n.s.	-
Location on Map*	Overall model					6.32	**<.01**	.17
	Gender	1.94	<.1	27.56 (14.22)	.18			
	Corsi Forward (product)	-3.78	**<.01**	-1.35 (.36)	-.36			
	Mental Rotation (slope)	-1.67	<.1	-.76 (.45)	-1.57			
Point to Start†	Overall model					7.50	**<.001**	.24
	Gender	2.67	**<.01**	.74 (.28)	.25			
	Perspective taking	2.69	**<.01**	.03 (.00)	.25			
	Corsi forward (Product)	-2.97	**<.01**	-.02 (.00)	-.27			
	Mental rotation (RT)	-1.67	<.1	-0.0(.00)	-.15			
Point to End†	Overall model					8.93	**<.001**	.22
	Perspective taking	1.73	<.1	.02 (.01)	.16			
	Corsi forward product	-3.46	**<.01**	-.03 (.00)	-.32			
	Mental rotation (accuracy)	-1.85	<.1	-.03 (.01)	-0.18			
Dynamic map perspective								
Distance Estimation	Overall model					3.83	<.1	.03
	Corsi Backward (product)	1.96	<.1	.19 (.09)	.19			
Location on Map*	Overall model					4.60	**<.05**	.05
	Corsi Backward (product)	-2.15	**<.05**	-.83 (.39)	-0.21			
Point to Start‡	Overall model					30.69	**<.001**	.24
	Perspective taking	5.54	**<.01**	.01 (.002)	.48			
Point to End‡	Overall model					12.31	**<.001**	.20
	Perspective taking	4.01	**<.01**	.005 (.00)	.37			
	Corsi forward product	-2.23	**<.05**	-0.002 (.00)	-.21			

*Outcome measured in deviation. A lower score indicated a higher performance.

† Data was square root transformed. ‡Data was log transformed. n.s. indicates non-significant, non-trend. Significant p-values printed in bold.

Pointing to End Location

A significant regression model was found for Point to End (first-person perspective), F (3, 96) = 8.93, p < 0.01 with a R^2 of 0.22. Corsi forward product significantly predicted Point to End score in the first-person learning condition (p < 0.001). Square-root transformed pointing deviation decreased by 0.03 degrees for each increment of Corsi forward product score. None of the other variables significantly predicted Point to End. The model included two trend-level relations for Perspective Taking ($p = 0.087$) and Mental Rotation (accuracy) ($p = 0.067$).

A significant regression model was found for Point to End (dynamic map perspective), F (2, 97) = 12.31, $p < 0.01$ with a R^2 of 0.2. Corsi forward product significantly predicted Point to End score in the map perspective condition ($p < 0.05$). Log transformed pointing deviation increased by 0.002 degrees for each increment of Corsi forward product score. Additionally, perspective taking significantly predicted Point to End score in the map perspective condition ($p < 0.001$). Log transformed pointing deviation increased by 0.005 degrees for each degree of pointing deviation in the perspective-taking task.

Due to a non-normal distribution of the Point to Start and Point to End data (in both perspective groups), the assumptions of a mixed model MANCOVA were not met. Therefore, Wilcoxon Signed Rank tests were conducted assess the effect of learning perspective on performance on the orientation tasks (Table 3.2). The Wilcoxon Signed Rank tests revealed a significant effect of perspective on performance on both the Point to Start ($Z = -7.65$, $p < 0.001$) and Point to End tasks ($Z = -7.32$, $p < 0.001$). Performance was significantly higher in the dynamic map perspective condition compared to the first-person perspective condition in both Point to Start (*M* = 24.58, *SD* = 25.21 *vs.* *M* = 49.29, *SD* = 20.56) and Point to End tasks (*M* = 28.18, *SD* = 15.24 *vs.* *M* = 51.78, *SD* = 23.12).

A schematic overview of the visuospatial tasks predicting performance on navigation subtasks is presented in Fig 3.2. Overall, the results reveal distinct patterns of visuospatial abilities predicting performance on route knowledge tasks for the two perspectives. Conversely, both shared and distinct visuospatial abilities predict performance on survey knowledge tasks in the two learning perspectives.

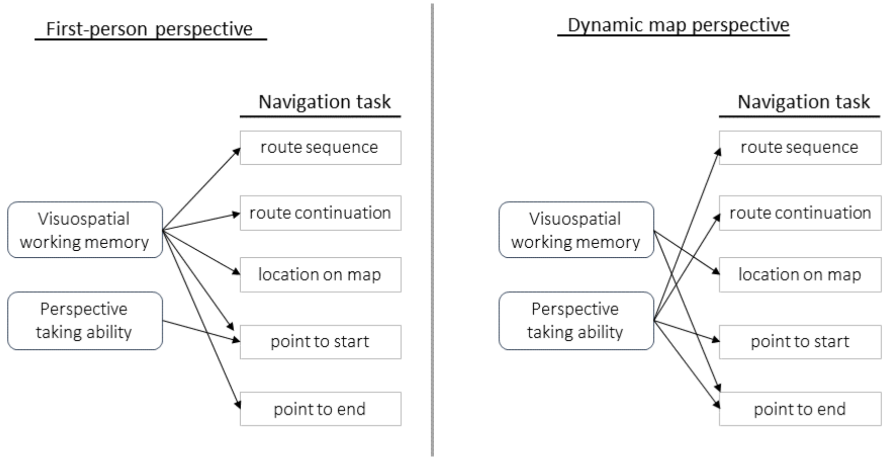

Fig 3.2 Summary of visuospatial task predicting performance on navigation tasks per perspective as obtained in regression models. Arrows indicate a significant predictive relationship of the visuospatial task on the navigation task

Discussion

Within the field of spatial cognition, there is debate revolving around the influence of learning perspective on the characteristics of mental representations of space (Zhang et al., 2014). One line of research suggests that spatial information is stored in a common representation of space (L. Latini-Corazzini et al., 2010; Shelton & McNamara, 2004), while other evidence points towards partially dissociable representations of space that are dependent on learning perspective (Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). The aim of the current study was to determine whether a common representation of space was formed when information was learned via different perspectives by assessing relations between visuospatial abilities and different types of spatial knowledge. The overlapping model of spatial representation would predict that the same visuospatial abilities would predict performance on the route and survey knowledge tasks after first-person and dynamic map learning. Conversely, the (partially) independent model would predict that different visuospatial abilities would predict performance on the route and survey knowledge tasks.

Our results indicate that distinct visuospatial abilities underlie the formation of route knowledge after learning from a first-person and dynamic map perspective. Visuospatial working memory predicted performance on the route knowledge tasks in the first-person learning condition, whereas perspective-taking ability predicted performance on route knowledge tasks in the dynamic map perspective condition. The importance of visuospatial working memory in the formation of route knowledge during direct navigation has been observed in (Garden, Cornoldi, & Logie, 2002; Ishikawa & Montello, 2006; Meneghetti et al., 2016). It has been suggested that visuospatial working memory is responsible for storing and processing of spatial information and facilitating other visuospatial abilities (Meneghetti et al., 2016). Perspective-taking ability is believed to play an important role in acquiring knowledge about locations and readjustment of orientation during information processing (Hegarty et al., 2006). This ability is predominantly involved in processing of configurational representation of spatial information. However, the ability has been shown to contribute to route knowledge (Kozhevnikov et al., 2006). The distinction in cognitive processes contributing to performance on the route knowledge tasks shows that route knowledge is processed differently depending on learning perspective. The involvement of visuospatial working memory in the first-person learning conditions suggests that participants recall the sequence of events in the video without computing perspective changes or transformations. The involvement of spatial transformation in the map perspective condition, suggest that participants adjusted their orientation on the mental image of the environment to complete the tasks (Fields & Shelton, 2006; Meneghetti et al., 2011). Therefore, it seems likely that route knowledge obtained through the first-person navigation is stored into an egocentric reference frame, whereas route knowledge obtained through dynamic map perspective is stored into a more allocentric oriented reference frame.

Assessment of the visuospatial abilities underlying performance on the survey knowledge tasks reveals a more complex interaction. While there are shared visuospatial abilities predicting survey knowledge in the first-person and dynamic map perspectives, there are also relations that are specific to the perspective conditions. In both perspective conditions, visuospatial working memory contributed to performance on configurational knowledge of the environment, in accordance with studies that studied the role of visuospatial working memory in static map study and direct navigation designs (Coluccia et al., 2007; Garden et al., 2002; Muffato et al., 2019; Wen, Ishikawa, & Sato, 2011). Furthermore, perspective-taking ability predicted performance on the orientation tasks in both perspective learning conditions. These results closely resemble an earlier study in which cognitive mechanisms underlying first-person and dynamic map perspective learning using a judgement of relative direction tasks were studied (Fields & Shelton, 2006). There are, however, distinct predictors of spatial knowledge related to the learning perspective. Visuospatial working memory predicted ‘pointing to start’ ability after first-person learning, which was not observed after dynamic map learning. Conversely, visuospatial working memory predicting 'point to end' performance in the dynamic map learning, which was not observed after first-person learning. As such, we argue that there are both overlapping and distinct cognitive processes in both learning perspectives. This suggests that survey knowledge acquired through first-person information is encoded and processed using a mental representation that is *at least* partially distinct from information obtained through map learning.

Perspective-dependent advantages of on route and survey tasks have been taken as evidence for differential spatial representations (Zhang et al., 2014). These studies have contrasted performances after static map study with direct navigation. However, when introducing sequential pacing of information in the map learning perspective, the quality of route knowledge is comparable to the first-person navigation. In contrast to the previous studies that employed cartographic maps and first-person learning (Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982), no advantage for first-person perspective learning over map perspective learning was found on performance on route knowledge tasks. These results are in line with more recent studies that employed a similar method of map presentation and route knowledge assessment (Muffato et al., 2019). Following Muffato et al. (2019), we argue that these discrepancies arise as a result of the presentation of a route information in the map perspective condition, as compared to a static cartographic map.

Mixed results were found for the advantages of learning perspectives on tasks that assessed survey knowledge of the environment. No performance differences were found for survey knowledge tasks that assessed the locations of landmarks in the environment, whereas an advantage for the dynamic map perspective was found on the orientation tasks that assessed relative directions between locations. Perspective-dependent advantages for configurational knowledge have been demonstrated in many studies (Muffato et al., 2019; Shelton & Pippitt, 2007; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982; Yamamoto & DeGirolamo, 2012). In line with these studies, our results support the notion that survey knowledge is processed differently depending on learning perspective. The results should be interpreted with caution, however. The stimuli used in the current tasks always corresponded to the perspective in which the environment was learned to minimize the prompting of a representation other than the input perspective (Muffato et al., 2019). This, however, required participants in the first-person perspective to take the heading direction into account when pointing to different locations, which was not the case in the dynamic map perspective. The additional cost of switching between the first-person stimulus presentation (egocentric) in the task and the allocentric representation in which information was encoded might explain the performance differences between learning perspectives (Lee & Tversky, 2001).

Overall, this study provides further evidence for the model that states that mental representations of space are dependent on learning perspective. While this result contributes to the theoretical understanding of navigation ability, it has implications for more applied research. There have been attempts to develop diagnosis tools and treatments for neurological patients (i.e., acquired brain injury, Alzheimer's disease) with navigation impairments (Bouwmeester et al., 2015; Cogne et al., 2017; Kober et al., 2013). Our results stress the importance of using a comprehensive set of navigation tests in the diagnosis of these impairments. Route knowledge, in particular, should be assessed using both first-person and map-based perspectives. In terms of treatment selection, our results support the idea of a compensationary approach to navigation impairments (Claessen, van der Ham, et al., 2016). The dissociable nature of route knowledge suggests that route knowledge impaired patients might benefit from using maps. Conversely, participants with survey knowledge impairments can be trained to develop a navigation strategy focusing on the acquisition of route knowledge from a first-person perspective.

The current study contained some limitations that must be mentioned. First, the Virtual Tübingen environment was limited in spatial dimensions. to keep the properties (length and number of intersections) of the routes similar, it was inevitable that parts of the routes overlapped. This overlap was kept to a minimum and kept similar between routes: All routes contained one overlapping street (path between two intersections) with one other route. This overlapping street was never visited in the same travelling direction. Regardless, it is possible that spatial information leaked over between the two perspective learning conditions. If this was the case, the task would be slightly biased towards the hypothesis supporting the common representation of space. However, as the results support the partial dissociation hypothesis, we argue that the overlap in routes had a minimal impact on the results. Second, the current study provides a comprehensive comparison of visuospatial and cognitive functions underlying a broad array of spatial abilities under different learning conditions. While the current selection of visuospatial and spatial abilities tasks cover the main components of spatial navigation, the assessment is far from complete. To gain a more complete understanding of the mental representations of space and how these are constructed under different learning perspectives, future studies should investigate the mechanisms underlying map sketching, scene/landmark recognition, and route completion abilities. Finally, to maximize the similarities between perspective learning conditions, the current study was limited to passive learning of the environment. Active navigation allows participants to learn an environment in a more ecologically valid manner as participants can utilize preferred and familiar spatial strategies (Chrastil & Warren, 2012)This approach might provide a more detailed insight into the cognitive mechanisms underlying the construction of mental representations.

When placing our findings in context of the two main models on the nature of spatial information, the overlapping model and partially dissociation model, we are able to contribute a novel observation. Distinct cognitive functions underlie route knowledge when information is obtained through first-person or map learning perspectives. Partially distinct cognitive functions underlie survey knowledge in the two perspective learning conditions. Additionally, when including a sequential pacing of information in map perspective learning and using a sufficiently complex environment, the observed advantages for first-person learning on route knowledge acquisition and map learning for survey knowledge diminish. Overall, our results support the notion that both route and survey knowledge representations are dissociated for different learning perspectives.

Supplementary Material

Supplementary Table 3.1 Pearson correlations matrix for navigation subtasks and neuropsychological tests.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Route Sequence (DMP)	1																			
2. Route Sequence (FPP)	0.11	1																		
3. Route Continuation (DMP)	0.05	0.09	1																	
4. Route Continuation (FPP)	0.19	**0.21***	**0.38****	1																
5. Distance Comparison (DMP)	0.14	**0.25***	0.07	0.13	1															
6. Distance Comparison (FPP)	-0.03	0.19	**0.35****	**0.28****	0.13	1														
7. Location on Map (DMP)	**-0.22***	-0.15	-0.19	**-0.32****	**-0.34****	**-0.27****	1													
8. Location on Map (FPP)	0.04	**-0.25***	-0.19	**-0.49****	**-0.26****	**-0.46****	**0.24***	1												
9. Point to Start (DMP) †	**-0.28****	-0.14	**-0.35****	**-0.21***	-0.08	**-0.26****	**0.22***	**0.24***	1											
10. Point to Start (FPP) ‡	-0.08	**-0.26****	-0.15	**-0.31****	-0.11	**-0.22***	0.18	**0.41****	**0.3****	1										
11. Point to End (DMP) †	**-0.32****	**-0.25***	**-0.26****	**-0.28****	-0.13	**-0.29****	**0.47****	**0.25***	**0.46****	**0.25***	1									
12. Point to End (FPP) ‡	-0.14	-0.19	**-0.21***	**-0.4****	-0.12	**-0.23***	**0.22***	**0.49****	**0.33****	**0.47****	0.18	1								
13. Perspective Taking (score)	-0.14	-0.03	**-0.43****	**-0.2***	-0.08	-0.1	0.14	**0.21***	**0.45****	0.16	**0.3****	**0.29****	1							
14. Corsi Span Forward (product)	**0.2***	**0.27****	0.11	**0.37****	0.1	0.08	-0.1	**-0.33****	-0.17	**-0.24***	**-0.25***	**-0.39****	-0.15	1						
15. Corsi Span Backward (product)	0.12	0.06	**0.24***	0.15	0.16	0	**-0.2***	-0.04	-0.19	-0.09	-0.18	**-0.2***	**-0.32****	**0.31****	1					
16. Digit Span Forward (product)	-0.02	0.03	0.08	0.15	-0.04	0.18	0.01	-0.15	0.01	-0.08	-0.08	-0.01	-0.07	0.15	0.01	1				
17. Digit Span Backward (product)	0.19	0.08	**0.21***	**0.2***	0	0.15	-0.07	-0.09	-0.11	-0.01	**-0.21***	-0.11	**-0.21***	**0.21***	0.14	**0.55****	1			
18. Mental Rotation (accuracy)	0.06	0.09	**0.28****	0.11	-0.02	0.13	-0.16	**-0.28****	-0.19	-0.17	**-0.2***	**-0.25***	**-0.28****	0.19	0.13	0.08	0.16	1		
19. Mental Rotation (reaction time)	0	0.13	0.08	**0.22***	-0.03	0.1	-0.07	**-0.31****	0.04	-0.15	0.01	-0.18	0.1	0.05	**-0.21***	0.06	0.04	**0.5****	1	
20. Mental Rotation (slope)	-0.04	0.03	-0.03	0.03	-0.09	-0.02	0.04	-0.15	0.06	-0.11	0.07	-0.04	-0.05	-0.1	-0.15	0.11	0.07	**0.43****	**0.69****	1

*DMP = Dynamic Map perspective. FPP = First Person Perspective. † = Transformed using 10 for correlation analysis. ‡ = transformed using SQRT for correlation analysis. * Significance at p<.05 ** Significance at p<0.01. Significant correlations printed in bold letters*

Supplementary Table 3.2 Multiple regression diagnostics (First-person perspective)

Regression analysis	Normal distribution of residuals	Homoscedasticity	Residual Independence	Multicollinearity		Cook's Distance
	PP plot	scatterplot	Durbin-Watson	TOL	VIF	Maximum
Route Sequence	✓	✓	1.822	0.989	1.011	0.57
Route Continuation	✓	✓	1.881	0.974	1.027	0.96
Distance Estimation	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Location on Map	✓	✓	1.807	0.985	1.015	0.1
Point to Start	✓	✓	1.968	0.953	1.049	0.157
Point to End	✓	✓	1.885	0.899	1.112	0.062

Supplementary Table 3.3 Multiple regression diagnostics (Dynamic map perspective)

Regression analysis	Normal distribution of residuals	Homoscedasticity	Residual Independence	Multicollinearity		Cook's Distance
	PP plot	scatterplot	Durbin-Watson	TOL	VIF	Maximum
Route Sequence	✓	✓	2.048	0.978	1.022	0.181
Route Continuation	✓	✓	1.171	0.93	1.075	0.238
Distance Estimation	✓	✓	2.107	1.00	1.00	0.062
Location on Map	✓	✓	2.181	1.00	1.00	0.89
Point to Start	✓	✓	2.069	1.00	1.00	0.163
Point to End	✓	✓	2.152	0.974	1.027	0.088

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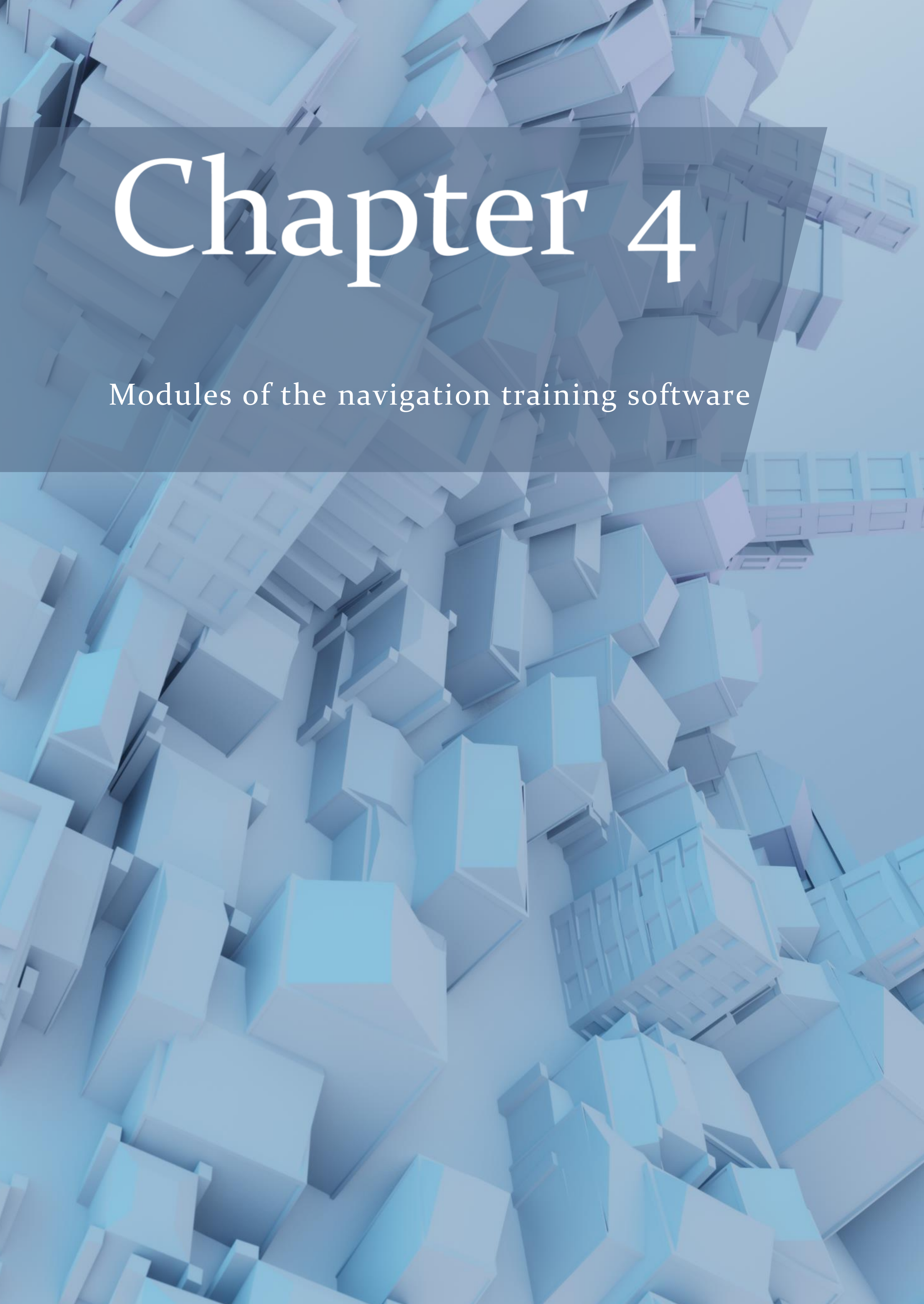
Chapter 4

Modules of the navigation training software



Designing training modules

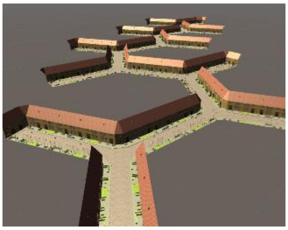
The training was composed of a face-to-face psychoeducation session and a software package. The psychoeducation session served to teach patients the fundamentals of navigation as understood within the field of spatial cognition. This information was then related to the impairment of each patient and a compensatory strategy was introduced. Accompanying the psychoeducation session, was a software package that included exercises and additional information and instructions regarding the use of the strategy that was to be trained. Patients had access to either an allocentric or egocentric version of the software. Within the versions, three modules were designed that each trained a subcomponent of the strategy. A navigational skill was introduced, trained and an explanation was given on how to integrate this into real life situations. Each module was inspired by experimental paradigms used the in spatial cognition literature. Key concepts of these paradigms were taken and designed as a serious game, with varying levels of difficulty. Importantly, the environments in which the exercises took place were constructed in a modular fashion, consisting of separate geographical features such a corridors, rooms and landmarks. These environmental elements were connected to each other using scripts that allowed for randomization. Every time a module was started, a novel environment was generated in which the exercise took place, thus avoiding undesired learning effects. The design of the modules, their theoretical background and intended learning component are described in this chapter.

Egocentric version

Spatial-temporal sequence memory

The core principle of this egocentric module was the adoption of a sequential egocentric strategy (Igloi, Zaoui, Berthoz, & Rondi-Reig, 2009; Rondi-Reig et al., 2006). This strategy comprises a rudimentary form of route-based navigation. The module was inspired by the classic T-maze paradigm (d'Isa, Comi, & Leocani, 2021), although multiple connected Y-shaped junctions were used (Fig 4.1). Patients were trained to remember routes through an environment by learning an array of bodily turns. No landmarks were present in the environment, so that sequence memory of body turns was trained rather than stimulus-response associations. The resulting spatiotemporal organization was at least partly reliant on episodic memory.

Within this module, patients discovered a basic navigation strategy that was not reliant on landmarks or geometric cues. This strategy could be used when the use landmarks in an environment is difficult or impaired. Furthermore, the module potentially strengthened sequence memory for navigational tasks, by forcing patients to pay attention to this component of navigation ability.



In each trial, a modular maze was generated that consisted out interlocking Y-junctions. The number of junctions determined the difficulty level for this module.

Patients watched a demonstration route through the maze. Patients were insturcted to focus on the order of turns.

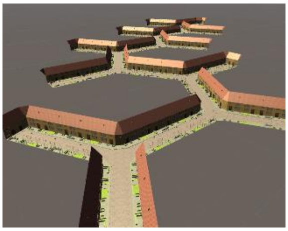
Patients were placed in starting area and were tasked to find their way to the end location. While traveling the correct path, stars were earned. Heading into an wrong corridoor resulted in the loss of a star

Fig 4.1 Description of the spatial-temporal sequence memory module

Landmark -direction associations

In this egocentric module, patients were trained to adopt a landmark-response-based strategy. This module trained a compartmentalized aspect of route-based navigation. The module was inspired by the T-maze paradigm, although Y-shaped junctions were used and landmarks were included at choice point (Baker & Holroyd, 2009). Participants observed a demonstration route, in which left or right turns were taken at landmarks (**Fig 4.2**). Participants would then replicate the actions of the demonstration route to reach an end location. Importantly, the order in which the landmarks were encountered was randomized after the demonstration, ensuring that participants focussed on forming landmark-response associations, rather than sequence memory. In this module, landmarks were used in a non-geometric manner, serving as anchor points along a route.

This module emphasized the use of landmarks along a route in an egocentric context. Patients were trained to pay attention to the identity of landmarks and the action required at the location to follow route. This strategy could be used in environments with prominent landmarks. The module rewarded patients that payed strong attention to landmarks and developed methods to remember the directional association with each landmark.



The modular maze was set up similar to **Fig 4.1**. In this module, easilt distinguisable landmarks were place in the middle of each junction points

Patients watched a demonstration route through the maze. Patients were insturcted to focus on the actions taken at landmarks. Following the demonstration, the order of the junction points was shuffled. The relation between the landmark and the correct direction remained intact.

Patients were placed in starting area and were tasked to find their way to the end location. While traveling the correct path, stars were earned. Heading into an wrong corridoor resulted in the loss of a star

Fig 4.2 Description of the Landmark-direction association module

Egocentric updating

This egocentric module trained spatial updating ability as part of more general egocentric navigation strategy. When using egocentric updating, the navigator continuously updates self-to-object relations towards a specific location whilst moving through an environment (Zhong & Kozhevnikov, 2016). This process relies on idiothetic signals and allothetic cues. When tracking a specific starting location in an environment, this process is often referred to as path integration. Egocentric updating can be regarded as an egocentric form of survey knowledge, as metric information regarding one's position and a location is processed. The module was inspired by scene depended perceptual pointing tasks frequently used in human navigation studies (Hodgson & Waller, 2006; Waller & Hodgson, 2006; Zhang, Copara, & Ekstrom, 2012). In this module, patients were placed in a starting room and were tasked to walk through a corridor that contained a number of turns (Fig 4.3). After a set amount of turns, patients were tasked to point to their starting position. The walls became transparent and gave feedback regarding their pointing accuracy.

This module emphasized and promoted the use spatial updating during navigation. Spatial updating can be used when landmarks are difficult to use or when forming sequence memory is to taxing. For example, when navigating a dense city, patients can attempt to maintain their orientation towards the location of a train station (or parking place) to be able to travel back home.

In each trial, a modular corridor was constructed consisting of straight, and turn segments. The number of turn segments present in the maze determined the difficult of the trial as well as intensity in which the maze spiralled around the starting location

Patients were tasked to remain focussed on the start location whilst traveling along the corridoor. At set intervals, patient's movement became locked. At this point were asked to point toward the starting location by rotating the camera.

After confirming their pointing direciton, the walls of the corridoor became transparent and the correct location was shown. The deviation in pointing angle determined the performance. Patients then continued through the corridoor towards the ending location.

Fig 4.3 Description of the Egocentric updating module

Allocentric version

Map use

In this allocentric module, patients were trained to use GPS-like map systems. Three types of maps were used in this module. In one set of exercises, a map was shown in which the current location of the navigator was continuously updated (GPS trial). In the second set of exercises, a map was shown that only indicated the starting location (traditional map). In the third set of exercises, a map was only shown before the trial started (temporary map). A key component of the module was the focus on switching between egocentric and allocentric perspectives (Colombo et al., 2017). The module was inspired by a variety of studies that concerned map learning and GPS-based navigation (Lobben, 2007; Munzer, Zimmer, Schwalm, Baus, & Aslan, 2006; Thorndyke & Hayes-Roth, 1982). Participants were placed in an environment with several rooms (Fig 4.4). Each room was marked with on a map. Participants were tasked to find the shortest route to an ending location. In the GPS trials, allocentric information could be readily obtained from the map and could be easily transferred to the egocentric perspective. In the traditional map trial, the switch between perspectives required patient comparing environmental elements obtained in the egocentric perspective and match those to information on the map. In the final trial, allocentric information was stored in memory and accessed when traveling the environment from an egocentric perspective.

The goal of this module was to train effective map use during and prior to navigation. In addition, the trials in this module were designed to make switched between allocentric and egocentric perspectives increasingly difficult. This module emphasized the use of allocentric information that is available using navigation systems on GPS and mobile devices.

In each trial a 3x3, 4x4 or 5x5 gridlike maze was generated containing landmarks and road blocks. Patients were tasked to find the shortest route the ending location whilst avoiding roadbloacks. Each room visited lead to a star beeing lost, whilst visiting a roadblock lead to two stars being lost

In the lower difficulty setting, A map was always present during navigation. Participants could track their current location on the map. In the intermediary difficulty setting, the map would only show that starting en ending locations, not the current location.

In the high difficulty setting, a map was only shown before the trial started. Patients had to plan a route before navigating.

Fig 4.4 Description of the Map-use module

Place learning

The key principle of this allocentric module was the adoption of an allocentric strategy in which geometrical information of landmarks was used to determine locations in an environment. The module trained map and place learning abilities as well as cognitive mapping. The design of the trials in the module were inspired by the Moris Water Maze paradigms (Vorhees & Williams, 2006). Landmarks in the environment were first presented on a map which included a marker for the goal location (Fig 4.5). Patients were then placed somewhere in the environment and were tasked to find the goal location. Starting and goal locations could only be determined by using the configuration of objects in the environment.

Within this module, patients practised with the use of geometric information during navigation. Both local and distal landmarks were used as markers in the module, so patient were trained to use landmarks that gave information regarding cardinal directions and more locally placed landmarks that could be used as anchor points in a coordinate frame. The module emphasized the use of geometric landmark information for navigation rather than route-based navigation strategies.

In each trial, a circular map was shown. On the map a goal location was shown and a set of landmarks. Landmarks could be local, within the circle, or global, far in the distance. The size of the circle and the number of landmarks present varied with the difficulty of the module.

Patients were task to use the landmarks to find the shortest route to the goal location, which was hidden during navigation. A steptracker measured how much distance was traversed. As this bar depleted, starts were lost.

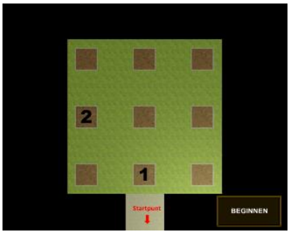
If patients found the goal location with a limited amount of steps, stars were earned. Is too many steps were taken, the goal location would be revealed.

Fig 4.5 Description of the Place learning module

Place and order learning from maps

The principle of this module was to train map learning in combination with route order and place learning. The inspiration for this module was the Walking Corsi Test, which in turn is a variation of the Corsi Block Tapping Task (Piccardi et al., 2013). A map depicted nine cubes, which contained numbers that indicated in what order they should be visited (Fig 4.6). After encoding the map, patients were placed in a 3D environment and were tasked to visit the locations in the correct order.

Patient were presented with spatiotemporal information was presented in an allocentric reference frame. This module mimics situations in which a route should be planned and remembered by studying the map of an environment.

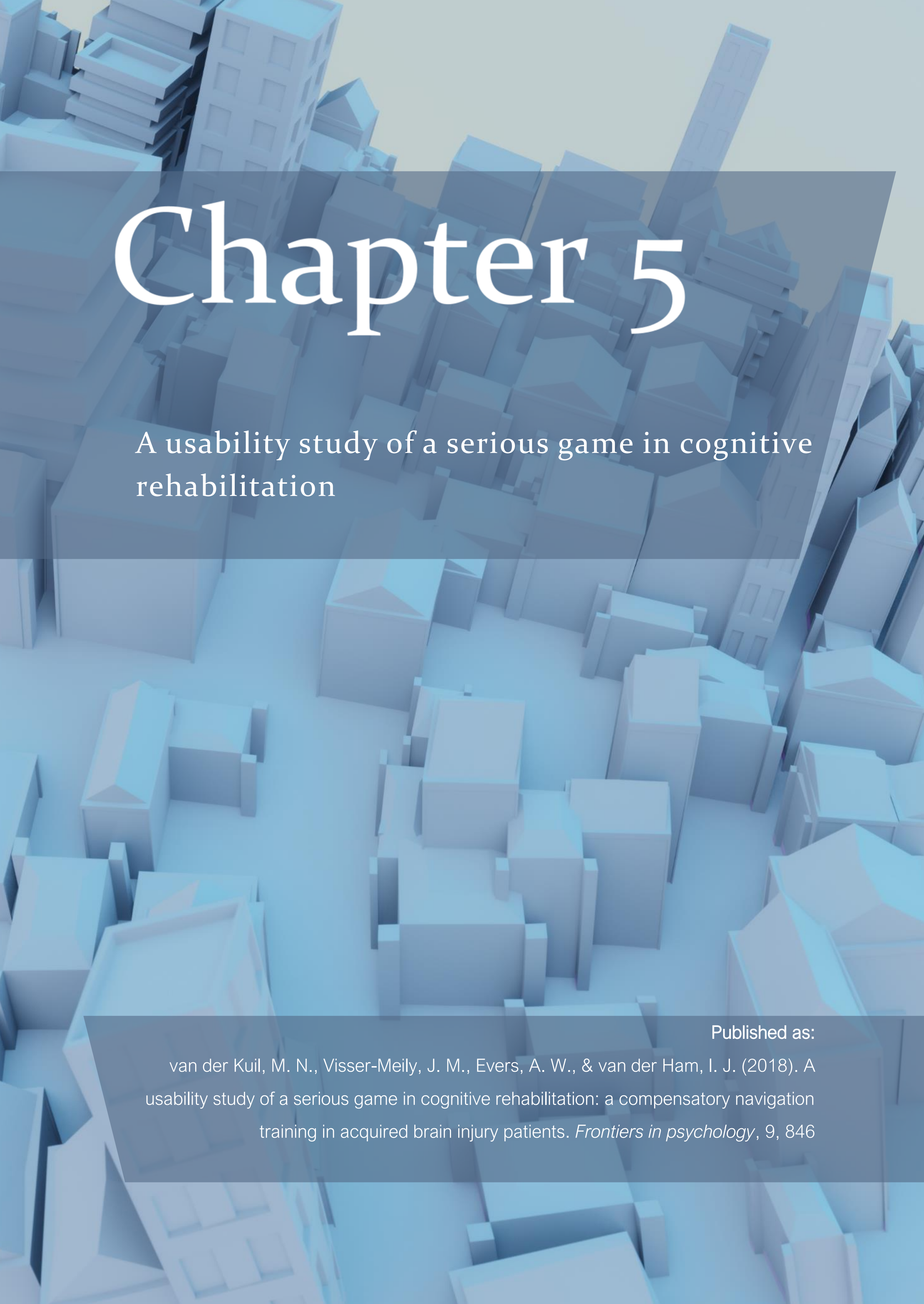


In each trial, a map of a garden was shown contained 9 allotments. Patients were tasked to water these allotments in the order indicated by the numbers on the map. The difficulty of the trial was determined by the number of allontments that needed to be visited.

Patients were placed in the garden and were instructed to travel to the allotments in the correct order. The map was not shown again during this phase.

Watering the correct allotment yielded a star, whilst watering the incorrect allotment lead to the loss of a star.

Fig 4.6 Description of the Place and order map-learning module



Chapter 5

A usability study of a serious game in cognitive rehabilitation

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Abstract

Acquired brain injury patients often report navigation impairments. A cognitive rehabilitation therapy has been designed in the form of a serious game. The aim of the serious game is to aid patients in the development of compensatory navigation strategies by providing exercises in 3D virtual environments on their home computers. The objective of this study was to assess the usability of three critical gaming attributes: movement control in 3D virtual environments, instruction modality and feedback timing. Thirty acquired brain injury patients performed three tasks in which objective measures of usability were obtained. Mouse controlled movement was compared to keyboard-controlled movement in a navigation task. Text-based instructions were compared to video-based instructions in a knowledge acquisition task. The effect of feedback timing on performance and motivation was examined in a navigation training game. Subjective usability ratings of all design options were assessed using questionnaires. Results showed that mouse-controlled interaction in 3D environments is more effective than keyboard-controlled interaction. Patients clearly preferred video-based instructions over text-based instructions, even though video-based instructions were not more effective in context of knowledge acquisition and comprehension. No effect of feedback timing was found on performance and motivation in games designed to train navigation abilities. Overall appreciation of the serious game was positive. The results provide valuable insights in the design choices that facilitate the transfer of skills from serious games to real-life situations.

Introduction

Serious games are games that are designed for a primary purpose other than entertainment (Michael & Chen, 2005). The key concept of serious gaming is the implementation of game attributes and game mechanisms to engage users toward achieving real-life goals. While many of these game attributes and mechanics are adapted from the entertainment video games, their underlying concepts correspond well to ideas originating in fields such as behaviourism, constructivism, and neuroscience (Yusoff, Crowder, Gilbert, & Wills, 2009). As such, effective implementation of goals, feedback, rules, challenges and fantasy elements enhances the motivation and engagement of users toward achieving learning outcomes (Charsky, 2010; Garris, Ahlers, & Driskell, 2002; Yusoff et al., 2009).

Over the past decade, serious gaming has proliferated into different areas such as healthcare, military, corporate, education and government (Susi et al., 2007). A notable application of serious gaming is its introduction into the field of neuropsychological rehabilitation. Acquired brain injuries (e.g., stroke, traumatic brain injury and brain tumours) are highly prevalent in modern society (Ma, Chan, & Carruthers, 2014; Peeters et al., 2015). Cognitive and behavioural deficits resulting from acquired brain injury have a profound effect on many daily life activities of these patients (Fann, Katon, Uomoto, & Esselman, 1995). The aim of neuropsychological rehabilitation is to aid brain injured patients in overcoming impairments and disabilities and to facilitate a return to usual self-care and daily activities (Dobkin & Dorsch, 2013). Rehabilitation programs often span over several months and require patients to engage in repeated exercises or mental rehearsals. Furthermore, patients are often required to continue with home-based therapies after they are discharged from hospital care (Legg et al., 2004). The combination of home-training, repetition of exercises, and high treatment costs provide interesting opportunities for innovative approaches such as serious gaming in rehabilitation.

A distinction can be made between physical and cognitive rehabilitation. Physical rehabilitation focusses on motor abilities and sensorimotor functioning. Serious games have been developed to aid in the rehabilitation of balance impairments (Betker, Szturm, Moussavi, & Nett, 2006), motor functions of the hand (Afyouni et al., 2017) and the upper limbs (Broeren et al., 2008; Yoo, Lee, Sim, You, & Kim, 2014), for instance. Motor rehabilitation games take a restitution-based rehabilitation approach, in which the aim is to restore impaired functions through intense and repeated stimulation of that function (Wolf, Blanton, Baer, Breshears, & Butler, 2002). Consequently, the application of serious games in physical rehabilitation benefits from the motivational and engaging components of video games. Furthermore, adaptive difficulty systems implemented through game mechanics, allow for the presentation of adequate challenges, further tailoring to the need of patients in the program.

Serious gaming in cognitive rehabilitation is less common. As of now, several serious games in cognitive rehabilitation have been developed with the intention of directly training cognitive functions by incorporating mental exercises in games ('brain training'). Brain training games such as "Lumosity" aim to strengthen attention, working memory and executive (Sternberg et al., 2013). The approach taken in these programs is similar to the restitution-based rehabilitation approach taken in serious games for motor rehabilitation, as patients repeatedly perform short task with increasing difficulty. Most brain training games have been developed for healthy elderly and persons with mild cognitive impairments. Randomized controlled trial studies have been performed to assess the effectiveness of brain training games in patients with cognitive impairments as a result of brain injuries. Evidence for the effectiveness of these brain training games in this population is inconclusive, as the effects of the training generally do not generalize beyond the training itself (van de Ven et al., 2017; Zickefoose, Hux, Brown, & Wulf, 2013).

Contrary to restitution-based rehabilitation, compensation-based rehabilitation has not been thoroughly explored with serious games. Compensation training is based on the concept that cognitive deficits can be overcome by substituting different latent skills or by acquiring new skills (Dixon & Bäckman, 1999). Compensatory training is one of the most important techniques in neurologic rehabilitation of acquired brain injury (Cicerone et al., 2000; Cicerone et al., 2005; Cicerone et al., 2011). Accordingly, the Cognitive Rehabilitation Task Force of the American Congress of Rehabilitation Medicine Brain Injury Interdisciplinary Special Interest Group has recommended compensation training as standard practice for memory impairments after traumatic brain injury and stroke (Cicerone et al., 2011).

Serious games designed to train compensation strategies will have additional design considerations compared to games designed to stimulate engagement. Aside from the affective components, emphasis is placed on the cognitive and educational components of the applications. Compensation strategies trained in serious games need to be transferred to daily activities. This requires patients to have a general understanding of the cognitive function that will be compensated and their own impairments regarding this function. Novel strategies will need to be introduced and trained. Finally, patients need to learn how and when a novel strategy can be applied in real-life situations (Geusgens, Winkens, van Heugten, Jolles, & van den Heuvel, 2007).

In the current project, we have developed a serious game for the rehabilitation of spatial navigation impairments after acquired brain injury. Navigation impairments are common among stroke patients and have profound effects on the quality of life, as patients experience reduced mobility, autonomy and spatial anxiety (van der Ham et al., 2013). Even though navigational impairments in stroke patients are prevalent, no standardized rehabilitation training is currently available. A recent article advocates a compensatory approach to the rehabilitation of navigation impaired patients (Claessen, van der Ham, et al., 2016). Instead of focusing on the rehabilitation of impaired cognitive function (such as memory or attention), The authors propose that the rehabilitation training should focus on training patients to use an alternative navigation strategy. Claessen, van der Ham, et al. (2016) identified patients' impaired components of the navigational ability through an extensive diagnosis procedure in a simulated virtual environment. Based on a profile resulting from this diagnosis, patients were trained to adopt a more advantageous navigation strategy in a series of virtual reality therapy sessions provided by a neuropsychologist. The results of the navigation compensation training were promising, as patients reported that they successfully adopted novel navigation strategies in real-life situations and improved on the trained navigation abilities.

As an extension to this therapy, we have developed a serious game that trains compensatory strategy use by providing multiple navigation exercises in combination with psycho-education. The goal of this serious game is to change patients' navigation strategy in order to improve their navigation ability in daily life. The key concepts of the virtual reality therapy are adapted into a serious game that can be used at home, without supervision of a therapist. In order to ensure the usability of the application by the target patient population, an extensive user interaction test was conducted. In this usability study, three core principles of the application were examined: interaction in 3D environments, instruction modality and feedback timing.

The game's training components take place in open, 3D environments, which patients view and interact with from a first-person perspective. In order to promote presence and stimulate the transfer of skills trained in the game, unrestricted, realistic movement in 3D environments is required. Effective movement within the 3D environments requires intuitive and accessible human–computer interaction. The manner in which users use buttons and sensors of input devices to control software events is referred to as a control scheme. Effective control schemes are believed to have a positive effect on game performance and the affective components of a game such as enjoyment, frustration and feelings of competence (Limperos, Schmierbach, Kegerise, & Dardis, 2011; McEwan, Johnson, Wyeth, & Blackler, 2012; Rogers, Bowman, & Oliver, 2015; Shin & Chung, 2017). Furthermore, input modality can affect working memory, presence and experienced realism during gameplay (Kent, Marraffino, Najle, Sinatra, & Sims, 2012; Shafer, Carbonara, & Popova, 2014; Shin & Chung, 2017). In terms of compensatory strategy training, suboptimal movement control might frustrate patients, reduce engagement, and shift attention away from the educative goals of the exercises. The first aim of current experiment was to assess the subjective experience and objective performance of movement in 3D environments using two simple movement control schemes.

The navigation training application consists of different training games. In each of the games a specific spatial skill is trained. In order for patients to integrate these skills into a compensatory strategy, patients require knowledge about the concepts that underlie the training. The concepts used in spatial cognition (e.g., egocentric navigation, mental mapping, landmark knowledge, etc.) can be particularly hard to grasp for the average user. Therefore, it was important that instructions and background information about the training concepts were presented in a format that was easy to understand for patients. As the games were presented on a multimedia computer, we had the option of presenting information using text-based or video-based instructions. Video-based instructions have the advantage of conveying graphical information supporting a narrative verbal instruction, which can be particularly useful for illustrating concepts in spatial cognition. However, the stream of information from videos might exceed the processing capacity of viewers and have an adverse effect on comprehension and knowledge organization (Chiu et al., 2018; Mayer & Moreno, 2003). This might be of importance as working memory is particularly vulnerable for impairment after acquired brain injury (Christodoulou et al., 2001; McDowell, Whyte, & Desposito, 1997). Consequently, we expected that the self-pacing nature of text-based information would allow for a more optimal transfer of knowledge in acquired brain injury patients. The second aim of the study was to determine whether text-based instructions are more effective than video-based instructions by assessing objective performance and subjective preferences in an instruction comprehension task.

Feedback presentation is an important component of effective serious game design (Charsky, 2010; Garris et al., 2002; Yusoff et al., 2009). The type, amount and timing of feedback has been shown to be of influence on learning efficacy and motivation in computer-based learning (Erhel & Jamet, 2013). The effect of feedback timing is often studied in the context of knowledge and skill assessments, where feedback is given directly after an answer is given or after a delayed period of time. Advantages and disadvantages of feedback timing on learning efficiency have been identified. Direct feedback allows learners to instantly correct erroneous responses, contributing to knowledge acquisition (Kulik & Kulik, 1988). However, processing direct feedback competes with cognitive resources required for learning process and can disrupt the learning process (Schooler & Anderson, 2008). Inversely, delayed feedback has been shown to facilitate knowledge retention over longer periods of time, but performance during knowledge acquisition is reduced (Shute, 2008). Feedback timing effects have predominantly been studied in educational scenario's such as classroom settings, quizzes and programming courses. In these scenario's responses can be directly evaluated and responses are often clearly correct or false. Less is known about the effects of feedback timing in games where skills are taught through interaction with a virtual game world. Responses are seldom binary in games, but rather expressed in a variable such as a score. Therefore, scoreboards are often implemented to allow users to monitor their performance during the gameplay. The timing and prevalence of this scoreboard can be controlled.

The current study focused on two methods of feedback timing: cumulative feedback and delayed feedback. Cumulative feedback refers to the explicit presentation of a patient's overall performance during gameplay. Cumulative feedback is shown directly after completing each challenge on an interval basis. Delayed feedback refers to explicit presentation of a patient's overall performance after gameplay. The third aim of the study was to determine whether feedback timing affects objective performance and motivation (engagement and self-efficacy) during a navigation strategy training game. Cumulative feedback has been shown to positively affect performance in a working memory task compared to a no feedback condition (Adam & Vogel, 2016). Furthermore, cumulative feedback is similar to direct feedback described in more traditional feedback timing studies in the sense that patients can adjust their behaviour during tasks. We hypothesized that cumulative feedback leads to increased performance during gameplay compared to delayed feedback.

The serious game will serve as a home-based rehabilitation treatment which patients will use over an extended period of time without supervision. In this usability study, three core principles of the application were examined: interaction in 3D environments, instruction modality, and feedback timing. As the game required patients to interact with 3D virtual environments, we have determined what type of movement control was most intuitive: mouse-controlled movement or keyboard-controlled movement. In order for the training to be effective, an understanding of complex spatial concepts was required. We therefore determined what instruction modality was most effective for the acquisition of knowledge in acquired brain injury patients: video-based instructions or text-based instructions. Furthermore, we have determined how performance and perceived competence were affected by cumulative and delayed feedback. Finally, as the serious game was designed to be effective for all patients with brain injuries, regardless of the nature of the brain injury, we assessed whether differences between brain injury types exist in the appreciation of the application.

Materials and Methods

Patients

A total of 30 acquired brain injury patients participated in the study (**Table 5.1**). All patients were included by occupational therapists at the Department of Rehabilitation of the University Medical Center Utrecht. Inclusion criteria were: (a) clinically diagnosed with acquired brain injury (e.g., cerebrovascular accident, traumatic brain injury, hypoxic-anoxic brain injury), (b) in the non-acute phase of brain injury, (c) between 18 and 80 years of age, (d) capable of operating a computer system using their left or right hand, (e) sufficient communication, comprehension and taxability (judged by an occupational therapist), (f) no visual impairments interfering with the tasks (e.g., blindness, neglect). All participants gave written informed consent before participating in the study. Patients did not receive monetary compensation for study participation.

Table 5.1 Characteristics of patients in study (n = 30).

Variable	
Gender, male N	15 (50%)
Age in years, mean (range)	47.2 (23-68)
Education*, mean (SD)	5.4 (1.07)
Brain Injury Type	
Cerebrovascular accident	16 (53.3%)
Traumatic brain injury	9 (30%)
Brain tumor	4 (13%)
Brain hypoxia	1 (3.33%)
Brain injury location	
Left	9 (30%)
Right	11 (36.67%)
Bilateral	3 (10%)
Unspecified / Unknown	7 (23.33%)
Months after brain injury, mean (SD)	26.43 (52.71)

* Education scores used the Verhage scale. This is a Dutch education classification system including 7 categories (Verhage, 1964): 1= lowest, 7= highest.

This study was exempted from ethical approval by the Medical Ethics Committee of the University Medical Centre Utrecht in accordance with the Dutch WMO law. This study was performed in accordance with the Declaration of Helsinki and the ICH guidelines for good clinical practice.

Tasks and Material

Three tasks were employed to assess different aspects of the software's usability: movement control, instruction modality and feedback timing. Each task was comprised of an objective component, performance on the task, and a subjective component, a questionnaire with questions regarding a patient's user experience (Table 5.2, Table 5.3). Furthermore, a questionnaire was used to assess the menu-interaction experience (Table 5.4). Additional questionnaires were presented at the start and end of the experimental session to measure computer experience and general appreciation, respectively (Table 5.5 and Supplementary Table 5.1).

Table 5.2 Movement control questionnaire (n = 30)

Variable	Question	Mouse* *M* (*SD*)	Keyboard* *M* (*SD*)	*p* [a]
Ease of use	I thought walking around in the environment was easy	4.2 (1.35)	3.33 (1.49)	**< 0.01**
Improvement	Over time I felt I improved at walking around in the environment	4.3 (1.09)	3.9 (1.37)	0.14
Other software	The controls of this application were similar to other software I have used	3.33 (1.77)	2.86 (1.59)	0.11
Enjoyment	I enjoyed walking in the environment	4.24 (1.06)	3.72 (1.22)	**< 0.01**
Presence	I could imagine myself walking in the environment	3.7 (1.26)	3.3 (1.44)	**< 0.05**

*Ratings on a Likert scale with 1 corresponding to "completely disagree" and 5 corresponding to "completely agree". Standard deviations appear in parentheses next to means. [a] Significant differences are printed in bold letters.

Table 5.3 Feedback Timing Questionnaire (n = 21)

Type	Question	Cumulative** M (SD)	Delayed** M (SD)	p*
Interest	I thought the task was interesting	4.33 (0.80)	4.57 (0.93)	0.17
Enjoyment	When I performed the task. I enjoyed myself.	4.38 (1.12)	4.57 (0.98)	0.26
Perceived difficulty	I thought the task was easy	2.90 (1.34)	2.90 (1.41)	0.96
Effort	I put a lot of effort into completing the task	3.86 (1.35)	3.48 (1.25)	0.32
Strive	I did the best I could during this task	4.62 (0.59)	4.48 (0.87)	0.41
Competence	I had the feeling I was good at the task	3.71 (1.27)	3.62 (1.36)	0.69
Accept results	I am content with my performance	3.57 (1.33)	3.52 (1.44)	0.79
Competition	I think my performance was above-average	2.67(1.15)	3.10 (1.37)	0.11
Desire to improve	I wish I was better at the task	3.81(1.36)	3.62 (1.32)	0.47

*Differences between responses in the delayed and cumulative feedback timing condition were compared per item using the Wilcoxon Signed Rank test.** Ratings on a Likert scale with 1 corresponding to "completely disagree" and 5 corresponding to "completely agree". Standard deviations appear in parentheses next to means.

Movement Control

The movement control task was designed to assess usability differences between mouse controlled and keyboard-controlled movement in 3D environments. A virtual environment was created resembling a sandy desert (Fig 5.1). A bordered plateau was placed in the middle of this environment. The plateau consisted of three distinct components: A broad meandering road, a large circular environment and a building consisting of narrow corridors and 8 90-degree turns (Fig 5.2). Three coloured cubes (red, green, blue) were placed in the circular environment. The starting-location was placed at the beginning of the meandering road and the end-location was placed at the end of the corridor inside the building. Following the one-way road lead to the end-location as no junction points or crossroads were present. A geometrically mirrored version of environment was created to facilitate comparable environments for the two movement conditions.

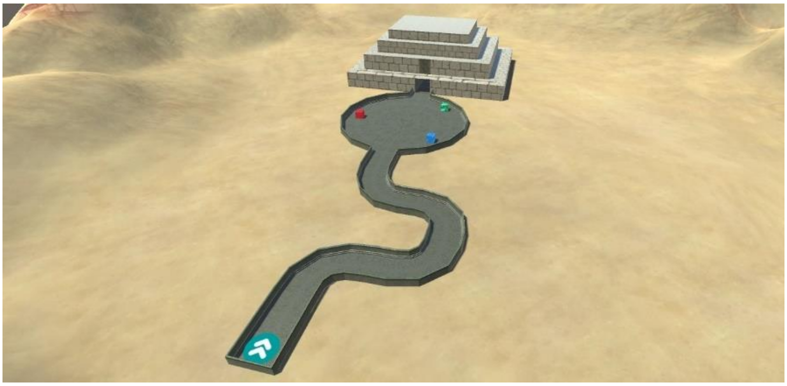

Fig 5.1 Design of the environment used in the movement control task. The environment can be subdivided in a meandering part, a circular area and a building featuring sharp turns. A mirrored version was created to accommodate for the two conditions.

Fig 5.2 Design of the corridor with sharp turns used in the movement control task. The corridors inside the building are made up of 8, 90 degree turns. The blue icon with arrows indicates the entrance of the building. The blue icon with the square indicates the end location of the task.

Keyboard controlled movement was performed by pressing the four arrow keys on the keyboard. “Up” corresponded to forward movement, “down” corresponded to backward movement and the "left" and "right" buttons corresponded to left and right rotation. Mouse controlled movement was performed by using the left and right mouse button and by utilizing the optical sensor. Left mouse button corresponded to forward movement, right mouse button corresponded to backward movement, moving the mouse left or right corresponded with rotation in the respective direction. Similar to the keyboard input condition, participants were unable to look up or down using the mouse. Movement speed was set to 5 in both conditions. This corresponded to a walking velocity of approximately 5 km/hour.

Patients were placed at the start of the meandering road and were asked to travel to the end-location which was placed at the end of the corridors in the building. Before entering the building, all coloured cubes had to be picked up. Cubes were picked up by bumping into them. Patients were instructed to travel to the end-location as fast as possible, without touching the walls. Time required to finish the task (seconds) and number of collisions with the walls were recorded. Patients performed a single trial in each condition. A usability questionnaire was filled in following each movement tasks. This questionnaire measured the following concepts: *ease of use*, *experienced improvement*, *similarity with other software*, *enjoyment and presence* on a 5-point Likert scale (Table 5.2). After both the mouse controlled and keyboard control tasks were completed, patients were presented with an open questionnaire consisting of four questions: (1) What method of movement did you like best? (2) Why did you prefer this method over the other? (3) Do you have suggestions on how we could further improve the movement in the game? (4) What method of movement control would like to see in the training?

Instruction Modality

As the serious game was designed for desktop computers, instructions could be provided using narrated video (tutorial video) as well as more traditional texts. The instruction modality task was designed to assess differences in knowledge acquisition between text-based instructions and video-based instructions. The instructions of 2 existing navigation training games were used ("sense of direction game" and the "map use game"). Text-based and video-based instructions were constructed for both games. In the video version, the text was read aloud by a narrator and supported by a video montage of a person playing the game. In the text version, text was printed on the screen and patients could scroll through the text at their own pace. When presented with the video version, patients were asked to watch and memorize the video. When presented with the text only version of the instructions, patients were instructed to read and memorize the text. No time limit was set. The order in which patients received the video-based or text-based instruction, as well as the combination of instruction modality and version of the game was counterbalanced across patients.

After observing the instructions, patients were shown 12 statements about the objectives of the game and the implications of using the navigation strategy that was trained in the game (**Supplementary Tables 5.2, 5.3**). Patients determined whether these statements were true or false. Following the true or false statements for both instruction modalities, participants answered three open questions: (1) What instruction type did you find most effective? (2) Why did you prefer this type of instructions? (3) Do you have suggestions on how we could further improve the instructions?

Feedback Timing

The feedback timing task was designed to assess the effect of cumulative vs. delayed feedback on performance and motivation during a play-through of a training game. A virtual environment was created resembling a sandy desert. In this middle of the environment, a bordered circular plateau was placed. Two versions of the game were used. In the first version, 4 distinct landmarks were placed in the north, south east and west of the plateau. These landmarks resembled the Horse of Troy, a Greek galley, a Greek temple and the Colossus. In the second version, 3 local landmarks were placed inside of the plateau. The landmarks resembled different coloured pillars (red, green, blue). A hidden goal location was placed on the plateau (**Fig 5.3**).

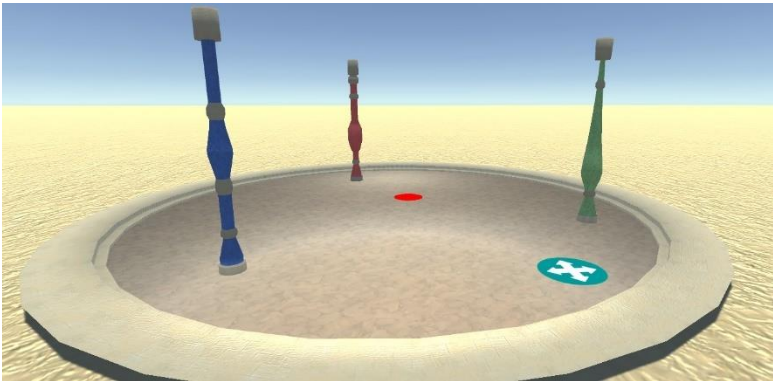

Fig 5.3 Design of the environment used in the feedback timing task. In this version of the task, participants study a map to remember the location of the goal (red dot) in

relation to the landmarks (pillars). Patients were then placed on the starting location (blue dot). The goal and start locations are not visible during a round.

At the start of a trial, a 2D map of the environment was shown on which the hidden plateau and the landmarks were highlighted. Patients were then placed in the 3D environment and were tasked to walk toward the hidden plateau, by orienting on the landmarks. The movement control was similar to the keyboard-controlled movement described in the movement task above. A pedometer bar was shown at the top of the screen to indicate the amount of distance a patient had travelled. The amount of coins in possession corresponded to the size of the pedometer bar. As such, patients were instructed to take as few steps as necessary to reach the end-location. Between 0 and 2 coins could be earned in each round. The goal of the game was to earn as many coins as possible over the course of 3 rounds. In the cumulative feedback condition, a large scoreboard was presented between rounds. This scoreboard showed the percentage of coins collected over the whole trial (so if patients collected 3 coins at the end of round 2, the score would show 75%). The scoreboard allowed patients to monitor their performance of the span of 3 rounds. In the delayed feedback condition, no overall score feedback was given between rounds.

At the end of the three rounds, an overall score was shown in both conditions. The total amount of coins earned was used the measure of performance. After completing a task, patients filled in a questionnaire that measured motivational components related to engagement: *interest in task*, *enjoyment*, *effort invested while playing*, *strive* (I did the best I could during this task), *desire to improve*, and components related to self-efficacy: *perceived difficulty, competence*, *result acceptance*, *comparative score* (Table 5.3). The items were rated on a scale from 1 to 5, 1 corresponding to “completely disagree” to 5 corresponding to “completely agree.”

Additional Measures

The menu interaction task was designed to assess the comprehensibility of the menu structure and phrasing of terms used in the game. Patients were required complete seven tasks by navigating through the menu tabs. In each task, specific information needed to be found or specific actions were required. Patients were asked to conduct the following activities: (1) log in, (2) start a specific game, (3) locate background information about the application, (4) determine the current level on a specific game, (5) start another game, (6) determine the amount of coins (score) currently in possession, (7) quit the application. Patients were instructed to think out loud while navigating the menu screens. When patients navigated to a wrong menu or when they indicated they were unable to find the requested information, the experiment would show the correct method of finding the information. Following the menu interaction task, a usability questionnaire was filled in (Table 5.4). The questionnaire was specifically designed to address layout, comprehensibility and interaction with important items of the menu interface.

The computer experience questionnaire consisted of nine items and was rated on a 5-point Likert scale (Supplemental Table 5.2). The items in this questionnaire were inspired by the Computer Attitude Scale and the Computer User Self Efficacy scale (Cassidy & Eachus, 2002; Nickell & Pinto, 1986). The first four items of this question addressed a patient's exposure to computers. Items 5–8 concerned a patient's self-reported knowledge of operating software and hardware. The ninth item addressed feelings of anxiety when using a computer.

The overall appreciation questionnaire consisted of nine items and was rated on a 5-point Likert scale (Table 5.5). Six items in this questionnaire were adapted from the Flow State Scale and three items constructed in context of the usability test (Jackson & Marsh, 1996). The items addressed the overall appreciation of the application and the experience of flow during the tasks. The items were rated on a scale from 1 to 5, 1 corresponding to "completely disagree" to 5 corresponding to "completely agree."

The tasks were constructed in the Unity 3D game engine, version 5.3.4.4.f1, and run as standalone applications. The application was run on a HP EliteBook 8760w laptop with a NVIDEA Quadro 3000M graphic processing unit. The laptop's screen size was 17.3-inch wide screen (15.5∗ 8.98) inch. The laptop's keyboard and a standard desktop mouse model (Dell Optical Mouse – MS116) were used as input devices. All questionnaires were constructed in Qualtrics and presented using an internet browser.

Procedure

The data was collected in a therapy room of the Department of Rehabilitation of the University Medical Center Utrecht. All patients read the study's information letter in advance and gave written informed consent prior to the session. All experimental sessions were planned prior to or after a patient's scheduled appointment with a doctor or occupational therapist. In order to comply to a patient's schedule during the visit to the medical center, each experimental session was brought to an end after approximately 60 min of testing.

At the start of the experimental session, patients were informed about the nature of the study. Patients were explicitly informed about the study's objective of tailoring the software to patients' capability and needs. As such, patients were encouraged to ask questions about the software, discuss design choices and propose suggestions for changes in the software's design. To stimulate communication with the patients, an informal and relaxed atmosphere was pursued.

The experiment started with the computer experience questionnaire. This was followed by the movement control task, the instruction modality task, the menu navigation task and finally the feedback task. Patients then filled in the overall appreciation questionnaire.

Statistical Analyses

Analysis of Objective Performance

Objective performance in the movement control, instruction modality and feedback timing tasks were analysed using within-subject tests. Data were tested for normality using Kolmogorov–Smirnov tests. Normally distributed data were analysed using a three-way mixed model ANOVAs with (condition) as within subject factor and (brain injury type) and (brain injury location) as between subject factors. Non-normal data were analysed using Wilcoxon signed-rank tests, in which conditions were contrasted. Separate Kruskal–Wallis H Tests were used to assess the effects of brain injury type and brain injury location on performance in non-normal datasets.

Analysis of Subjective Measures

Internal reliability analyses were performed on all questionnaires. Non-parametric tests were used to analyse the effect of condition on subjective measures. Additionally, the proportion of responses for the preference (what condition did you prefer?) items in the open questionnaires were analysed using Chi-square tests of independence. The effects of brain injury type and brain injury location on subjective responses were assessed using Kruskal–Wallis tests.

Exploratory Analysis

Exploratory analyses were performed to inspect the relation between objective performance and subjective measures for the movement control task and the feedback timing task. Pearson correlations analyses were conducted to investigate the relation between objective performance and items of the subjective measure questionnaires.

Attrition

Six patients were unable to complete all tasks of the experiment within 60 min. Additionally, 2 patients were unable to complete the instruction modality task due to reading impairments. One patient was unable to complete the feedback timing task due to severe navigation impairments. Technical difficulties lead to missing data of 1 patient in the movement control task and 2 patients in the feedback timing task. As such, the sample size for the objective performance analysis for the movement task was 29 (30 for the subjective measures), the sample size of the instruction task was 27(29 for the preference response) and the sample size of the feedback timing task was 21.

Results

Movement Control

In order to compare objective movement performance in the mouse and keyboard controlled conditions, time required to finishing the task (time) and the number of collisions with the walls (wall bumps) were analysed as main measures. A Kolmogorov–Smirnov test indicated that the data for time (mouse), $D(29) = 0.21$, $p < 0.01$ and wall bumps (keyboard), $D(29) = 0.17$, $p < 0.05$, were both significantly non-normal.

A Wilcoxon signed-rank test revealed that time in the mouse control condition ($M = 85.29$, $SD = 44.19$) was significantly shorter than time in the keyboard control condition ($M = 132.42$, $SD = 58.63$), $z = -4.68$, $p < 0.01$, $r = -0.61$ (Figure 4). No significant effects of condition were found on the number of wall bumps $z = -0.92$, $p = 0.36$, $r = -0.12$. Additional Wilcoxon signed-rank tests were performed to compare the effects of movement control type within in the three sections of the environment. Mouse controlled movement was faster than keyboard-controlled movement in the meandering area ($p < 0.01$) the circular area ($p < 0.01$) and the area with the sharp turns ($p < 0.01$) (**Fig 5.4**).

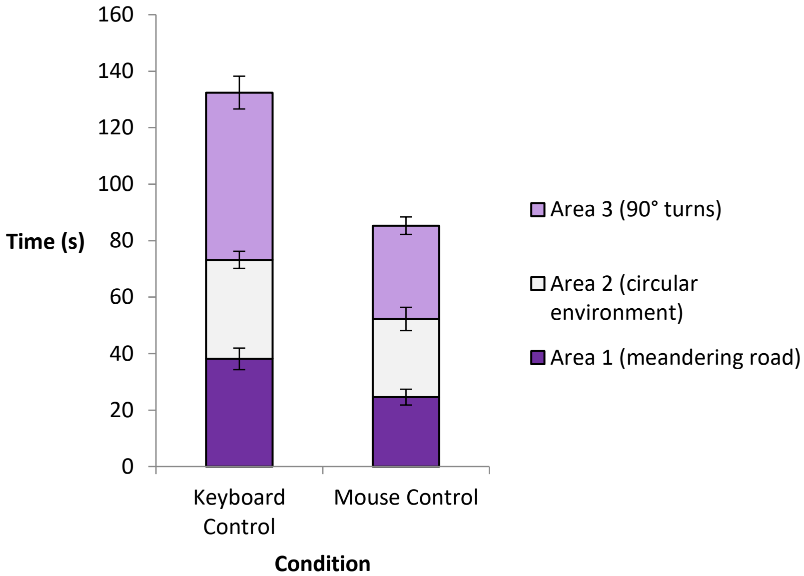

Fig 5.4 Performance on the movement task for keyboard and mouse-controlled movement (n=29). The average time spend (seconds) in each area is indicated by the different coloured stacks in the graph. The error bars represent the standard error of the mean

A Kruskal–Wallis *H* Test revealed that there was no effect of brain injury type on performance in the keyboard ($\chi^2(3) = 3.71, p = 0.29$) and mouse controlled ($\chi^2(3) = 5.49, p = 0.14$) movement tasks. Similarly, no effect of brain injury location was found on performance in the keyboard ($\chi^2(3) = 1.99, p = 0.57$) and mouse controlled ($\chi^2(3) = 2.94, p = 0.40$) movement task.

After completing the movement task, patients filled in a subjective preference questionnaire. A reliability analysis was performed and revealed an internal reliability of $\alpha = 0.85$ for the keyboard condition and $\alpha = 0.69$ for the mouse condition. Each of the 5 items of the questionnaire were compared for the mouse control and keyboard control condition using a Wilcoxon signed-rank test. A significant effect of condition was found for ease of use, as the mouse controls ($M = 4.2$, $SD = 1.35$) were rated as easier to use than keyboard controls ($M = 3.33$, $SD = 1.49$), $z = -2.67$ $p < 0.01$, $r = -0.34$. Mouse control ($M = 4.24$, $SD = 1.06$) was also rated as significantly more *enjoyable* than keyboard control ($M = 3.72$, $SD =$

1.22), $z = -2.67$, $p < 0.01$, $r = -0.34$. Furthermore, a higher level of *presence* was experienced during mouse-controlled movement ($M = 3.7$, $SD = 1.26$) compared to the keyboard control ($M = 3.3$, $SD = 1.44$), $z = -2.36$, $p < 0.05$, $r = -0.30$ (**Table 5.2**).

Analysis of the open questionnaire revealed that 90.0% of the patients reported a preference for mouse controls, 10% of the patients reported a preference of keyboard control and 0% of the patients did not have a clear preference. A Chi-square test of independence revealed a significant difference in proportions, $\chi^2(1) = 19.20$, $p < 0.01$.

Using Spearman correlation analyses, the relation between objective performance (time) in the movement tasks and the ratings on the 5 items of the questionnaire was explored. A correlation between objective performance and *enjoyment* was found for both the mouse control, $r = 0.43$, $p < 0.05$, and keyboard control $r = 0.39$, $p < 0.05$, conditions. Additionally, a correlation between objective performance and *presence* was found for both the mouse control, $r = 0.41$, $p < 0.05$, and keyboard control $r = 0.40$, $p < 0.05$, condition.

Instruction Modality

In order to determine the effect of instruction modality on learning, patients answered 12 true of false questions about the content of the instructions. Percentage correct was compared for the video-based and text-based condition. A Kolmogorov–Smirnov test indicated that the video-based instruction data was significantly non-normal $D(27) = 0.19$, $p < 0.05$. A Wilcoxon signed rank test was used to compare percentage correct for the video-based and text-based condition. No significant effect of instruction modality was found, $z = -0.82$, $p = 0.41$, $r = -1.12$. Percentage correct did not differ between the video-based ($M = 70.20$, $SD = 15.64$) and text-based ($M = 66.13$, $SD = 17.25$) condition.

A Kruskal–Wallis *H* Test revealed that there was no effect of brain injury type on percentage correct in the video-based ($\chi^2(2) = 1.78$, $p = 0.41$) and text-based ($\chi^2(2) = 1.01$, $p = 0.60$) conditions. Furthermore, no effect of brain injury location was found on the percentage correct in the video-based ($\chi^2(3) = 0.9$, $p = 0.83$) and text-based ($\chi^2(3) = 1.09$, $p = 0.78$) conditions.

The proportion of self-reported instruction preference was investigated using a chi-square test of independence. 65.51% of participants indicated a preference for the video-based instructions compared while 20.69% of the patients preferred the text-based instructions. 13.79% of the participants did not have a clear preference. The chi-square test revealed that this difference in proportions was significant, $\chi^2(2) = 13.72$, $p < 0.01$.

Feedback Timing

The effect of feedback timing on objective performance was investigated by comparing the total amount of coins between the cumulative and delayed feedback condition. The total score was calculated by summing the amount of coins over three rounds for the cumulative feedback (M = 3.48, SD = 1.63) and delayed feedback (M = 3.95, SD = 1.75) tasks (**Supplementary Table 5.4**). A Kolmogorov–Smirnov test indicated that the total score (cumulative), $D(21) = 0.15, p = 0.2$ and total (delayed), $D(21) = 0.17, p = 0.14$ were normally distributed.

A three-way repeated measures ANOVA was performed to compare the effect of feedback timing on total score in the delayed and cumulative feedback condition with brain injury type and brain injury location as between subject factors. No significant main effect of condition was found $F(1,12) = 0.13, p = 0.27, \eta_p^2 = 0.10$. No significant interaction effect was found for brain injury type and condition ($p = 0.41$) and brain injury location ($p = 0.73$).

After completing the feedback timing task, patients filled in the motivation questionnaire. Each of the 9 items of the questionnaire were compared between the cumulative and delayed feedback conditions using a Wilcoxon signed-rank test. No significant effect of condition was found in any of the items (**Table 5.3**).

In an explorative analysis, the relation between objective scores on the feedback tasks and ratings on the questionnaire were analysed using Spearman correlations. In delayed feedback condition, a significant relation was found between objective score and ratings in *perceived difficulty*, $r = 0.59, p < 0.01$, *competence*, $r = 0.55, p < 0.01$, *result acceptance*, $r = 0.74, p < 0.01$ and *competition*, $r = 0.73, p < 0.01$. The subjective raring on the items correlated in a positive linear fashion with the objective score.

Similar relations were found between objective score and self-reported ratings on the cumulative feedback condition. Objective score significantly related to *perceived difficulty*, $r = 0.61, p < 0.01$, *competence*, $r = 0.64, p < 0.01$, *result acceptance*, $r = 0.72, p < 0.01$ and *competition*, $r = 0.57, p < 0.01$. The subjective raring on the items correlated in a positive linear fashion with the objective score. Additionally, a strong negative relation was found between *desire to improve*, $r = -0.65, p < 0.01$, and objective performance. The rating on the desire to improve item correlated negatively with objective score in linear fashion.

Additional Measures

After performing the menu interaction tasks, patients rated the usability of the menu navigation (Table 4). The 11-item questionnaire showed a high internal reliability of α = 0.81. An overall score of the menu-navigation was computed by averaging the ratings of each item. A Kruskal–Wallis test was conducted to compare appreciation ratings between brain injury type and between brain injury location. No effect of brain injury type or location was found on the ratings on the overall menu interaction questionnaire.

The overall appreciation questionnaire was filled in at the end of the session to obtain ratings of overall appreciation and the experience of flow (Table 5.5). The 9 items of this questionnaire yielded a reliability rating of α = 0.76. An overall rating of appreciation questionnaire was computed by averaging the ratings of each item. A Kruskal–Wallis test was conducted to compare usability rating between brain injury types and brain injury locations. No effect of brain injury type or location was found on the ratings on the overall appreciation of the game.

Table 5.4 Menu-interaction experience (n = 29)

Statement	Response* *M* (*SD*)
The text was easy to read	4.41 (1.09)
The information was placed where I expected it to be	4.14 (0.88)
The color and layout used in the application was distracting**	4.62 (0.78)
The terms used in the application were comprehensible	3.93 (1.36)
I understood what was meant with the term "levels"	4.38 (1.12)
I knew what the training was about by reading the names of the games	3.89 (1.26)
It was easy to navigate between different menus	4.03 (1.27)
It was easy to view the progression that was made on different challenges	3.97 (1.35)
I thought logging in was difficult**	4.48 (1.24)
Controlling the application was easy to learn	4.69 (0.81)
Learning what the terms meant was easy	4.14 (1.30)

*Ratings on a Likert scale with 1 corresponding to “completely disagree” and 5 corresponding to “completely agree”. Standard deviations appear in parentheses next to means. **Data shown on a reversed scale, higher scores indicate higher ratings of usability.

Table 5.5 Overall appreciation questionnaire (n = 24)

Variable	Statement	Response* *M* (*SD*)
Ease of use	The software was use to use	3.63 (0.25)
Enjoyment	I enjoyed the experience	4.17 (0.23)
Clear goals	The goals were clearly defined	4.00 (0.24)
Rewarding	The experience was rewarding	3.92 (0.22)
Control	I had a feeling of total control	3.29 (0.26)
Attention	My attention was completely directed on the task at hand	4.79 (0.10)
Concentration	I was concentrated	4.54 (0.19)
Willingness to play again	I would like to play the game again	4.13 (0.23)
Challenge	The game was challenging	4.08 (0.21)

*Ratings on a Likert scale with 1 corresponding to “completely disagree” and 5 corresponding to “completely agree”. Standard deviations appear in parentheses next to means.

Discussion

The usability of a serious game designed to train compensatory navigation strategies in acquired brain injury patients was investigated. The usability of three core principles of the application was examined using objective and subjective measures: movement control, instruction modality and feedback timing.

Intuitive control schemes in games contribute to motivation, engagement and reduction of cognitive load (Limperos et al., 2011; McEwan et al., 2012). The importance of responsive controls in serious games has been identified by several guidelines and frameworks concerned with usability (Pinelle, Wong, & Stach, 2008). In order to optimize interactivity with the virtual environments used in the game, two control types were assessed: mouse and keyboard. The acquired brain injury patients clearly preferred mouse-controlled movement over keyboard controlled movement. Mouse controlled movement was rated easier to use, more enjoyable and a stronger feeling of presence in the environment was experienced. While there is no consensus about the positive effects of presence in training programs, several studies have suggested that high levels of presence might aid in the transfer of skills acquired during the training (Alexander, Brunyé, Sidman, & Weil, 2005; Stevens & Kincaid, 2015; Youngblut & Huie, 2003). The advantages of mouse-controlled movement over keyboard controlled movements were reflected in the objective performance measurements. Time required to finish the tasks was lower is using the mouse, while the number of wall collisions between control type did not differ. This indicates that patients did not lower accuracy in favour of speed when using mouse controlled input. Additionally, mouse controlled movement was faster in all three areas of the environment, revealing that the advantages of mouse movement were not specific to a single manoeuvre, such as taking sharp turns. An exploratory analysis revealed a positive relation between objective performance and ratings of enjoyment and presence in the environment in both movement control conditions. This finding further supports the notion that effective interaction results in a more enjoyable and natural gameplay experience. In sum, the implementation of simple, mouse-controlled movement in 3D environments is recommended over keyboard-controlled movement based on objective and subjective evidence in this study.

Unrestricted movement in virtual environments allows patients to develop and experiment with novel navigation strategies. However, patients can only progress through the game when specific strategies are successfully adapted. It is therefore important that the underlying concepts of the compensatory strategies are clearly communicated. Computers are multimedia systems that allow for different instruction modalities. In the current experiment, we examined the effects of video-based and text-based instruction on knowledge acquisition. No clear learning advantages of video-based instructions over text-based instruction were found. Similar results are found in studies that assess knowledge acquisition of complex topics (the news) through printed text and video (Furnham & Gunter, 1985; van der Molen & van der Voort, 2000). While the results do not indicate an advantage for either modality, a clear preference for the video-based instructions was found in the questionnaire responses. During conversations with the patients about their preferred instruction modality, patients mentioned the advantage of visual information in explaining spatial concepts. This discrepancy between performance and preference can be explained in terms of cognitive capacity. Patients recognized that more information was presented to them in the video condition compared to the text condition. However, this additional information was not effectively maintained. We suspect that the continuous stream of information in the instruction video might have disrupted the information encoding process. Capacity constrains were not limited to the video-based instructions. Two patients were unable to complete the text-based instruction task due to their impairments. While these patients were able to read short texts, they were incapable of maintaining their attention when reading extensive bodies of text. The overload of cognitive capacity can be managed by providing patients with additional control over the pacing of the video (Mayer & Moreno, 2003). The aim for the instructions in the current game is to provide short and effective information before starting a gaming module. In this context, requiring patients to systematically analyse a video might not be an optimal solution. Subsequently, the addition of visual static images to text-based instructions might be more effective than both video-based and solely text-based instruction. This suggestion is supported by studies with healthy subjects (Mayer et al., 2005). More research is required to determine if this combination will indeed enhance knowledge acquisition in acquired brain injury patients. Overall, in this study we have established that patients prefer video-based instructions over text-based instructions. Video-based instructions are not more effective in context of knowledge acquisition and comprehension.

Feedback presentation is an important component in education and serious gaming (Charsky, 2010; Garris et al., 2002; Yusoff et al., 2009). Contrary to our expectation, we did not find a beneficial effect of cumulative feedback on objective performance. Updating patients on their overall score between rounds did not enhance performance in the task. Furthermore, the motivational components of the game were not affected by the timing of feedback as cumulative feedback did not affect engagement and self-efficacy. An earlier study showed beneficial effects of cumulative feedback on performance in a working memory tasks when compared to a no-feedback condition (Adam & Vogel, 2016). There might be several reasons why this effect was not observed in the current study. First, the current task included only 3 trials per condition, whereas Adam and Vogel (2016) employed 150 short trials. It is possible that the beneficial effects of cumulative feedback only arise after participants are familiar with the task and start performing at a stable level. In the current task, it is possible that participants were still experimenting with strategies to complete the task. Second, the current task was considerably more complex than the working memory task employed by Adam and Vogel (2016). This might have lead to a greater variation in performance in both feedback timing conditions. Another explanation for this finding is that patients were not heavily invested in their performance within the game, as patients were explicitly informed that the goal of the study was to test the usability of the application. However, further analysis revealed positive linear relations between objective score and result acceptance ("*I am happy with my performance*"), indicating that patients were indeed concerned with their score. The exploratory analysis also revealed a negative linear relation between willingness to improve ("*I wish I was better at the task*") and the objective score in the cumulative feedback condition. This finding hints at a subtle effect of cumulative feedback on motivation. It is, however, unclear whether this effect is beneficial or disadvantageous, as this statement can be interpreted as a lack in confidence induced by the feedback or an increase in motivation to perform better. Overall, the current experiment did not provide evidence for the advantageous learning or motivational effects of cumulative feedback over delayed feedback.

Interaction with the menu screens and the overall appreciation of the game were evaluated positively. Importantly, neither the type of brain injury nor the location of the brain injury affected ratings on the appreciation and menu interaction questionnaires. Similarly, no effect of brain injury location and type were found on any of the objective tasks. The results suggest that the overall design and interaction with the serious game was suitable for all types of brain injury patients in the sample.

Summarizing, in this study we have established what design choices should be made in order to enhance the usability of a serious game designed to train navigation strategies.

From this first study, we can conclude that mouse-controlled movement in 3D environments is more accessible than keyboard controlled movement. Video-based instructions are strongly preferred over text-based instructions, but not more effective in transferring knowledge. Feedback timing did not affect performance and motivation in the current training games. Based on the scores and usability questionnaires, the results suggest that usability of the serious game is adequate for the target patient population after the implementation of the appropriate features as determined in this study.

Author Contributions

MvdK, JV-M, and IvdH developed the theoretical framework and conceived of the presented idea. JV-M contributed to organizing the experiments. MvdK carried out the experiment. MvdK wrote the manuscript with support from AE, JV-M, and IvdH. AE, JV-M, and IvdH provided critical feedback on the drafted manuscript. AE, JV-M, and IvdH supervised the project.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary Material

Supplementary Table 5.1 Computer experience questionnaire.

Question/Statement	Response** mean (SD)
Based on the past year … (ranging from yearly to daily)	
How often do you use a computer	4.43 (1.10)
How often do you play video games	1.9 (1.35)
Hof often do you use the arrow keys when playing videogames	1.57 (1.14)
How often do you use a joystick or controller when playing videogames	1.63 (1.13)
Please answer:	
I know how to start a computer	4.83 (0.75)
I know how use a computer mouse	4.83 (0.59)
I know how to use text editing software	4.53 (1.25)
I know how to use the internet to find things	4.87 (0.73)
I feel stressed when I use the computer*	4 (1.46)

*Data shown on a reversed scale. **Ratings on a Likert scale with 1 corresponding to "completely disagree" and 5 corresponding to "completely agree". Standard Deviations appear in parentheses next to means.

Supplementary Table 5.2 Questions following instruction text/video for game A

Nr.	Question
	Sense of direction game
1	In this task I train my memory of landmarks (false)
2	I can confirm my pointing direction by pressing "Enter" key (false)
3	Whenever I have to point towards the stone a green arrow will appear (true)
4	The stone is located in the starting room (true)
5	If I point directly towards the stone I earn 1 coin (false)
6	I have to remember where the ending location is (true)
7	When the wall become transparent I can reorient myself (true)
8	When I use this strategy in the real world I do not have to remember landmarks (true)
9	I can imagine my sense of direction as a compass pointing to a certain location (true)
10	It is important I form a mental map of the environment (false)
11	I have to remember the layout of the corridors (false)
12	When I have to point to the stone I can always walk back (false)

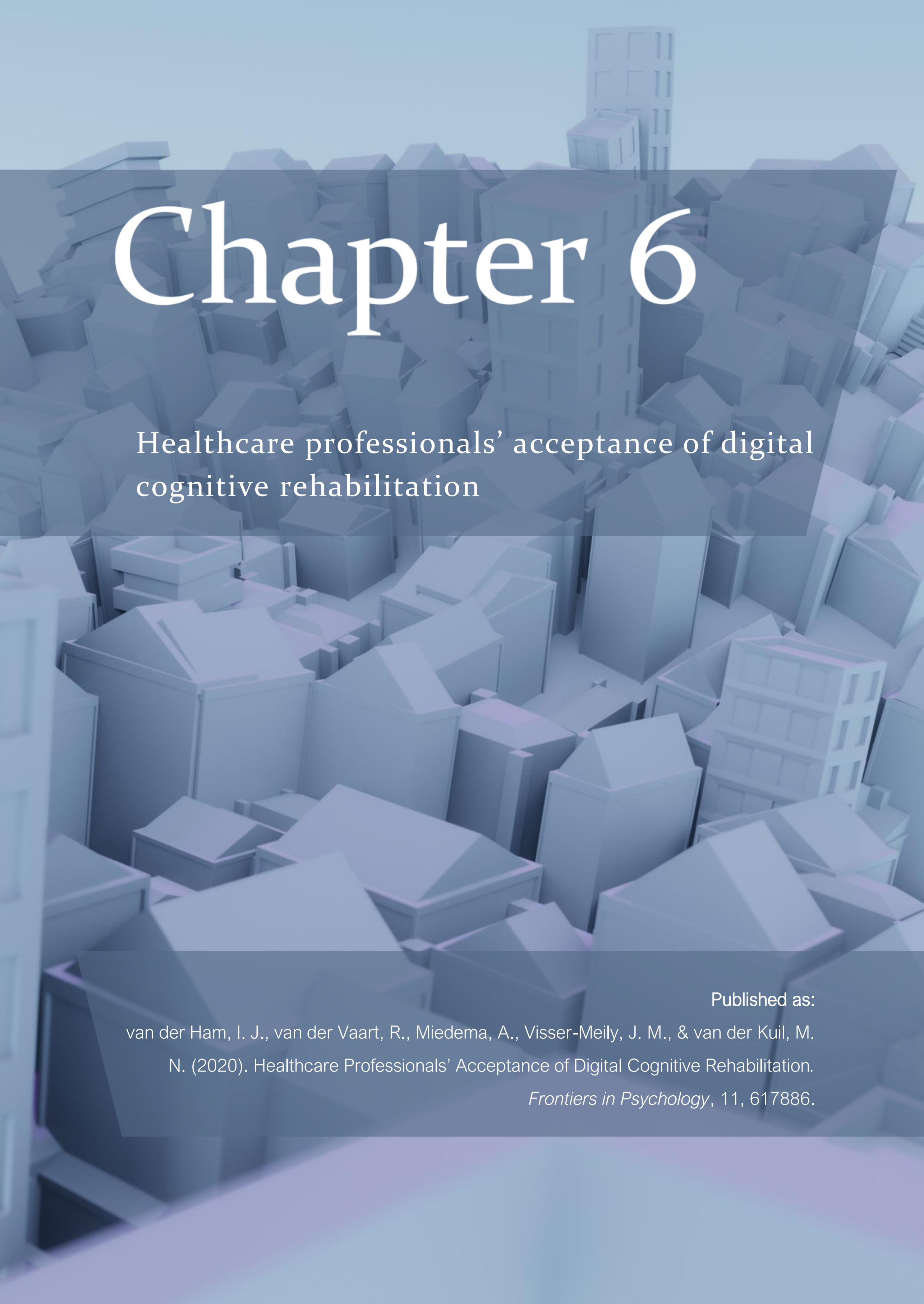
Supplementary Table 5.3 Questions following instruction text/video for game B.

Nr.	Question
	Map use game
1	In this task I train my sense of direction (false)
2	In this task I learn how to interact with maps (true)
3	I have to walk towards the room containing the minotaurs (false)
4	I must try to visit as few rooms as possible (true)
5	I lose a coin whenever I enter a dead-end corridor (false)
6	The landmarks in the maze are shown on the minimap (true)
7	Planning of the route is important in the last round (true)
8	I have to remember how many minotaurs are in the maze (false)
9	I can use the dead-ends to determine my location on the map (true)
10	If I master this exercise, I will become better at using google maps to navigate in a city (true)
11	The tasks will be easier when there a more rooms in the maze (false)
12	The best strategy is to always turn left (false)

Supplementary Table 5.4 Objective performance in the feedback timing task.

Round	Cumulative Feedback	Delayed Feedback
	mean (SD)	*mean (SD)*
All	3.48 (1.63)	3.96 (1.75)
1	1.00 (0.84)	1.43 (0.93)
2	1.48 (0.87)	1.67 (0.66)
3	1.00 (0.95)	0.86 (0.96)

Average number of coins are shown for each round. Two coins could be collected per round.



Chapter 6

Healthcare professionals’ acceptance of digital cognitive rehabilitation

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Abstract

With technological possibilities in healthcare steadily increasing, more tools for digital cognitive rehabilitation become available. Acceptance of such technological advances is crucial for successful implementation. Therefore, we examined technology acceptance specifically for this form of rehabilitation in a sample of healthcare providers involved in cognitive rehabilitation. An adjusted version of the Technology Acceptance Model (TAM) questionnaire was used, including the subscales for perceived usefulness, perceived ease of use, subjective norm (toward use), and intention to use, which all contribute to actual use of a specific technology. Results indicate a generally favorable attitude toward the use of digital cognitive rehabilitation and positive responses toward the TAM constructs. Only for subjective norm, a neutral mean response was found, indicating that this could pose a potential obstacle toward implementation. Potential differences between subgroups of different age, gender, and professional background were assessed. Age and gender did not affect the attitude toward digital cognitive rehabilitation. Occupational therapists showed lower scores than healthcare psychologists and physiatrists with regard to perceived usefulness, possibly linked to a difference in operational and managerial tasks. The findings of his study stimulate further implementation of digital cognitive rehabilitation, where the role of subjective norms should be specifically considered.

Introduction

A clear increase in the use of technology in rehabilitation is observable over the last decades. Many of the newly developed methods focus on the rehabilitation of motor skills. For instance, robotics, virtual reality, and advanced motor analyses can be used to improve specific motor activities (e.g., Holden, 2005; Nef and Riener, 2005; Howard, 2017). The effective application of such technology for cognitive rehabilitation is currently less common, but is quickly evolving (see e.g., Mantovani et al. , 2020). Within cognitive rehabilitation, technology can be applied to both the content and the format of treatment. In terms of content, cognitive exercises can be digitized, for instance (Schatz & Browndyke, 2002), whereas the format can benefit from communication solutions such as audio or video chat functions to provide care remotely (Kampik, Larsen, & Bellika, 2015). The development of digital treatments is benefitting from widely accessible tools such as virtual reality applications. Recent studies demonstrate the value of such treatment approaches (Claessen, van der Ham, et al., 2016; Edwards, Vess, Reger, & Cernich, 2014; van der Kuil, Visser-Meily, Evers, & van der Ham, 2018), especially in terms of ecologically valid and controllable environments. The traditional approach to rehabilitation involves a team of healthcare professional that provide exercises and instructions for everyday cognitive activities. Commonly, pen and paper workbooks are used to instruct patients, monitor progress, and communicate between healthcare professionals. Notable advantages of digitally based treatments as compared to these traditional counterparts include the automatic and secure storage of test data, highly reliable administration of stimuli, improvements in standardization, and the possibility to administer treatments remotely (Edwards et al., 2014; Kampik et al., 2015; Schatz & Browndyke, 2002). Moreover, the current Corona pandemic situation has accelerated the demand and development of these techniques, which allow for online continuation of treatment (e.g., Hosey and Needham, 2020). Despite the fast increase in the popularity of this form of treatment and its obvious advantages, the implementation of digital cognitive rehabilitation can still be challenging due to various obstacles. Furthermore, this form of rehabilitation extends to a range of clinical applications, including treatment of neurodevelopmental disorders (e.g., Yerys et al., 2018; Voss et al., 2019) Lack of endorsement and lack of acceptance for digital treatment methods among health care providers may pose such obstacles, as their attitude clearly plays a crucial role in the adoption process (Chismar & Wiley-Patton, 2002; Mora, Nevid, & Chaplin, 2008). One factor that could affect health care provider attitude is a critical evaluation of earlier methods of digital cognitive rehabilitation, which often focus on restoration of isolated cognitive functions. However, newer methods are currently introduced, which use a more holistic approach, aimed at increasing participation and offering blended care (e.g., van Heugten et al., 2016; Cogollor et al., 2018). Therefore, the current study is aimed at identifying the attitude of healthcare providers toward digital cognitive rehabilitation, in order to gain insight in this important factor for success of implementing digital cognitive rehabilitation techniques and to pinpoint potential obstacles toward its implementation.

The identification of an individual's attitude toward a specific form of technology can be accomplished by using the "Technology Acceptance Model" (TAM; Davis, 1989). This scale was originally designed to discover the underlying factors causing a negative attitude toward technology. It is based on the notion that the degree of technology acceptance depends on multiple constructs (F. D. Davis, 1989). In 2000, the scale has been updated (Venkatesh & Davis, 2000). Subjective norm, perceived usefulness, and perceived ease of use contribute to the intention to use, which ultimately leads to actual use. Additionally, subjective norm, an evaluation of the preferences of an individual's peers and superiors, is directly related to perceived usefulness (Cheon, Lee, Crooks, & Song, 2012; Chismar & Wiley-Patton, 2002; Dalcher & Shine, 2003; Surendran, 2012; Venkatesh, Morris, Davis, & Davis, 2003).

Individual differences might additionally influence the constructs of the TAM and technology use. Demographic information such as gender and age of potential users had an effect on their degree of acceptance (Abu-Dalbouh, 2013; Almeida, Farias, & Carvalho, 2017; Gartrell, Trinkoff, Storr, Wilson, & Gurses, 2015; Khalifa & Alswailem, 2015; Moore, Rothpletz, & Preminger, 2015; Venkatesh et al., 2003). Given the specificity of the current focus on cognitive rehabilitation and the incongruence in the literature, gender, age, and professional background will be considered in our examination of the attitude of healthcare providers toward digital cognitive rehabilitation.

In our use of the TAM, the mean ratings across the different subscales were explored to assess the current state of healthcare providers' attitude toward digital cognitive rehabilitation. Next, individual items of the questionnaire used were studied in order to identify potential obstacles toward technology acceptance and eventually actual system use. In literature, impact of age, gender, and professional background has been found in some but not all cases, therefore, no clear hypotheses can be formulated and an exploratory approach will be used. Lastly, the outcomes of this study will provide information about the current degree of acceptance for digital cognitive treatments among healthcare providers working in the field of cognitive rehabilitation. The degree of acceptance along with the identification of potential obstacles can be consulted in future implementation of such digital treatment solutions.

Materials and Methods

Participants

The target population for the questionnaire consisted of healthcare providers administering cognitive treatment to patients suffering from cognitive complaints. This particularly includes healthcare providers not only working in care facilities with a specialization in cognitive rehabilitation, such as neurological rehabilitation centers, but also more general facilities such as hospitals. In order to answer the questionnaire adequately, a fluent understanding of the Dutch language was required. No requirements for participation were made based on gender or age. Participants were selected and contacted by the researchers, through professional networks concerning rehabilitation, relevant professional social media groups, and email to direct professional contacts. Dutch as well as Belgian practitioners took part in the questionnaire. Ethical approval for the study was provided by the local ethical committee.

Measures

A questionnaire was used to assess the attitude of healthcare providers toward digital cognitive rehabilitation. The questionnaire was designed based on the core constructs of the TAM and TAM2 (F. D. Davis, 1989; Venkatesh et al., 2003). This included the subjective norm construct as well as this has been shown to directly predict the intention to use technology. Each construct is measured with a separate subscale. In order to answer the main question of the attitude of healthcare providers toward digital cognitive rehabilitation, we examined the scores of each of the subscales of the TAM2 (perceived usefulness – six items, perceived ease of use – six items, subjective norm – three items, and intention to use – two items; for a complete list of questions, see **Table 6.1**). To avoid confusion and to ease comparability to other studies based on the TAM, we defined the constructs in the terms of Venkatesh and Davis (2000). As such, the construct of perceived usefulness was defined as the belief the participant has about the extent the use of the cognitive rehabilitation program will enhance their job performance. The construct of perceived ease of use was defined as the extent to which the participant believes the use of the program will be effortless. The construct of subjective norm was defined as the participants' impression that the use of the program would be or would not be encouraged by peers or superiors important to the respondent. Intention to use referred to the intention to use the technology, provided it is available.

Table 6.1 List of individual items of the questionnaire with mean scores of all participants grouped together.

Subscale	Item	Mean (SD)	t
Perceived usefulness	Using digital cognitive treatments would improve the care I provide	4.80 (1.16)	8.42**
	Using digital cognitive treatments would increase my productivity	4.54 (1.22)	5.42**
	Using digital cognitive treatments would make the care I provide more effective	4.82 (1.18)	8.50**
	Using digital cognitive treatments would be useful for my work	4.99 (1.28)	9.37**
	Using digital cognitive treatments would enable me to provide care for my patients more quickly	4.72 (1.47)	5.95**
	Using digital cognitive treatments would make it easier to provide care for my patients	4.70 (1.32)	6.43**
Perceived ease of use	My interaction with digital cognitive treatments would be clear and understandable	4.27 (1.11)	2.89*
	Interacting with digital cognitive treatments would not require a lot of effort	4.35 (1.11)	3.87**
	I would find digital cognitive treatments easy to use	4.43 (1.08)	4.82**
	I would find it easy to apply digital cognitive treatments for what I want them to do	4.08 (1.36)	0.73
	Learning to provide digital cognitive treatments would be easy for me	5.30 (1.11)	14.16**

	It would be easy for me to become skillful at using digital cognitive treatments	5.29 (1.17)	13.44**
Subjective norm	Most of my patients would welcome me using digital cognitive treatments	4.07 (1.47)	0.56
	My superior(s) think(s) that I should use digital cognitive treatments	4.06 (1.66)	0.45
	Colleagues who are important to me think I should use digital cognitive treatments	3.78 (1.52)	-1.72
Intention to use	If I had access to digital cognitive treatments, I would intend to use them	5.37 (1.36)	13.44**
	If I had access to digital cognitive treatments, I predict I would use them	5.37 (1.29)	12.87**

Each score was contrasted with the neutral value of 4.0 with a Bonferroni corrected one-sample t-test (score range 1-7). *SD* = standard deviation. *p<.01, **p<.001

The questionnaire was supplemented by demographic and job related questions to additionally explore the potential impact of age, gender, and professional background on the attitude toward digital cognitive rehabilitation. Questions were selected and rephrased based on relevance to healthcare providers working in the field of cognitive rehabilitation. We expected the Cronbach's alpha scores of the constructs used in this questionnaire to be similar to the ones found in the originals. This entailed a Cronbach's alpha score of approximately 0.86–0.98 for the perceived usefulness, 0.79–0.98 for the perceived ease of use, 0.81–0.95 for the subjective norm, and 0.82–0.97 for the intention of use (Asua, Orruno, Reviriego, & Gagnon, 2012; Chismar & Wiley-Patton, 2002; F. D. Davis, 1989; Hu, Chau, Sheng, & Tam, 1999; Liang, Xue, & Byrd, 2003; Van Schaik, Bettany-Saltikov, & Warren, 2002; Venkatesh & Davis, 2000; Yi, Jackson, Park, & Probst, 2006). The possible professional backgrounds of the participants were grouped into meaningful response options. Five categories were determined based on the most likely options within our target demographic. These job categories were occupational therapist, physiatrist, healthcare psychologist (post-graduate level), psychologist, and cognitive therapist. An additional "other" category was added to make the item exhaustive.

Procedure

At the beginning of the questionnaire, the participants were given a brief explanation of the purpose of the study. Next, the participants were asked to digitally give their informed consent. First, demographic information including their gender, age, professional background, years as a healthcare professional, years of experience with cognitive rehabilitation, and self-reported internet skills were collected. This was followed by 17 questions to measure the participants' perceived usefulness, perceived ease of use, their subjective norm, and their intention to use the program. These questions were all measured on a 7-point Likert scale following an item phrased as a statement. The scores ranged from 1 (complete disagreement) to 7 (complete agreement), with 4 as the neutral center of the range. Finally, participants were asked additional questions to indicate their preference for several specific design related aspects of a digital cognitive rehabilitation tool developed by the researchers. These last questions were not part of the current study.

Statistical Analysis

The program IBM SPSS Statistics version 25 was used to conduct the analyses. Cronbach's alpha for all subscales was determined by conducting a reliability analysis on all items of the subscale. All mean scores were compared to the neutral centre of the response options (4.0) to evaluate whether or not participants significantly showed agreement or disagreement for each subscale, using Bonferroni corrected one-sample t-tests. Additionally, the individual scores per item were evaluated in the same way, in order to identify potential specific obstacles to the acceptance and use of digital cognitive treatment. Lastly, for gender, age group, and professional background, the nonparametric Kruskal-Wallis H test was performed to identify potential significant differences between groups. For age, participants were divided into three age groups of similar size: younger (<31), middle (31–40), and older (>40). An alpha below 0.05 was considered significant in all analyses and Bonferroni correction was applied in case of multiple comparisons.

Results

Participants

In total, 147 participants completed the questionnaire, with a mean age of 38.2 (*SD* = 10.2, range 22–63). A description of the demographic characteristics and self-reported internet skills of the sample is provided in **Table 6.2**. The sample was skewed in terms of gender, had a sufficiently varied age range, and covered all professional groups included. However, there was only one cognitive therapist among the participants; therefore, this individual was grouped with the "other" category. All participants indicated at least an average level of internet skills.

Table 6.2 Demographic variables of the sample

Variable	**Response option**	**N (%)**
Gender	Female	128 (87.1)
	Male	19 (12.9)
Professional background	Occupational therapist	45 (30.6)
	Psychologist	28 (19.0)
	Healthcare psychologist	30 (20.4)
	Physiatrist	24 (16.3)
	Cognitive therapist	1 (0.7)
	Other*	32 (21.8)
Years as healthcare worker	1-5 years	35 (23.8)
	6-10 years	35 (23.8)
	11-20 years	50 (34.0)
	>20 years	27 (18.4)
Experience cognitive treatment	1-5 years	62 (42.2)
	6-10 years	48 (32.7)
	11-20 years	30 (20.4)
	>20 years	7 (4.8)
Internet skills	Very poor	0
	Poor	0
	Average	19 (12.9)
	Good	69 (46.9)
	Very good	59 (40.1)

*For example, clinical psychologist, and physical therapist.

Subscale Scores

Table 6.3 depicts mean scores for each subscale, along with Cronbach's alpha, and the outcome of the one-sample *t*-tests, comparing the mean scores to 4.0. Results indicate that

Cronbach's alpha was well within the expected ranges for perceived usefulness, perceived ease of use, and intention to use. For all three subscales, the mean score was significantly higher than neutral. Subjective norm, however, showed a lower Cronbach's alpha than expected and did not significantly differ from neutral. Therefore, it is more appropriate to assess scores for the three individual items rather than the subscale as a whole.

Table 6.3 Mean scores for each of the technology acceptance subscales and for all participants grouped together.

Subscale	N items	Mean (SD)	Cronbach's alpha	t (comparison to 4.0)
Perceived usefulness	6	4.76 (1.01)	0.884	9.13*
Perceived ease of use	6	4.62 (0.88)	0.851	8.56*
Subjective norm	3	4.00 (1.20)	0.664	-0.30
Intention to use	2	5.37 (1.25)	0.975	13.31*

Reliability was assessed by calculating Crohnbach's alpha, and each score was compared to the neutral value of 4.0 with a Bonferroni corrected one-sample t-test (score range 1-7). SD = standard deviation. Two-tailed, corrected for multiple comparisons (alpha = .0125), *p<.001

Identification of Possible Obstacles

All individual items were included in a two-tailed, one-sample *t*-test, corrected for multiple comparisons (alpha: 0.05/17 = 0.0029; see **Table 6.1**). All individual items of the subscales perceived usefulness and intention to use had mean scores significantly above 4.0, the neutral center of the scale. For the perceived ease of use, all individual items were significantly higher than 4.0, with the exception of "I would find it easy to apply digital cognitive treatments for what I want them to do." This specifies that general use is perceived as easy, with the exception of the application of the treatment in practice. Furthermore, all three items of the subjective norm were not significantly different from 4.0, indicating that the subjective norm as presented by patients, superiors, or colleagues is not favorable.

Individual Differences

Lastly, the impact of individual differences on the subscale scores was assessed. In **Table 6.4**, all means scores per subgroup are provided for each of the four subscales. As gender was skewed, a Mann-Whitney U test was used as a nonparametric alternative. No significant differences between males and females were found (p > 0.10 in all cases).

Table 6.4 Mean scores for each subscale divided by the subgroups of the sample, based on gender, age group, and professional background.

Factor	Subgroup	N	Perceived usefulness	Perceived ease of use	Subjective norm	Intention to use
Gender	Males	19	4.74 (1.05)	4.60 (1.00)	4.16 (1.12)	5.66 (0.99)
	Females	128	4.77 (1.01)	4.62 (0.86)	3.94 (1.21)	5.33 (1.28)
Age group	Younger (22-30)	41	4.85 (0.87)	4.83 (0.75)	4.01 (1.19)	5.56 (1.19)
	Middle (31-40)	50	4.64 (1.01)	4.55 (0.91)	3.86 (1.33)	5.24 (1.33)
	Older (41-63)	56	4.81 (1.11)	4.52 (0.92)	4.04 (1.09)	5.35 (1.22)
Professional background	Occupational therapists	45	4.33 (1.12)	4.37 (0.87)	3.61 (1.25)	5.06 (1.46)
	Psychologists	28	4.70 (0.97)	4.64 (0.92)	3.92 (1.27)	5.48 (1.19)
	Healthcare psychologists	30	5.05 (0.84)	4.62 (0.86)	4.06 (1.11)	5.42 (1.21)
	Physiatrists	24	5.06 (0.93)	4.76 (0.86)	4.36 (1.01)	5.52 (0.99)
	Other	20	5.04 (0.87)	5.00 (0.79)	4.25 (1.17)	5.68 (1.09)

Standard deviation in parentheses.

To assess the impact of age, the participants were grouped into three age groups, roughly based on the distribution of participants: younger (22–30), middle (31–40), and older (41–63). A one-way ANOVA on the mean scores of the four subtasks did not reveal any significant differences between the three age groups.

A nonparametric approach was also appropriate for the analysis of different professional categories. An independent samples Kruskal-Wallis test was performed and showed that for perceived ease of use, subjective norm, and intention to use, no significant differences were found between professional categories. In contrast, the scores for perceived usefulness were significantly different between professional categories (p = 0.014). A Bonferroni-corrected *post hoc* analysis showed that the scores of the occupational therapists were significantly lower than those of the healthcare psychologists and the physiatrists ($p < 0.05$ in both cases).

Discussion

There is an ongoing increase in the availability of digital cognitive rehabilitation tools with digital applications both in terms of format and content. Technology acceptance is a key in the successful implementation of such treatment protocols as it has been shown to accurately predict actual system use. Here, we studied technology acceptance among healthcare providers in order to answer the main question, concerning the attitude of healthcare providers toward digital cognitive rehabilitation. First, the mean ratings across the different elements of the TAM were explored. Next, individual items of the questionnaire used were studied in order to identify potential obstacles toward technology acceptance and eventually actual system use. Lastly, the impact of individual characteristics including age, gender, and professional background was examined.

First of all, with regard to digital cognitive rehabilitation, health care providers showed convincing levels of agreement with perceived usefulness, perceived ease of use, and the intention to use. In contrast, for the subjective norm subscale, the mean scores showed that this factor is regarded neutrally by our participants. Furthermore, Cronbach's alpha was rather low for this particular subscale. Therefore, it is informative to also consider each individual item. This analysis revealed that for all three sources of subjective norm included – patients, superiors, colleagues – a neutral attitude is present. This presents a potential obstacle toward technology acceptance and eventually actual system use and is therefore an important element in the implementation of digital cognitive rehabilitation tools. The interpretation of this effect could be 2-fold: either subjective norm is not as high as it needs to be to stimulate system use or the subjective norm is neutral because the attitude of peers and superiors is not known. In the first case, establishing a more positive attitude toward digital cognitive rehabilitation, established by, e.g., visible use of such technology and exchange of positive experiences, could promote system use. In the latter case, a more explicit discussion of attitude concerning digital cognitive rehabilitation would be appropriate, e.g., by discussion this in formal meetings and with patient organizations (e.g., Ploeg et al., 2007; Andreassen et al., 2015). In line with this finding, it should be noted that only few effective methods are currently in use, due to recent improvements in terms of content and required technology. A number of methods have been available for longer, but have not been able to show clear positive results as they often focus on restoration of isolated cognitive functions. In contrast, newer methods use a more holistic approach, in which participation and blended care are focused on (e.g., van Heugten et al., 2016; Cogollor et al., 2018). Only a limited number of studies are currently available for effective cognitive digital cognitive rehabilitation due to its novelty and the need of follow-up study (e.g., Larson et al., 2014; Mansbach et al., 2015). The process of creating a positive subjective norm is hindered by the scarcity of successful and commendable methods. Furthermore, there is substantial variation in the application of cognitive rehabilitation, in terms of, e.g., pathology, patient characteristics, and specifications of cognitive deficits. Combined with the observation that scores are especially high for the intention to use items, this suggests that health care providers are highly willing to use effective novel methods for digital cognitive rehabilitation, which are not yet widely available. In line with this, implementation strategies that target subjective norms are recommended, e.g., gradual implementation of novel technology, starts with a small group of enthusiastic users (e.g., De Veer et al., 2011).

In the creation of the TAM2, demographic factors were included, with a direct relationship to perceived ease of use (Venkatesh et al., 2003). However, findings on the impact of these factors have been contradictory. Gender may affect the overall acceptance of technology, with a higher level of acceptance of digital therapeutic tools for males, in comparison to females (Mora et al., 2008). In contrast, Khalifa and Alswailem (2015) found that gender did not have a significant influence on the satisfaction of a system. With regard to age, Mora et al. (2008) report a specific age effect for digital chat sessions replacing tradition face-to-face treatment. Psychologist with an older age was more accepting. Similarly, Gartrell et al. (2015) found that older nurses' approval of an electronic health record for patients was higher in comparison to younger nurses. However, Schnall and Bakken (2011) found no significant relationship between the age of the user and their acceptance for health information technology. In addition to age and gender, professional background can be of impact in acceptance of healthcare technology. Khalifa and Alswailem (2015) found that especially pharmacists and physicians were less inclined to endorse health information technology, while nurses, technicians and administrators did not differ from one another. R. van der Vaart, Atema, and Evers (2016) found that mental health counselors tended to have a higher use as well as intention to use online interventions than primary care psychologists. In contrast, Schnall and Bakken (2011) have found no relationship between the professional backgrounds of several different employment classes working in healthcare. These different professional backgrounds included several management positions, social workers, and case follow-up workers. In short, literature is unclear about the impact of demographic variables; therefore, an examination of individual differences was performed. It should be noted that gender did not affect any of the subscales included. Therefore, gender is not expected to have a substantial contribution to actual system use. Age of the health care provider also did not show any effect on the degree of agreement to any of the four subscale of the TAM. Lastly, professional background affected only perceived usefulness. It was found that occupational therapists responded with less agreement to perceived usefulness, in comparison to healthcare psychologists and physiatrists. In terms of task description, the healthcare psychologists and physiatrists are concerned more with an overview of treatment plans for individual patients and generally more involved with management tasks, where occupational therapists are more hands-on in their daily activities and executing the selected treatment plans.

It should be noted that our sample was of sufficient size to accurately assess technology acceptance at group level, but that the individual characteristics of gender and professional background were rather skewed in the sample. Non-parametric statistics were selected to accommodate the sample composition in the analyses. It should be noted that the current questionnaire was focused on the perspective and the opinions of healthcare providers. Another limitation could be that all questions were phrased positively, which could stimulate more positive responses. However, we aimed to use the TAM in the original format, as this has been validated in a range of studies (F. D. Davis, 1989; Venkatesh & Davis, 2000). Other potential threats toward successful implementation like policy, insurance, and financial considerations are not considered, but could have a significant impact as well. This may be a prominent cause of why there is currently no common use of this technology. However, such potential barriers should be surveyed among managers and directors, rather than healthcare providers. Lastly, a potential threat of insufficient computer skills was addressed by verifying the level of internet skills in our sample, and we found that all participants indicated at least average internet skills.

To conclude, technology acceptance for digital cognitive rehabilitation is considerable among a sample of healthcare providers with experience in cognitive rehabilitation. Our findings indicate that one potential obstacle toward technology acceptance and eventually actual systems use lies with the subjective norm as perceived by health care providers. Overall, they consider the norms as implied by patients, superiors, and colleagues as neutral. To reach successful implementation, we advise to specifically address this issue in the implementation process, with, e.g., starting with a small group of enthusiastic users, followed by gradual expansion of use. Lastly, systematic individual variation seems limited, and the age and gender do not appear to have an impact. Only professional background, most likely linked to a difference in focus on execution vs. policy affects perceived usefulness to some extent. Overall, the current results indicate that healthcare professionals hold a positive attitude toward digital cognitive rehabilitation tools. The combination of this receptive attitude, technological advances, and increasing strain on healthcare provide ample opportunities for the development and implementation of evidence-based rehabilitation tools.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics Statement

The studies involving human participants were reviewed and approved by the Committee of Ethics Psychology, Leiden University. The patients/participants provided their written informed consent to participate in this study.

Author Contributions

AM, MK, and IH performed data processing and wrote the manuscript. AM and IH performed data analyses. AV and RV critically revised the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Chapter 7

Influencing strategic navigation preferences in healthy subjects

Published as

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Abstract

One approach to the rehabilitation of navigation impairments is to train the use of compensatory egocentric or allocentric navigation strategies. Yet, it is unknown whether and to what degree training programs can influence strategic navigation preferences. In validating this approach, the key assumption that strategic preference can be changed by using a navigation training was assessed in a group of healthy participants (n = 82). The training program consisted of a psychoeducation session and a software package that included either allocentric or egocentric navigation exercises in virtual environments. Strategic navigation preference, objective and self-reported spatial abilities were assessed in pre- and post-training sessions. Based on their pre-training strategic preference, participants received either the egocentric training (n = 19) or the allocentric training (n = 21) version of the training. These participants engaged in four training sessions over a period of 2–3 weeks. The second group of participants did not use the training software (n = 43) and served as a control group. The results show that 50% of participants that received the egocentric training shifted from an allocentric to and an egocentric strategic preference. The proportion of participants that switched their strategic preference as a result of the allocentric training was identical to this proportion in the control group (19%). The training did not affect objective and self-reported navigation abilities as measured in the pre- and post-training sessions. We conclude that strategic navigation preferences can be influenced by using home-based training in healthy participants. However, using the current approach, only a preference shift from an allocentric to an egocentric navigation strategy could be achieved. The effectiveness of this navigation strategy training should next be assessed in relevant patient populations.

Introduction

Spatial navigation is a complex cognitive ability that is essential to our daily functioning. On a daily basis, humans traverse a range of environments (e.g., a crowded city or an open rural environment), with different navigational goals (e.g., exploration, finding one's way home). In order to adapt to the variety of spatial challenges we are faced with regularly, evolution favored a complex and flexible navigation system in the human brain (Cashdan & Gaulin, 2016). Neuroimaging and lesion studies have identified a large neural network associated with spatial navigation, including the hippocampal formation, parahippocampal gyrus, retrosplenial cortex, medial temporal lobe, prefrontal cortex, precuneus and regions of the parietal lobe (Boccia et al., 2014; Chrastil, 2013; Maguire, Burgess, & O'Keefe, 1999; Spiers & Barry, 2015). This widespread recruitment of the brain renders the navigation ability highly vulnerable to brain damage. Disruption of neural networks involved in navigation often results in navigation impairments (also known as topological disorientation) as observed in patients with acquired brain injury (Claessen & van der Ham, 2017), neurodegenerative diseases (Kalova, Vlcek, Jarolimova, & Bures, 2005) and developmental (Lind, Williams, Raber, Peel, & Bowler, 2013) and mental disorders (Hanlon et al., 2006). Navigation impairments are known to have a debilitating effect on the daily life activities of patients (Aguirre & D'Esposito, 1999). As such, navigation impairments have been associated with lowered quality of life, heightened levels of spatial anxiety and reduced autonomy (van der Ham et al., 2013).

Developing a standardized treatment for navigation impairments has proven to be a challenge due to the multifaceted nature of spatial navigation (Claessen & van der Ham, 2017; Maguire et al., 1999; Wolbers & Hegarty, 2010). Problems reported by navigation impaired patients are diverse and deficits are often specific. This is illustrated by a wealth of rapports of patients displaying specific spatial impairments: difficulty encoding novel landmarks (Herdman et al., 2015), recognizing famous landmarks (Rainville et al., 2005), understanding the order in which landmarks are encountered (van der Ham et al., 2010), remembering what actions to take at a landmark to follow a route (van der Ham et al., 2010), utilizing maps (Suzuki, Yamadori, Hayakawa, & Fujii, 1998), forming a topological understanding of an environment (Ino et al., 2007) or switching between spatial reference frames (Ruggiero, Frassinetti, Iavarone, & Iachini, 2014).

Over the past years, training programs have been developed with the goal of improving navigation ability in healthy subjects and patients. Most training programs for healthy subjects have been directed towards knowledge acquisition of specific environments. Examples of these include training for firefighters (Bliss, Tidwell, & Guest, 1997), evacuation scenarios (Burigat & Chittaro, 2016) and astronauts learning to orient themselves in a space station (Aoki, Oman, Buckland, & Natapoff, 2008). One notable training program that has been developed for healthy participants has been reported in a study in which pre-school children were trained for 12 weeks to enhance their spatial orientation skills. After engaging in a variety of spatial exercises, children were able to encode and utilize map-like knowledge of an environment, a spatial skill that normally arises years later in development (Boccia et al., 2014). Several training programs have been reported that were specifically tailored to the impairments of a patient (Bouwmeester et al., 2015; Brooks et al., 1999; Claessen, van der Ham, et al., 2016; Incoccia et al., 2009). Some rehabilitation programs have focused on learning how to navigate a specific route through the environment (errorless learning; Lloyd et al., 2009) while other programs aimed to strengthen general spatial abilities by developing route learning (Kober et al., 2013). Generally, patients do benefit from navigation rehabilitation training. However, previous training programs have been either specifically designed for an individual patient or were directed at training navigation in a specific, spatially limited environment. Furthermore, the programs involve intensive supervision of experts as training programs required repeated sessions.

There is a need for a standardized navigation training that can be used to treat a broad range of navigation impairments. To account for the diversity in navigation impairments, the training should include exercises for navigational abilities in different spatial domains. Becoming acquainted with different navigation abilities should allow for the development of a more beneficial, compensatory navigation strategy, which can be used in real life. In order for this standardized training to be feasible in today's healthcare system, the training should include both face-to-face therapy and repeated (unsupervised) training sessions (Wentzel, van der Vaart, Bohlmeijer, & van Gemert-Pijnen, 2016). To this end, we propose a home-based navigation rehabilitation training that can be installed on and used from a patient's home computer. Training exercises provided by the software should be modelled after experimental paradigms described in the field of spatial cognition.

When interacting with an environment, humans encode, update and process spatial information using distinct representations of space, referred to as reference frames (Igloi et al., 2009; Roberta L Klatzky, 1998). Spatial information about objects in the environment, in relation to the navigator's own body is encoded into a body-centered, egocentric reference frame. Spatial relations between objects in the environment, irrespective of the navigators own position, are encoded into a world-centered, allocentric reference frame. The type of spatial information that is encoded and used during navigating reflects the employed navigation strategy. Remembering sequences of bodily turns (Igloi et al., 2009), landmark-direction associations at intersections (Wiener et al., 2013) and path integration (R. X. F. Wang et al., 2006) are all spatial abilities that rely on egocentric reference frames. As such, spatial behavior that relies on these abilities can be regarded as an egocentric navigation strategy. Conversely, spatial abilities such as place finding (Parslow et al., 2004), utilizing configurational knowledge of landmarks (Igloi et al., 2009) and the use of maps during navigation (Palermo et al., 2012), makes use of a world-oriented, allocentric reference frame. Spatial behavior that focusses on external cues during navigation can be classified as an allocentric navigation strategy. It is well established that (partially) distinct neural subsystems underlie navigation based on egocentric and allocentric reference frames (Boccia et al., 2014; Colombo et al., 2017; Jordan, Schadow, Wuestenberg, Heinze, & Jancke, 2004; Zaehle et al., 2007). This distinction between navigation strategies and their underlying neural correlates, suggests that a compensatory rehabilitation approach might be an effective approach to rehabilitation of navigation impaired patients.

Compensatory and metacognitive strategy training programs are practice standards in the rehabilitation of cognitive functions after brain injury (Cicerone et al., 2000; Cicerone et al., 2005; Cicerone et al., 2019; Cicerone et al., 2011). Such training programs start with the construction of a strengths and weaknesses profile in which a patient's impairments and intact cognitive abilities determined. Then, training is constructed that focusses on the improvement of the intact abilities and the development of strategies that are beneficial to a patient. In terms of navigation impairment, participants with intact egocentric abilities, but difficulties in the allocentric domain, should be trained to adopt an egocentric navigation strategy and vice versa.

It is currently unknown whether navigational strategies can be influenced by training interventions. The aim of the current study was to test the key assumption that strategic navigation preference can be influenced by using home-based navigation training. By validating the concepts of the training in healthy subjects, we will provide the basis for a randomized control trial with navigation impaired acquired brain injury patients. To demonstrate a change in strategic navigation preference, we will train participants to adopt a navigation strategy other than their naive strategic preference. To this end, a home-based navigation training was developed in the form of a serious game. Two versions of the game were constructed: a version designed to train allocentric navigation strategies and a version designed to train egocentric navigation strategies. In order to provide evidence that strategic shifts were the result of the training intervention, a control group was used that did not receive the intervention. In addition, we aim to provide insight into the mechanisms by which a shift in strategic preference might occur. We will explore to what degree individual differences in objective and subjective navigation abilities determine naive strategic preference. Furthermore, we aim to examine individual characteristics that could potentially predict training success.

We hypothesized that participants who used the training program would display a preference for the navigation strategy trained in a situation where using both strategies can be deployed. As we expected the training to induce the strategic preference shifts, we expected a higher proportion of strategy shifts in the training group compared to the control group. Second, we hypothesized that using the training will lead to increased performance on spatial abilities associated with the trained domain. Specifically, egocentric spatial abilities (e.g., route continuation) will improve after the egocentric training, and allocentric spatial abilities (e.g., location on map) will improve after allocentric training. No performance changes were expected in the control group. Third, we hypothesized that subjective navigation ability will increase after using the training, whereas no change in subjective navigation ability was expected in the control group.

Materials and Methods

Design

A pre-test–post-test design was employed in this study including a control group, consisting of a "control" and "control + psychoeducation" subgroup and an experimental group consisting out of an "allocentric training" subgroup and an "egocentric training" subgroup. Measurements took place during two sessions: pre- and post-training. These measuring phases were separated by a 2 week intervention period. During the pre-training session, participants completed the screening/general questionnaire, the strategy assessment task, the Virtual Tübingen testing battery, which measured objective navigational ability, wayfinding questionnaire, which measured self-reported navigation and four neuropsychological assessments. During the post-training session, participants again completed the strategy assessment task, the Virtual Tübingen testing battery, and the wayfinding questionnaire. Participants in the experimental condition would engage in either the allocentric or egocentric training software in the period between pre- and post-training sessions.

Participants

Participants were recruited from the university campus using posters, the university's recruitment website, and social media. The inclusion and exclusion criteria for the study were: (1) between 18 and 35 years old; (2) Dutch-speaking; (3) access to personal computer and internet; (4) willingness and capability to complete the training program; and (5) no history of neurological or psychiatric disorders. All participants were required to sign an informed consent form in order to participate and were compensated for participation in participant hour credits or with a monetary reward of 6 € per hour. The study was performed in concordance with the Declaration of Helsinki (2013) and was approved by Leiden University's local ethics committee for psychological research.

Materials

Screening/General Questionnaires

All participants completed a screening questionnaire in which they filled in demographic characteristics such as age, gender, handedness, level of education and gaming experience. Furthermore, screening information about psychiatric or neurological disorders was obtained.

Navigation Strategy Assessment

Strategic navigation preference was assessed during the pre- and post-training sessions using an adapted version of the Starmaze (Igloi et al., 2009). Two variants of the Starmaze were used: the original environment described by Igloi et al. (2009)and a mirrored environment. The Starmaze consisted out of five alleys that formed a pentagon and five alleys that radiated from this pentagon. The alleys were surrounded by a small wall that could not be traversed. Surrounding the environment were two distinct mountains, two distinct forests, and two radio towers, which were visible throughout the maze. Participants were instructed to explore the environment to find the goal location, which was located in one of the arms. Upon finding the goal location, the text "Bravo" would be displayed on-screen and the next trial was started. Over the course of the first five trials (training trials), participants would start in the same arm of the maze and learn to find the goal location. In the 6th trial (probe trial) participants started in a different arm of the maze. Participants could navigate using either the sequence of left-right turns that was learned during the training trials or by determining their location based on the configuration of landmarks in the environment. Participants utilizing the turn sequence approach would end in an alley that was different from the goal location in the training trials. Participants that utilized the configuration of cues would end in the original ending alley.

The ending location and the travel path measured in the probe trial were used to identify egocentric, allocentric or mixed navigation strategies. Participants who ended at the different goal location, and thus utilized a sequential egocentric navigation strategy, were classified as egocentric navigators. Participants who travelled directly (using the shortest route) to the original goal location, and thus utilized the configuration of landmarks to orient themselves, were classified as allocentric navigators. Participants that initially followed the turn sequence strategy, but changed direction and headed for the original goal location, were classified as mixed navigators.

Subjective Navigation Ability

Self-reported navigation ability was assessed during the pre- and post-training sessions using the Wayfinding Questionnaire (de Rooij et al., 2019). The Wayfinding Questionnaire contains 22 items in three subscales: navigation and orientation (11 items), distance estimation (three items) and spatial anxiety (eight items). All items were rated on a seven-point Likert scale.

Objective Navigation Ability

Objective navigation ability was assessed during the pre- and post-training sessions using an adapted version of the Virtual Tübingen testing battery (Claessen, Visser-Meily, et al., 2016a; van Veen et al., 1998). Four routes through the city were selected that were comparable in terms of distance and number of intersections. Participants watched a video of a route through a virtual replication of the city of Tübingen. Participants were instructed to memorize as much as possible about the spatial characteristics of the route and the environment. Afterward, participants completed 6 tasks in which navigation abilities were assessed.

Participants completed two variations of the task at each measuring phase. In the first variation of the tasks, participants saw the route from a first-person perspective. In the second variation, participants observed a red arrow icon moving along a route from a birds-eye view, the map perspective. The camera was placed at a height of 38 m and was focused on the red arrow. The camera did not rotate with the arrow and thus, was always aligned in the same direction.

After viewing the video, a Route Sequence task was conducted. Participants had to indicate what action was taken sequentially at each intersection point along the route. Options were left-turn, right-turn or straight. No images of the related decision points were shown. Numbers 1–8 were listed and participants selected the arrow icon indicating the response options for each number. Scoring was based on the number of correct responses. A participant's score was the sum of correct responses (ranging from 1 to 8).

Then the Route Continuation task was performed. Participants were presented with eight images of the intersection points in random order. Participants had to indicate whether they turned left, right or went straight ahead at each decision point by pressing the arrow keys left, right or up arrow, respectively. Scoring was based on the number of correct responses. A participant's score was the sum of correct responses (ranging from 1 to 8).

Participants then performed the Point to Start and Point to End tasks. Participants were shown eight scenes taken along the route in random order. Participants were asked to indicate where the start/end location of the route was using a rotational device. In the first-person perspective version, the rotational device was placed horizontally on the desk in front of the participants. Participants were asked to point from the perspective shown in the image. In the dynamic map perspective version, the rotational device was placed vertically on the desk next to the monitor. Participants had to indicate the start/end location on the map, relative to the red arrow icon the camera was following. Scoring was based on the mean pointing deviation angle for each trial, ranging from 0 to 180 degrees deviation.

In the Distance Comparison task, participants were shown a target image and two response images. In the first-person perspective version, the images corresponded to locations visited along the route. In the dynamic map perspective version, the images were landmarks encountered along the route. Participants had to indicate which of the two response locations was closest to the target location (direct path distance). A participant's score was the sum of correct responses (ranging from 1 to 8).

Finally, participants performed the Locations on Map task. Participants were shown a schematic map of the city including icons indicating starting and ending locations. In the first-person perspective version, participants were shown images of eight locations along the route in random order. Participants had to indicate the correct location on the city map using the mouse. In the dynamic map perspective version, participants had to indicate where landmarks were located on the city map. Scoring was based on the amount of pixels deviation from the correct location.

Neuropsychological Assessment

Four neuropsychological tests were performed to assess general cognitive ability. The Corsi Block tapping tasks, both forward and backward, were used to asses visuospatial working memory (Roy P. C. Kessels et al., 2000). The WAIS VI Digit span test, both forward and backward, was used to assess verbal working memory (D Wechsler & Scale—Revised, 1987). A digital 46-item adaptation of the Mental Rotation test was used to assess object-based transformation ability (Shepard & Metzler, 1971; Vandenberg & Kuse, 1978). An adaptation of the 12-item Santa Barabara perspective-taking test was used to assess egocentric transformation ability (Hegarty & Waller, 2004).

Training Intervention

The training intervention consisted of a short psychoeducation session and home-based navigation training software that was used over the course of 2–3 weeks.

Psychoeducation

The psychoeducation session took 20–30 min. The experimenter placed a document with illustrations on the table and read an educational text for the participants. After reading the text aloud, the experimenter discusses the illustrations on the document to clarify the content. The educational text addressed the following topics: the formation of egocentric and allocentric reference frames and the use of egocentric and allocentric navigation strategies. It was explained that people are capable of using both strategies and that certain strategies are more effective in specific situations. To verify whether participants understood the concepts, participants were asked to give examples of both egocentric and allocentric navigation strategies they have used. Participants were told that they would engage in a training program designed to train egocentric or allocentric navigation strategies. Importantly, participants were not informed about their performance or strategy preference in the Starmaze and Virtual Tübingen tasks.

Home-Based Training Software

Two versions of the training were constructed. Participants would receive either the egocentric navigation training or the allocentric navigation training. Each training consisted of 3 modules that were designed to train spatial abilities that are central to either an egocentric or allocentric navigation strategy. The egocentric training was composed of the modules: "landmark-action association," "turn-sequence" and "egocentric updating." The allocentric training was composed of the modules: "place-finding: distal landmarks," "place-finding: local landmarks" and "effective map-use." Each module resembled a simple game, set in the theme of ancient Greece. A comprehensive description of the training modules can be found in the Supplementary Material (**Supplementary Figures 7.1-7.10**).

The navigation training software was installed on the participants' home computer. Participants received a personal account, which allowed for data transfer with an online server. Via the server, progress during the training could be stored and tracked. Furthermore, training adherence was recorded by storing training time and the number of trials started and completed. Participants were instructed to engage in at least four separate training sessions, in which all three training modules should be used. Mails reminding the participant to train were automatically sent two times per week.

During a single training session, participants were instructed to perform at least one attempt to increase their level in all three training modules that were available to them. Each training module contained four difficulty blocks. Each difficulty block was composed of three levels of increasing difficulty levels. All participants started on difficulty block 1. When engaging in a training session, participants completed three levels within a difficulty block. If participants scored 75% or more of the points obtainable over the levels, participants would advance to a higher difficulty block. If participants failed to obtain 75% of the points, participants would remain on the same difficulty block. Depending on the participant's skill level and progress, a training session was estimated to take 10–15 min.

Procedure

All participants were invited to the laboratory at the Faculty of Social Science at the Leiden University, where participants read the information letter and signed the informed consent form in accordance with the Declaration of Helsinki (2013). Participants filled in the screening/general questionnaire followed by the Wayfinding Questionnaire and completed the Starmaze task.

Participant was assigned to the control or training condition based on participation order. The first half of the participants were assigned to the control groups. The second half of the participants were allocated to the training condition. Participants allocated to the training condition were assigned to the egocentric or allocentric training depending on the navigation strategy displayed in the Starmaze. Participants ending in the allocentric ending location, thus displaying a mixed or allocentric navigation strategy, received the egocentric training program. Participants ending in the egocentric ending location received the allocentric training program.

Following the Starmaze task, participants would complete the Virtual Tübingen testing battery. Route and order of the perspective (first-person or map perspective) were counterbalanced between conditions. A 10-min break was introduced following the Virtual Tübingen test. After the break, the four neuropsychological tests were completed.

For participants in the control condition, the first session ended here. Participants in the experimental condition would continue to receive psycho-education and were instructed on how to use the home-training software. During the training period, participants in the experimental condition would practice with the navigation training software during four occasions. During a training session, participants were instructed to perform all three training modules at least once. A periodically repeating mail was sent to the participants, reminding them to use the training application.

After 2 weeks, participants were invited back to the lab to perform the post-intervention measurement. The Starmaze, Virtual Tübingen and Wayfinding Questionnaire were conducted. The session ended with a debriefing.

Analysis

Demographics, Neuropsychological and Visuospatial Measures

MANOVA analysis was performed to assess potential differences between participants in the conditions. Demographic, neuropsychological and visuospatial scores were compared between conditions.

Navigation Strategy

A Fishers' exact test was used to compare the proportions of participants who changed strategy between the pre- and post-training sessions. To assess the effect of psychoeducation, the proportion of strategy shifts in the control conditions was analyzed. Then, proportional analysis was performed on the control condition and the egocentric and allocentric training conditions. In order to assess whether factors other than condition determined strategy change, the proportional analysis was performed for gender, gaming experience and education between strategy shifters and those who did not shift. Binary logistic regression was performed to investigate the relationship between training adherence and strategic shift.

Objective Navigation Ability

The effect of condition on performance in the Virtual Tübingen tasks was analyzed using a differences score analysis. A difference score was calculated for each navigation task by subtracting the pre-training score from the post-training score. A MANOVA was used to assess the effect of condition (control, egocentric training or allocentric training) on performance change. Three participants had an extreme score ($Z > 3$) on the map perspective point to start task and were removed from the analysis.

Subjective Navigation Ability

The effect of condition on self-reported navigational ability, measured using the Wayfinding questionnaire, was analyzed using a differences score analysis. A difference scores for each of the subscales (Spatial Anxiety, Navigation and Orientation and Distance estimation) was calculated by subtracting the pre-training score from the post-training score. A MANOVA was used to assess the effect of condition (control, egocentric training or allocentric training) on wayfinding questionnaire change scores.

Interaction Between Strategic Preference, Preference Shift, and Navigation Abilities

To explore the interaction between strategic navigation preference and navigation abilities, a MANOVA was conducted with strategic preference at T1 as between-subject factor (egocentric, allocentric or mixed strategy) and performance on egocentric (composite score of route sequence, route continuation and point to start) and allocentric (composite score of point to end, distance estimation and location on map) tasks as dependent variables. Separate composite scores were calculated for the egocentric and allocentric tasks for the first-person and map-perspective tasks. A similar analysis was conducted with the self-reported navigational scores (spatial anxiety, navigation and orientation, and distance estimation) as dependent variables.

MANOVAs were conducted to assess differences in objective and self-reported navigation abilities between participants that shifted their strategic preferences between T1 and T2 and participant that did not shift strategic preference.

A binary logistical regression was conducted to assess whether performance on objective egocentric (composite score of route sequence, route continuation and point to start) and allocentric (composite score of point to the end, distance estimation and location on map) predicted strategic preference shifts. A similar analysis was performed with self-reported navigational abilities (spatial anxiety, navigation and orientation and distance estimation) as predictors.

Results

Participants and Demographics

One-hundred and twenty-nine participants were recruited into the screening procedure. To maintain a gender balance in the egocentric training condition, the sessions of 29 females and one male were terminated during screening as they displayed an egocentric navigation strategy in the Starmaze, while this condition was already filled. Revealing a clear gender effect for strategy preference (22.97% females vs. 42.85% males displayed an allocentric navigation strategy during the first Starmaze task). Seven participants were screened on the basis of exclusion criteria as they reported psychological or neurological disorders, two participants did not perform the training at home (or trained for less than 5 min), three participants were lost to attrition, two participants were wrongly classified into the allocentric training condition. As a result, 82 participants successfully completed the experiment.

Participant characteristics for each condition are presented in Table 1. A MANOVA revealed that were no differences in scores on visuospatial and neuropsychological assessments between conditions, $F_{(12,148)} = 0.40$, $p > 0.05$; Wilk's $\Lambda = 0.94$, partial $\eta^2 = 0.03$, nor were there differences between age, education and gaming experience between conditions, $F_{(6,154)} = 0.77$, $p > 0.05$; Wilk's $\Lambda = 0.94$, partial $\eta^2 = 0.03$. Independent *t*-tests did reveal that training time significantly differed between the egocentric and allocentric strategy training groups, $t_{(37)} = 4.05$, $p < 0.01$, and the number of trials completed in the allocentric strategy training group was significantly higher than in the egocentric strategy training group, $t_{(37)} = -7.21$, $p < 0.01$.

Table 7.1 Overview of demographics data, neuropsychological scores and training adherence.

Variables	Control (n= 43)	Experimental (n =39)	
		Egocentric Training (n = 18)	Allocentric Training (n = 21)
Demographics			
Age in years, *M (SD)*	22.42 (2.85)	22.44 (3.11)	21.48 (2.14)
Gender, *% female*	62.79	55.56	57.14
Education, *M (SD)*†	6.77 (0.43)	6.80 (0.43)	6.76 (0.44)
Gaming experience, *M (SD)*‡	1.51 (0.94)	1.72 (1.18)	1.67 (1.02)
Neuropsychological test scores at T1			
Corsi block tapping task forward span, *M* (*SD*)	6.51 (0.94)	6.33 (1.03)	7.43 (0.87)
Corsi block tapping task forward product score, *M* (*SD*)	66.3 (20.16)	62.11 (20.91)	63.76 (16.68)
Corsi block tapping task backward span , *M* (*SD*)	6.74 (0.82)	6.61 (0.92)	6.52 (0.81)
Corsi block tapping task backward product score , *M* (*SD*)	71.14 (17.98)	69.11 (18.76)	66.86 (16.93)
Digit span forward span, *M* (*SD*)	6.14 (1.21)	6.78 (1.39)	6.38 (1.43)
Digit span forward product score, *M* (*SD*)	60.67 (24.19)	69.56 (25.67)	64.52 (30.44)
Digit span backward span, *M* (*SD*)	5.35 (1.15)	5.83 (1.15)	5.38 (1.12)
Digit span backward product score, *M* (*SD*)	52.98 (22.13)	57.89 (21.96)	53.04 (22.34)
Santa Barbara perspective taking test , deviation, *M* (*SD*)	14.99 (9.15)	15.04 (9.05)	16.88 (9.48)
Mental rotation slope, accuracy, *M (SD)*	76.98 (12.09)	76.67 (12.97)	75.29 (11.93)
Mental rotation slope, reaction time, *M (SD)*	4992.63 (2822.06)	5520.32 (2047.83)	5047.36 (2765.06)
Mental rotation slope, ms/degree, *M (SD)*	19.11 (11.69)	24.06 (19.65)	20.2 (15.11)
Training adherence			
Training time in minutes, M (*SD*)	-	62.31 (31.95)*	30.70 (15.00)*
Training Trials completes, *M (SD)*	-	27.94 (8.29)*	78.90 (28.94) *

†Level of Education measured on the Verhage scale, a Dutch scale of education level ranging from 1 (low) to 7 (high) (Verhage, 1964).

‡ Gaming experience was measured on a 5 point scale, represented indicating 1= 0-2 hours/week, 2 = 2-4 hours/week, 3 = 4-8 hours/week, 4 = 8-12 hours/week, 5 = 12 + hours/week.

*T-tests indicate significant differences between groups ($p < 0.05$)

Strategy Change

A Fisher's Exact test revealed a significant effect of condition on the proportion of strategic preference changers (p < 0.05; *FET*, Fig 7.1). *Post hoc* analysis, using Bonferroni corrected Chi-squared tests, revealed that a higher proportion of participants changed strategy in the egocentric training condition compared to the control condition[1] (50% vs. 19%), $\chi^2_{(1)}$ = 5.95, p = 0.015. *Post hoc* analysis did not reveal a significant difference between the proportion of participants that changed strategic preference after the "egocentric training condition" compared to the proportion of participants that changed strategic preference after the "allocentric training condition" (50% vs. 19%), $\chi^2_{(1)}$ = 4.18, p = 0.041 (not passing the Bonferroni correction). No significant differences were found between the allocentric training condition and the control condition in the proportion of participants that changed strategic preference (19% vs. 19%), $\chi^2_{(1)}$ = 0.0 p = 1. Overall, this analysis revealed that strategic preference shifts between pre- and post-training were present in all groups. However, the proportion of the participants who shifted strategic preference after receiving the egocentric training was significantly larger compared to the control group.

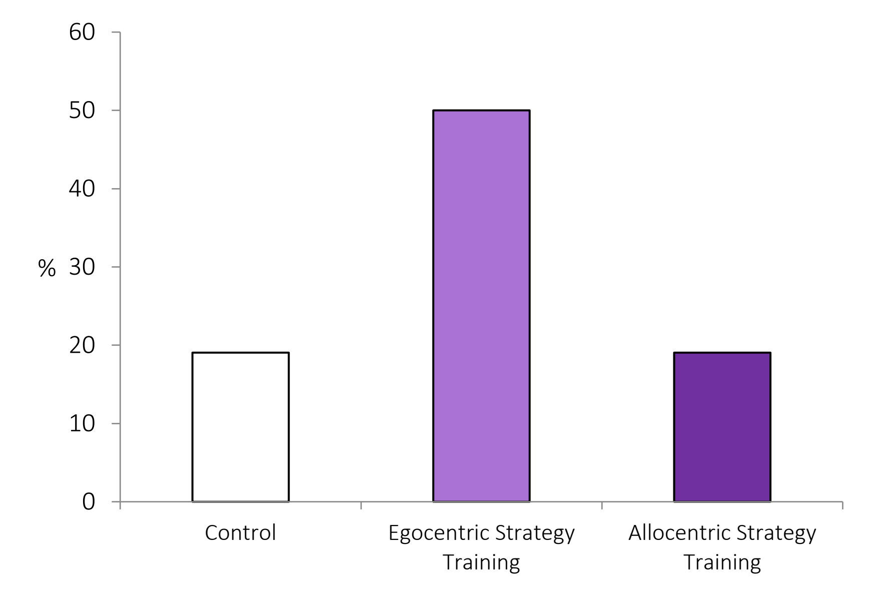

Fig 7.2 Proportion of participants that changed navigation strategy between the pre- and post-training sessions.

Additional proportional analyses were performed to determine whether strategic preference change could be attributed to other factors that are known to influence navigation strategy or learning processes. No effect of gender, $\chi^2_{(1)} = 0.65$, $p > 0.05$, education, $p > 0.05$; *FET*, or gaming experience, $p > 0.05$; *FET*, was found. Training time and number of trials completed differed significantly between the egocentric and allocentric training groups (Table 7.1). Exploratory binary logistical regression analyses were conducted to explore whether strategy change could be attributed to these differences. Binary logistic regression revealed that there was no effect of training time on strategy change, $\chi^2_{(1)} = 1.07$, $p = 0.74$. However, a significant relationship between the number of trials completed and strategy change was found, $\chi^2_{(1)} = 4.8$, $p < 0.028$), with fewer trials completed leading to higher training success.

Inspection of the strategic preference changes shows that the direction of the change in the control condition was not uniform. Participants in the control group changed from egocentric to allocentric strategic preference and vice versa (Table 7.2).

Table 7.2 Direction of change in participant that changed navigation strategies between the pre- and post-training sessions.

Strategy T1	Strategy T2	Control (n = 42)	Egocentric Training (n = 18)	Allocentric Training (n = 21)
egocentric	allocentric	0	-	2
egocentric	mixed	1	-	2
allocentric	egocentric	2	5	-
allocentric	mixed	1	1	-
mixed	egocentric	3	2	-
mixed	allocentric	1	1	-

Objective Navigation Ability Assessment

MANOVAs were performed to test the hypothesis that navigation training leads to an increase in performance on the objective navigation tasks compared to the control group. Specifically, we expected that participants in the egocentric training condition had a higher, positive differences score on egocentric navigation tasks (route sequence, route continuation, point to start), whereas allocentric training would lead to higher, positive differences scores on allocentric navigation tasks (distance comparison, location on map, point to end). First, the analysis was run for the dynamic map perspective condition. A MANOVA on the difference scores (post-training—pre-training) of six navigation tasks as independent variables and conditions as a between-subject factor was

Table 7.3 Mean and standard deviation of performance on navigation tasks on the pre- and post-training sessions and differences scores.

	Control			Egocentric Training			Allocentric training		
Subtask in Virtual Tübingen Battery	T1	T2	ΔT,2	T1	T2	ΔT,2	T1	T2	ΔT,2
Map Perspective									
Route Sequence, % correct	61.01 (25.78)	70.35 (22.50)	8.93 (28.19)	76.39 (25.69)	61.81 (31.35)	-14.58 (38.41)	67.26 (23.54)	68.45 (25.50)	1.19 (36.64)
Route Continuation, % correct	82.56 (17.71)	84.01 (14.52)	1.45 (19.33)	88.89 (9.48)	82.64 (16.12)	-6.25 (20.22)	79.17 (17.38)	80.95 (18.38)	1.79 (24.78)
Distance Estimation, % correct	63.08 (15.66)	70.35 (20.05)	7.27 (23.82)	67.36 (17.22)	75.00 (16.61)	7.64 (18.26)	72.02 (20.88)	75.00 (15.81)	2.98 (26.49)
Point to Start, average deviation	22.04 (13.61)	23.71 (21.60)	1.67 (19.23)	32.77 (39.31)	33.35 (38.88)	0.58 (23.90)	24.64 (33.84)	24.76 (14.23)	0.13 (37.56)
Point to End, average deviation	28.44 (14.59)	34.78 (26.83)	6.34 (29.19)	22.42 (9.28)	35.11 (25.02)	12.69 (22.25)	27.17 (12.38)	35.63 (16.14)	8.46 (14.77)
Location on Map, average pixels	128.40 (68.54)	121.26 (83.95)	-7.14 (85.90)	110.91 (79.53)	80.19 (57.32)	-30.72 (72.83)	114.70 (56.18)	110.72 (63.06)	-3.98 (75.01)
First-Person Perspective									
Route Sequence, % correct	59.59 (28.33)	61.34 (28.58)	1.74 (32.23)	64.58 (36.19)	75.00 (26.78)	10.42 (49.31)	60.71 (25.40)	72.62 (24.24)	11.90 (26.36)
Route Continuation, % correct	70.93 (18.44)	70.93 (18.84)	0.00 (22.66)	74.31 (18.92)	76.39 (22.23)	2.08 (21.54)	65.48 (19.73)	66.67 (17.38)	1.19 (27.64)
Distance Estimation, % correct	63.66 (21.27)	62.50 (17.25)	-1.16 (26.70)	70.83 (16.04)	64.58 (20.22)	-6.25 (26.52)	68.45 (21.51)	63.10 (19.56)	-5.36 (28.66)
Point to Start, average deviation	47.64 (19.67)	47.63 (20.44)	0.00 (27.94)	48.85 (28.14)	44.74 (24.00)	-4.11 (17.71)	47.75 (14.05)	42.31 (17.47)	-5.43 (23.74)
Point to End, average deviation	48.07 (22.53)	60.75 (29.84)	12.68 (31.99)	46.92 (21.64)	48.14 (21.67)	1.22 (25.68)	58.20 (24.10)	61.19 (23.71)	3.00 (32.56)
Location on Map, average pixels	139.96 (73.62)	163.24 (89.51)	23.28 (87.74)	135.69 (69.65)	139.62 (72.10)	3.93 (56.38)	149.54 (69.87)	152.72 (68.59)	3.18 (68.65)

performed (**Table 7.3**). A trend effect of condition was found on the differences scores $F_{(12,140)}$ = 1.65, p = 0.07; Wilk's Λ = 0.77, partial η^2 = 0.13. Second, the analysis was run for the first-person learning condition. A MANOVA with the difference scores of six navigation tasks as independent variables and conditions as a between-subject factor was performed. No significant effect of condition was found on the differences scores $F_{(12,148)}$ = 2.083, p > 0.05; Wilk's Λ = 0.94, partial η^2 = 0.03.

Subjective Navigation Ability

MANOVAs were performed to test the hypothesis that navigation training leads to an increased rating of subjective navigation ability on the "Navigation and Orientation" and "Distance Estimation" scales and decreased score on the "Spatial Anxiety" subscale, in the experimental groups compared to the control group (**Table 7.4**). No main effect of condition on difference scores was found, $F_{(6,148)}$ = 1.29, p > 0.05; Wilk's Λ = 0.90, partial η^2 = 0.05.

Table 7.4 Scores on the Wayfinding Questionnaire pre- and post-training.

	Control			Egocentric Training			Allocentric Training		
Wayfinding Questionnaire subscales	T1	T2	ΔT1.2	T1	T2	ΔT1.2	T1	T2	ΔT1.2
Navigation and Orientation	50.16 (9.96)	50.47 (9.79)	0.30 (3.91)	49.44 (8.54)	50.56 (7.37)	1.11 (3.80)	49.62 (9.35)	48.90 (10.11)	-0.71 (4.79)
Distance Estimation	11.44 (3.19)	11.42 (3.49)	-0.02 (2.23)	11.00 (2.83)	10.61 (2.91)	-0.39 (1.24)	11.19 (3.71)	11.57 (3.80)	0.38 (1.99)
Spatial Anxiety*	21.42 (8.34)	22.19 (8.25)	0.77 (3.89)	21.78 (5.48)	22.06 (6.91)	0.28 (3.77)	24.24 (8.19)	23.76 (8.70)(	-0.48 (3.93)

Interaction Between Strategic Preference, Preference Shifts, and Navigation Abilities

MANOVAs were performed to explore the relation between strategic preferences at T1 an objective and self-reported navigational abilities. Performance on egocentric and allocentric spatial tasks did not differ between participants with allocentric, egocentric or mixed strategic preference, $F_{(8,148)}$ = 1.51, p > 0.05; Wilk's Λ = 0.85, partial η^2 = 0.08. Similarly, self-reported navigation abilities did not differ between subjects with different strategic preferences $F_{(6,152)}$ = 0.26, p > 0.05; Wilk's Λ = 0.98, partial η^2 = 0.01.

To explore differences in egocentric and allocentric spatial abilities between participants that shifted strategy after the intervention and those who maintained the same strategic preference, a MANOVA was performed. Performance on egocentric and allocentric tasks did not differ between strategy shifters and non-shifters, $F_{(4,75)} = 0.82$, $p > 0.05$; Wilk's Λ = 0.96, partial $\eta^2 = 0.04$. Similarly, self-reported navigation abilities did not differ between strategy shifters and non-shifters, $F_{(3,77)} = 0.26$, $p > 0.05$; Wilk's Λ = 0.99, partial $\eta^2 = 0.01$.

Binary logistic regression analysis was performed to determine whether objective navigation abilities would predict shifts in strategic preference. Shifts in strategic preference were not predicted by objective navigation abilities, $\chi^2_{(4)} = 2.2$, $p = 0.69$, or self-reported navigation abilities $\chi^2_{(3)} = 0.54$, $p = 0.91$ at T1.

Discussion

There is a strong need to develop rehabilitation programs for acquired brain injury patients with navigation impairments. A core approach to cognitive rehabilitation is the application of compensatory strategies. In the current study, we assessed the effectiveness of a home-based rehabilitation software designed to train and develop alternative navigation strategies in healthy participants.

The current study shows that strategic navigation preference can be influenced by using a navigation training program. A large portion of the participants that received the egocentric navigation training shifted from an allocentric or mixed navigation strategy preference before training, to an egocentric navigation strategy preference after training. This shift in strategic preference was the result of the training intervention as the proportion of shifters observed in the control group was significantly lower. Exploration of the individual characteristics of participants indicated that strategy shift was not predicted by a demographic factor such as gender, education or gaming experience. Furthermore, objective and self-reported navigation abilities did not predict strategic preference shifts. While an earlier study has shown that navigation strategy can be influenced by the use of intensive therapy sessions (Claessen, van der Ham, et al., 2016), these findings provide support for the hypothesis that strategy training can be achieved by the use of a standardized home-training program in combination with psychoeducation.

Important to note, however, is that the increase in strategy shifts was only demonstrated for the egocentric strategy training program. Participants who engaged in the allocentric training did not change strategy more often than the control groups. These results suggest that the current home training program was ineffective in inducing an allocentric navigation strategy. There are several factors that might explain why the allocentric training seemed to be ineffective in altering strategy preference.

First, the training time was significantly higher in the egocentric training condition compared to the allocentric training condition. This difference was the result of inherent differences between the training modules that were used in both programs. The duration of the allocentric modules was mostly dependent on the skill of the participant, as the goal of the modules was to find the shortest path to a location. Conversely, the turn sequence and landmark-action modules in the egocentric training required participants to traverse lengthy routes through an environment regardless of a participant's skill level. While a higher training time was observed in the egocentric training condition, a significantly higher number of trials were attempted and completed in the allocentric training. Exploratory analysis revealed that within the experimental groups, training time did not predict the strategic preference shift. Conversely, a lower number of trials completed predicted a higher chance of preference shifts. Clearly, exposure time and the number of exercises were not the most prominent factors that predict training success. Rather, the content and presentation of the training exercises in the allocentric training modules should be improved. A small number of lengthy trials seemed to be preferable over many short trials for the development of navigation strategies.

A second explanation for the lack of strategy shifts observed after allocentric training regards the difficulty of switching between allocentric and egocentric reference frames during navigation. Egocentric navigation entails a focus on landmark-response associations, sequences, and spatial updating rather than forming relational representations (Bullens et al., 2010). Conversely, the formation and utilization of map-like representation of space are central to allocentric navigation. Constructing such allocentric representations is cognitively demanding (Nemmi, Boccia, & Guariglia, 2017; Ruggiero, Iavarone, & Iachini, 2018; Wen et al., 2011). Furthermore, a considerable processing cost is involved in switching between egocentric and allocentric reference frames (Lee & Tversky, 2001). As such, shifting from an allocentric to an egocentric navigation strategy reflects a shift towards a strategy that is cognitively less demanding, whereas a switch from an egocentric to an allocentric navigation strategy, can be regarded as a switch to a more demanding strategy. The environment used to assess the navigation strategy in this study was developed to facilitate both allocentric and egocentric strategies (Igloi et al., 2009). It is, therefore, possible, that participants who received the allocentric training, were not prompted by the environment to adopt the trained strategy and instead reverted to their default strategy.

Related this explanation are the results reported by Francesca Pazzaglia and Taylor (2007), who examined the cognitive style of spatial processing in participants with high and low survey abilities. In this study, participants with high survey abilities were less depended on learning perspective and were able to shift more efficiently from one representation to another compared to participants with low survey abilities. A similar effect was found when regarding the participants with a naïve allocentric preference as the high survey participants, as participants with an allocentric strategic preference were more responsive to the training. One important difference with this study however, is that naïve strategic preference did not correspond performance in objective navigation tasks in this study.

In addition to a shift in strategic navigation preference, we expected that exposure to the training programs would lead to an increase in objective navigation ability and self-reported navigation ability. Contrary to expectations, no effect of the training was found on both objective and subjective navigation ability. This result indicates that the strategy training did not strengthen specific navigational abilities, but rather, affected meta-cognition and behavioral selection. Additionally, we did not find differences in objective navigational abilities between the groups before the training. Preferred strategy during the pre-training session, did not correspond to higher performance on allocentric or egocentric objective navigation abilities. This finding supports a study that has shown that strategic navigation preference does not correspond to navigation ability (Prestopnik & Roskos-Ewoldsen, 2000). The relation between strategy preference and navigation skills has yet to be studied thoroughly, but might be of particular importance to the rehabilitation of navigation impairments. It appears that someone's preferred navigation strategy is not grounded in their spatial strengths and weaknesses. When developing compensatory strategy therapies for navigation impaired patients, care should be taken to make patients aware of their strengths and focus their efforts to maximizing the use strategies that utilize these abilities.

An important distinction between this study and the intended clinical application should be noted. In order to assess whether strategy use can be changed, participants were trained to adopt a navigation strategy that was contrary to their initial preferences. Patients however, will be trained to focus on and expand upon their intact navigation abilities. Ineffective strategies and abilities will be recognized and discouraged, while effective a strategies and abilities will be expanded upon. As the training is tailored to their strengths, rather than to their weakness, we expect that it will be easier for patients to utilize the training and transfer this information to real life situations.

Furthermore, the rehabilitation training that was investigated here focused on promoting the use of allocentric and egocentric navigation strategies. Both strategies rely on the use of landmarks. There have been rapports of patients with specific impairments in landmark recognition, encoding and processing (Rainville et al., 2005). Therefore, future therapies should be developed that train navigation strategies that include a minimal focus on landmarks.

Using the current iteration of the navigation training, participants with an egocentric navigation strategy preference did not adopt an allocentric navigation strategies. While it might not be possible to train allocentric navigation strategies, we expect that improvements to the training program will lead to training success. Based on the findings of this experiment, we propose to following improvements. First, fewer but lengthier training modules in the allocentric training. One explanation for the training success of the egocentric strategy training is the longer training time compared to the allocentric training. Second, as the "distal landmarks" and "local landmarks" place learning modules might have been too similar in terms of what navigation techniques were taught. A larger variety of training modules in the allocentric might be beneficial to strategy development. Third, an extended discussion of an individual's strengths and weaknesses during the psychoeducation phase of the training. The results suggest that people display navigation strategies that are not necessarily in line with their spatial abilities. Making people aware of their strengths and weaknesses might lead to higher adherence to beneficial navigation strategies. More research should be performed to determine whether a change towards an allocentric strategy preferences can be achieved when these novel features are implemented.

Over the past years, there has been a growth in software applications that combine game-like features with health related goals such as diagnosis of cognitive impairments. Spatial cognition in particular, lends itself well to serious-gaming adaptations as illustrated by applications such as "Sea Hero Quest" (Coutrot et al., 2018), "Navigeren kun je leren" and "Squirrel away" (Prpic et al., 2019). While substantial progress is being made in regards to the diagnosis of spatial impairments using these tools, the validity of treatment applications has yet to be explored. In context of this emerging field, the current study provides the encouraging results for a compensatory approach to the rehabilitation of navigation impairments using a game-like application.

In conclusion, we have developed a home-based rehabilitation training designed to treat navigation impairments that are often reported in acquired brain injury patients. A key assumption of this training is that strategic navigation preferences can be influenced by using a training. This study demonstrates that strategic navigation preference can indeed be influenced in healthy participants. Allocentric navigators could be trained to adopt an egocentric strategic preference. The current version of the training, did not induce a change in strategic preference in egocentric navigators. This may be due to factors inherent to the allocentric training such as its focus on multiple short exercises or a lack of diversity between exercises. Alternatively, switching from an egocentric to an allocentric navigation strategy, requires a switch towards a strategy that is cognitively more demanding. Egocentric navigators might not have been prompted to rely on the trained strategy in an environment, which was ambiguous regarding navigation strategies. Future research should be conducted to optimize the training for acquired brain injury patients with navigation impairments. The feasibility and effectiveness of the current approach should next be assessed in a patient population.

Data Availability Statement

The datasets generated for this study are available on request to the corresponding author.

Ethics Statement

The studies involving human participants were reviewed and approved by CEP FSW LEIDEN. The patients/participants provided their written informed consent to participate in this study.

Author Contributions

MK, AE, JV-M, and IH conceptualized, prepared the original draft and wrote the manuscript. MK and IH contributed to the methodology. MK was responsible for the formal analysis and investigation. IH was responsible for the funding acquisition. AE, JV-M, and IH supervised the study.

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Conflict of Interest

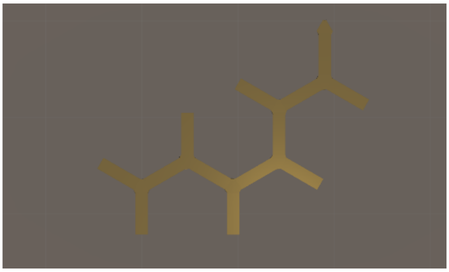
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

Home-based Navigation training

Egocentric Training

The egocentric training was composed of the modules: "landmark-action association", "turn-sequence" and "egocentric updating". In the "landmark-action association" module, a virtual environment was constructed consisting of an array of 3-way intersection points connected by corridors. The corridors connected to the intersection points formed a 120-degree angle. At each junction point, one corridor served as entry point, one corridor lead to a dead end and one corridor lead to either the next junction point or to the exit (**Supplementary Figure 7.1**). A square landmark was placed in between the two-response corridor, facing the entrance corridor. A mist was present in the environment, obscuring the rooms at the other end of the corridors. In each trial, an environment was generated using a semi-randomized procedure. This determined the order the of intersection points along the route (e.g. left, right, right, left). Landmarks were randomly selected from a database of 46 images (black and white symbols).

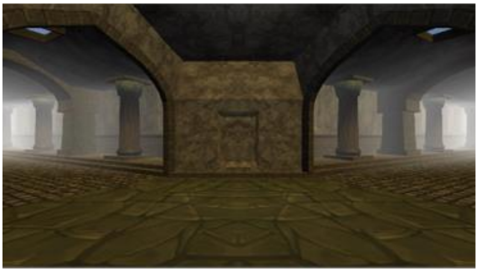


Supplementary Figure 7.1 Overview of an environment as constructed through a randomized procedure in the landmark-action association and turn sequence modules

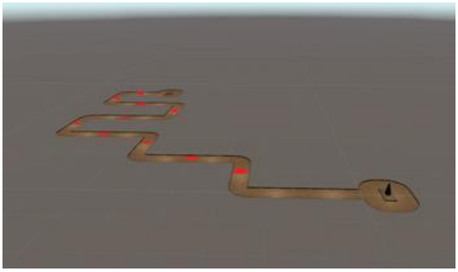
Supplementary Figure 7.2 Landmarks are presented at intersection points in the landmark-action association module.

A demo route through the maze was shown. Participants were instructed to remember what action was taken at each landmark (**Supplementary Figure 7.2**). Afterwards, participants were placed in the maze and had to find their way to the ending location. When visiting a dead end, a point was subtracted, when entering the correct corridor, a point was earned. The difficulty of a level was determined by how many intersection points were present in the environment: difficulty block 1 contained 3 levels consisting of 2, 3 and 4 intersection points, difficulty block 2 contained 3 levels consisting of 4, 5, 6 intersection points, etc.

The “turn-sequence” module, was similar to the “landmark-action association” module with two important exemptions. First, no landmarks were present in the environment (**Supplementary Figure 7.3**). Second, the participants were instructed to remember the order of turns taken as shown in the demo video. Thus, participants could only find their way to the ending location by encoding and reproducing a egocentric turn sequence.



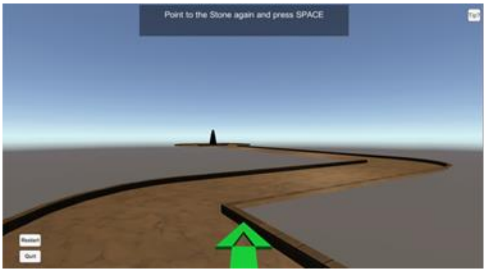
Supplementary Figure 7.3 An intersection as seen in the turn sequence module.



Supplementary Figure 7.4 The layout of an environment constructed in the egocentric updating module. The black pyramid in the starting room is the target of the pointing task. Red dots indicate measuring points, these were not visible to the player while traversing the environment

In the “egocentric updating” module, a virtual environment was constructed consisting ending and starting room connected by a single corridor (**Supplementary Figure 7.4**). This corridor was composed of three types of interconnected sections: 90-degree left turns, 90 degree right turns and strait sections. Ten measurement locations were present in each environment.

In each trail, participants had to remember the location of the starting room, while traveling through the corridor to the ending room. The participants were instructed to maintain their sense of direction, by imagining a compass always pointing to the starting location. When a participant arrived at a measuring point, an arrow would be shown in front of the camera pointing forward (**Supplementary Figure 7.5**). Participants were tasked to point towards the starting location by rotating the camera. After pointing, the walls in the environment became transparent (**Supplementary Figure 7.6**). This allowed participants to observe their pointing deviation and recalibrate their orientation. Points were earned depending on the pointing deviation: a deviation between 0 and 30 degrees resulted in 2 coins earned, a deviation between 30 and 60 degrees resulted in 1 coin earned. A deviation greater than 60 degrees resulted in 0 coins earned. After recalibrating the wall turn opaque and participants proceeded further along the corridor.



Supplementary Figure 7.5 The measuring phase in the egocentric updating module requires payers to orient the arrow to towards the starting room.

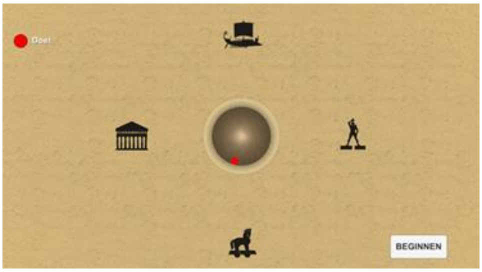
Supplementary Figure 7.6 Feedback in the measuring phase, after pointing the walls of the environment become transparent and navigators can reorient themselves towards the starting location.

The difficulty of a level was determined by the amount of sections that composed the corridors, and thus the distance traversed between measuring points: Difficulty block 1 contained 3 environments with 10 sections (each with a measuring point), or 20 sections (a measuring point alternately placed between non-measuring point sections). Difficulty block 2 contained 3 environments with 20 sections or 30 sections (a measuring point alternately placed between 2 non-measuring point sections), etc.

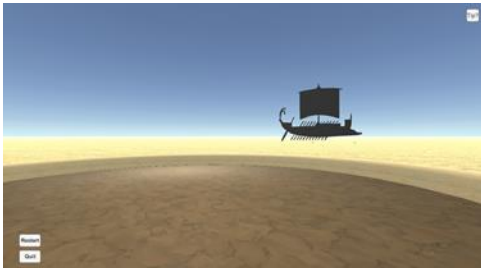
Allocentric Training

The allocentric training was composed of the modules: “place-finding: distal landmarks”, “place-finding: local landmarks” and “map-use”. In the “place finding: distal landmark” module, a virtual environment was constructed consisting of circular platform surrounded by 1 to 4 landmarks that were placed outside of the platform in the north, south, east or west direction. A start location and target location were present in the environment. In each trial, an environment was generated using a randomization procedure. The procedure determined the identity and locations of the landmarks. Furthermore, the starting and target locations were selected from a list of 48 coordinate combination.

At the start of a trail, participants were presented with a 2D map of the environment (**Supplementary Figure 7.7**). The start location was not visible on the map. The target location was indicated with a red dot. After studying the map, participants were placed on the starting location. The target location was not visible in this first-person perspective. Participants were instructed to use the distal landmarks and their relative position on the platform to find the shortest path to the target location (**Supplementary Figure 7.8**). A 'step counter' bar was present on the top of the screen. Traversing distance cause the bar to decrease. If participants traveled less than 2 time the minimal 2 points were earned. If participants travelled 2 to 4 times the minimal distance they would earn 1 point. If participants travelled more than 4 times the minimal distance to reach the target location, no points were earned.

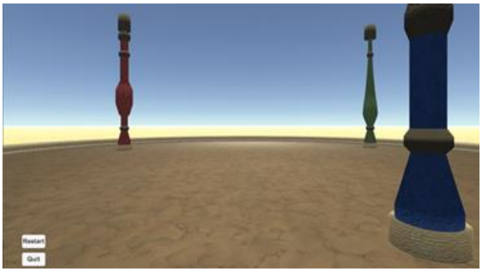


Supplementary Figure 7.7 A map is presented at the start of the trial that contains the target location (red dot) and the distal landmarks (black figures).

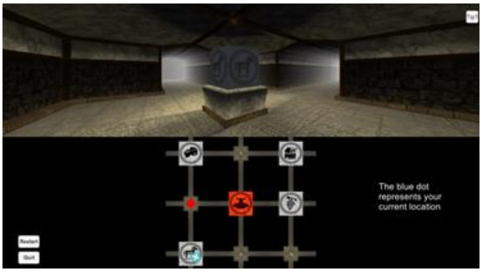


Supplementary Figure 7.8 Players use distal landmarks to find the target location.

The difficulty of a level was determined by the amount on distal landmarks present in the environment and the size of the circular platform itself. Difficulty block 1 contained 4 landmarks. Within each difficulty block, participants would perform 3 trails in small, medium and large platforms. The "place finding: local landmarks" module, was similar to the "landmark-action association" module with one important exemption. No distal landmarks were present in this module. Instead, 3 local landmarks (pillars) were placed inside the circular platform (**Supplementary Figure 7.9**). Participants were instructed to find the shortest path the target by using the configuration of the 3 pillars in relation to their own location and the location of the target. The difficulty of a level was determined by the placement of the target location in relation to the local landmarks. In the first difficulty block, the target location was always placed and the foot of a pillar. In the second difficulty block, the target was placed on a 'line' between two pillars. In the third difficulty, the target was placed inside the 'triangle area' formed by configuration the three pillars. In the fourth difficulty block, the target was placed outside the ‘triangle area’ formed by the configuration of the three pillars.



Supplementary Figure 7.9 Players use local landmarks to find the target location.



Supplementary Figure 7.10 Players can use the map in the bottom screen to orient themselves in the environment. The map shows their current location (blue dot), the goal location (red dot), the landmarks and the red landmarks.

In the “map-use” module, a virtual environment was generated consisting of a variable number of square rooms placed in a grid formation. Each room had 4 corridors. Corridors connected to the adjacent rooms or to dead ends (in rooms in the outer layer of the environment). A randomization procedure filled each room with landmarks derived from a database of 46 images (black and white symbols), ‘red’ landmarks, a start and an end location. The starting and ending rooms were randomly determined but a set travel distance between these rooms was always maintained. Depending on the trial condition, participants had access to ‘dynamic’, ‘static’ or ‘temporary’ map information. The map was a 2D overview of the environment depicting the rooms, landmarks and ending location (red dot). In the ‘dynamic’ and ‘static’ conditions participants were presented with a split-screen. In the top screen, a first-person perspective of the environment was shown. In the bottom screen, a map of the environment was shown. In the ‘dynamic’ condition, a participant’s current location was updated and shown on the map (blue dot). In the ‘static’ condition, the starting location was shown on the map (blue dot), but the current location was not shown (**Supplementary Figure 7.10**). In the ‘temporary’ map condition, a map of the environment was only show prior to navigating in the environment. The map could be studied as long as required and disappeared after starting the trial, leaving only the first-person perspective. Participants were instructed to use the map to find the shortest route to the ending room and avoid visiting the rooms containing a ‘red’ landmark. Participants started with a number of points. Visiting the room resulted in a point lost. Visiting a room with a ‘red’ landmark lead to a loss of 2 points. Difficulty In the “map-use” module was determined by the size of the environment. Difficulty block 1 contained an environment consisting of 9 (3x3) rooms. Difficulty block 2 contained an environment consisting of 16 (4x4) rooms. During each block participants completed a ‘dynamic’, ‘static’ and ‘temporary’ map condition in 3 randomly generated environments.

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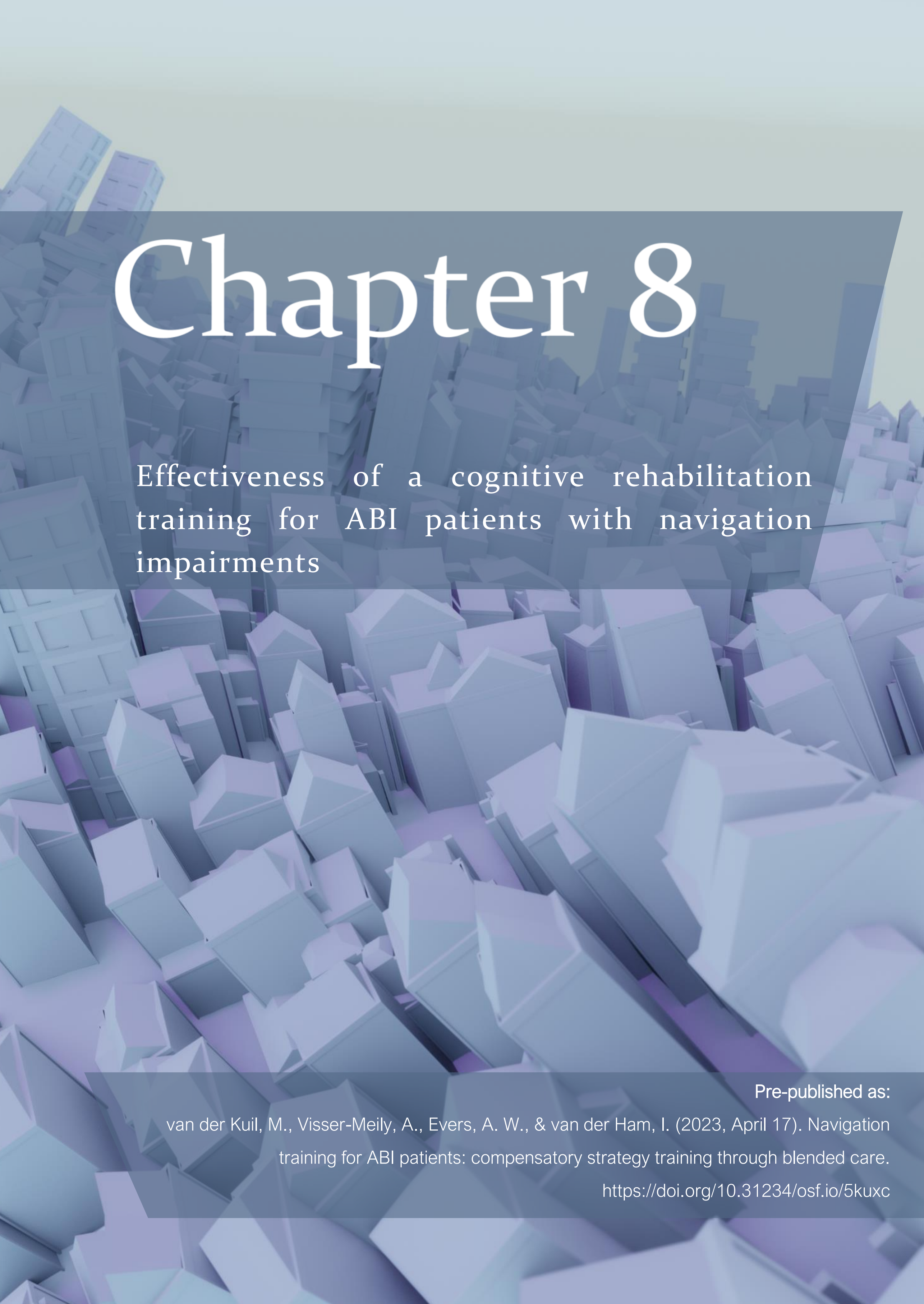

Chapter 8

Effectiveness of a cognitive rehabilitation training for ABI patients with navigation impairments

Pre-published as:

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Abstract

Objective – Patients with acquired brain injury (ABI) often report navigation problems. A navigation training was designed to introduce compensatory navigation strategies. The training was a blended care program, consisting of a psycho-education session and a 6-week training period using a serious game. In this study, the effectiveness of the training was evaluated in terms of self-reported and objective navigation abilities and societal participation levels.

Methods – A randomized controlled trial was conducted that included 42 ABI patients with varying types of brain injuries. Patients in the experimental condition engaged in the rehabilitation training whereas patients in the control condition received treatment as usual. Patients in the control condition were given the option to engage in the training after participation. Self-reported navigation abilities were assessed using the Wayfinding Questionnaire, objective navigation abilities were measured using the Virtual Tübingen testing battery and societal participation was measured with the Utrecht Scale for Evaluation of Rehabilitation Participation. In addition, patients in the experimental condition completed a goal attainment assessment. Measures were taken before, directly after and 4 weeks after the intervention period.

Results - Self-reported navigation ability improved significantly for patients in the experimental condition compared to their baseline scores and the post-intervention scores of patients in the control group. Within the experimental group, personally set goals were attained after the training. No effect of the intervention was found on objective indicators of navigation abilities and societal participation.

Conclusion - The intervention was effective in improving perceived navigation ability. Next, the navigation training should be examined in a clinical setting to ensure its effectiveness.

Introduction

Spatial navigation is an important component of many daily activities and is essential to an autonomous life (van der Ham et al., 2013). Widespread networks of the brain support this cognitive function, rendering navigation ability vulnerable to brain injury (Boccia et al., 2014; Cona & Scarpazza, 2019; Y. Qiu et al., 2019). As such, 39% of ABI patients report navigation problems (Van der Kuil, Visser-Meily, Evers, & van der Ham, 2021).

Rehabilitation of navigation ability has proven difficult due to the multifaceted nature of the spatial navigation. Earlier treatments have taken one of two approaches to rehabilitation: 1) treatments specifically tailored to unique cases (e.g., Bouwmeester, van de Wege, Haaxma, & Snoek, 2015; Brooks et al., 1999; Incoccia, Magnotti, Iaria, Piccardi, & Guariglia, 2009) or 2) treatments designed to memorize specific routes and environments (e.g., Kober et al., 2013; Lloyd, Riley, & Powell, 2009). While effective, these treatments are few, experimental, case-focussed and not generalizable to clinical practise. There is need for a standardized treatment that can be employed in clinical settings.

To allow for a standardized treatment, the training protocol should incorporate distinct types of representation used during navigation: egocentric (view-centred) and allocentric (world-centred) (Roberta L. Klatzky, 1998). These reference frames form the foundation of distinct navigation strategies. Egocentric strategies include memorizing routes, directional heading and spatial updating and whereas allocentric strategies utilize configurational knowledge and map use (Igloi et al., 2009; R. X. F. Wang et al., 2006; Wiener et al., 2013). Functional and neurological dissociation (Colombo et al., 2017; Holdstock et al., 2000; Jordan et al., 2004; C. Wang, Chen, & Knierim, 2020; Zaehle et al., 2007) of these strategies suggests that a compensatory approach to the rehabilitation is possible, allowing for a more generalized treatment.

In this study, we assess the effectiveness of a compensatory strategy training for navigation impaired ABI patients in a clinical trial. Patients in the treatment condition were trained to adopt a navigation strategy beneficial to their intact spatial abilities by training with a serious game. We hypothesized that patients who received the training would improve on measures of navigation ability (self-reported and objective) and societal participation levels compared to patients in the control group.

Methods

Participants

Inclusion criteria were: A) clinically diagnosed ABI in the chronic stage of brain injury (> 6 months post onset), B) between 18 and 85 years of age, C) self-reported navigation impairments during screening D) access to a home computer with an internet connection, E) motivation to partake in the training. Exclusion criteria were A) spatial neglect, B) interfering psychiatric disorders (dementia, depression, autism, personality disorder etc.) or substance abuse, C) non-Dutch speaking and D) physical/mental inability to complete the training.

Approval was obtained from independent ethics committees (METC Leiden, NL62050.058.17). All participants gave informed consent for the screening procedure and for their enrolment in the study. Participants gave informed consent that medical data would be requested from their treating medical professional. Participants received compensation for their travel expenses. The first participants was included on 21-6-2018, the last measurement took place on 31-1-2020. Trial Registration: Trialregister.nl/trial/7097.

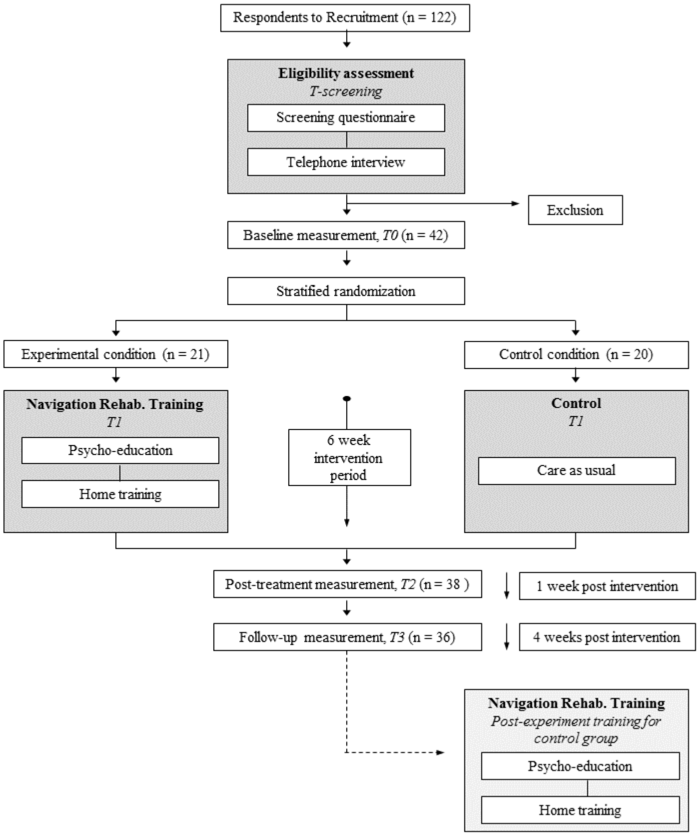


Fig 8.1 Design of the trial.

Design

The study employed a partially blind, randomized control trial design with an experimental and control group (Fig 8.1). Respondents were screening using an online questionnaire and a telephone interview (T-screening). Eligible respondents were invited to the university to perform the baseline measurements (T0). Afterwards, a stratified randomization process based on gender was used to allocate participants to the experimental and control groups. Participants in the experimental group were reinvited to the lab for psycho-education and started a six week home-training period (T1), while participants in the control group received no treatment (treatment as usual). Seven weeks after the start of the intervention period, participants were invited back to the university to perform the post-intervention measurements (T2). Four weeks later, all participants filled in an online follow-up questionnaire (T3). After completing this follow-up questionnaire, participants in the control group were given the opportunity to partake in the training, outside of the experimental procedure.

Treatment

The treatment was developed in a close collaboration with patients (van der Kuil et al., 2018) and experts in the field (e.g. occupational therapists, neuropsychologists) and was validated in a study with a group of healthy participants (van der Kuil, Evers, Visser-Meily, & van der Ham, 2020). The goal of the treatment was to introduce and train the use of a compensatory navigation strategy which participant could employ in their daily life. The treatment consisted out of a face-to-face psycho-education session and a home-training period in which patient used a specifically developed software package. Each patient would train one of three compensatory strategies: egocentric, allocentric or a combination. Allocation to a compensation training was dependent on a strengths and weaknesses profile constructed from the baseline measurements (T0) for each participant directly after the randomization procedure (**Supplementary document A**).

The egocentric strategy training was centred on navigation from a first-person perspective. The strategy focusses on developing route knowledge, categorization (left and right) of environments, attention to temporal components of routes and egocentric updating. The allocentric strategy training was centred on the construction of mental maps and the use of cartographic maps. The strategy focusses on effective map use, including allocentric and egocentric perspective switching, place finding using important landmarks in the environment and encoding locations. The combination strategy training was specifically designed for participants with landmark knowledge impairments. An approach to navigation was taught that centred around locations, map-use and egocentric updating whilst minimizing the reliance on landmark information. Elements of both egocentric and allocentric navigation were used in this strategy.

Psycho-education

Participants were invited to the university to participate in a face-to-face psycho-education session. An experimenter with knowledge of spatial cognition educated participants on the underlying cognitive theories of spatial navigation. Topics discussed included allocentric/egocentric representations and processing, route and survey knowledge and navigation (compensation) strategies. This information was provided based on a pre-written text with illustrations to maintain consistency between participants (**Supplementary document B**). Information was provided on comprehension level appropriate to the participant and in an interactive format, allowing experimenters to relate the topics to participant's current navigation problems. To ensure comprehension, participants were asked to give examples of key concepts of the text in relation to their own neighbourhood and navigation behaviour. More information was provided until correct examples were given. The experimenter demonstrated the training software and discussed how the application can be used to develop an appropriate compensation strategy.

eHealth navigation training software

Participants installed the navigation training software on their home computers. Each participant received a personal login code that provided access to either the egocentric, allocentric or combination version of the training. Each version contained 3 modules in which a specific component of navigation ability was trained (**Table 8.1**). Note that the combination training shared modules with the egocentric and allocentric versions. Each module consisted of a spatial challenge in the form of a serious game, set in an interactive 3D virtual environment. The objective in each module was to earn points by successfully solving challenges using a specific navigation strategy. During a training session with a module, participants engaged in three trials. If enough points were earned over the span of these trials, participants were granted access to more difficult levels. If a participant earned too little points over three consecutive training sessions with a module, the difficulty level of this module would remain the same. Nine difficulty levels were available for each module. Using a (restricted) randomization process, environments and landmarks varied each time a participant started a challenge, allowing for a novel experience each time a module was restarted. Feedback on performance was provided after each set of challenges followed by advice regarding the transfer of the trained strategy to real life situations.

Table 8.1 Summary of navigation modules.

Module	Training type of module	Training goal
Egocentric updating	Egocentric & Combination	Maintaining a sense of direction towards an important location while traveling. This egocentric process known as path integration, allows navigators to monitor their current location without explicit landmark knowledge.
Sequential turns	Egocentric & Combination	Remembering a sequence of turns when traversing an environment. This egocentric sequence strategy allows for route learning in the absence of landmarks.
Landmark association	Egocentric	Forming landmarks-action associations. The navigation strategy trained here is known as egocentric stimulus-response learning.
Mental mapping	Allocentric & Combination	Memorizing allocentric knowledge of location and knowledge of (temporal) order. The navigation strategy trained here allows participant to become adept at using maps during navigation
Map-use	Allocentric	Switching between allocentric representations and egocentric perspectives. The navigation strategy trained here allows participant to become adept at using maps during navigation. This includes using landmarks, planning routes and exploring the environment.
Landmark configuration	Allocentric	Orientation in an environment using distal or local landmarks. The navigation strategy trained here requires participants to learn the location of places in relation to geographical and landmarks information.

Measurements

Outcome measurements

Subjective navigation ability

The main outcome measure of the study, self-reported navigation ability, was assessed using the Wayfinding Questionnaire (WQ) (de Rooij et al., 2019). The WQ consists out of 22 questions, corresponding to three domains: navigation & orientation (NO), spatial anxiety (SA), and distance estimation (DE). All questioners were presented on a 7-point Likert scale ranging from 1 (not applicable to me) to 7 (fully applicable to me). Earlier studies have shown high internal (Claessen, van der Ham, et al., 2016) and discriminant (de Rooij et al., 2019) validity for the WQ. Self-reported navigation ability was assessed at T-screening, T2 and T3.

Objective navigation ability

An adapted version of the Virtual Tübingen (VT) task was used to measure objective navigation ability (van der Kuil et al., 2020). Participants watched a route through a virtual replica of the city of Tübingen twice (260s). Afterwards, participants completed 9 sub-tasks that measured specific components of navigation ability: scene/landmark recognition, turn sequence, route continuation, route order, point to start location, distance estimation, direction estimation, route on map recognition, location on map recognition. Two versions of the task were available to ensure different routes at T0 and T2.

USER-P

The 'Utrecht Scale for Evaluation of Rehabilitation-Participation' (USER-P) questionnaire was used to assess experienced participation restrictions in relation to a patient's disability at the different assessment points (Post, Van de Port, Kap, & Berdenis van Berlekom, 2009). The questionnaire has been shown to be responsive (van der Zee, Kap, Mishre, Schouten, & Post, 2011), reliable (Van der Zee et al., 2010) and has high validity (Post et al., 2012). The USER-P contains 32 questions, which correspond to three domains: Frequency (e.g. frequency of partaking in household tasks), Restrictions (e.g. possibility of visiting relatives) and Satisfaction (e.g. satisfaction with current outdoor mobility). The questionnaire measured participation levels on a Likert scales. The questions corresponding to the frequency scale ranged from 0 (never) to 6 (36 hours/19 times or more per week). The questions corresponding to the restriction scale ranged from 0 (not possible) to 4 (without difficulty). The questions corresponding to the satisfaction scale ranged from 0 (very dissatisfied) to 5 (very satisfied). USER-P was measured at T0, T2 and T3.

Goal attainment scaling

Using the Goal Attainment Scale method (Turner-Stokes, 2009), participants in the experimental condition filled in and reflected on a personal rehabilitation goal before the start of the training. Patients formulated a real life goal (e.g. being able to cycle to the mall independently), and classified their current progress in relation to this goal (ranging from -2, far lower to +2, far higher than the goal, with 0 being the achievement of the goal) The training goal was determined on T1, and was re-evaluated on T2 and T3.

Training data

The data generated by the intervention software was collected using an online database. Training data included training level per module, training time per session, points earned and the randomization seeds for each module.

Baseline characteristics

Demographics

General demographic information was obtained during at T-screening using an online questionnaire including age, gender, education level and access to computers.

Neuropsychological assessment

Baseline cognitive functioning over different cognitive domains was determined during baseline using a battery of neuropsychological assessment. Forward and Backward Corsi block tapping tasks were used to assess visuospatial working memory (R. P. C. Kessels et al., 2008; Roy P. C. Kessels et al., 2000). The WAIS IV digit span task was used to assess verbal working memory (David Wechsler, 1955). Version A and B of the Trial Making Task were used to assess attention and cognitive flexibility (Reitan, 1992). The Dutch Adult Reading Test was used to assess premorbid verbal intelligence (Schmand, Lindeboom, & Van Harskamp, 1992). Set I of the Raven AMP was used to assess premorbid non-fluent intelligence (Raven, Raven, & Court, 1962). The Line Bisection task was used to determine the presence of visuospatial neglect (Hausmann, Ergun, Yazgan, & Güntürkün, 2002). Neuropsychological testing was performed at T0.

Computer Skills

The Computer User Self-Efficacy scale (CUSE) questionnaire was assessed during baseline to examine computer ability (Cassidy & Eachus, 2002). The questionnaire consists out of 36 items corresponding to three scales: Self-efficacy, Familiarity and Experience. This questionnaire was used to inspect the level of computer literacy amongst the patients, as the intervention was largely computer based. The CUSE was measured at T0.

Statistical

Primary analysis

A WQ overall score was calculated using by summing the NO, and DE scores and subtracting the SA score. A difference WQ score was calculated for the control group and the experimental group by subtracting the score at T2 from T0. The SD for both groups was calculated using: $\sqrt{(Variance\ T2 + Variance\ T0 - 2Covariance(T2, T0))}$, thereby correcting for covariance between the two measurements. An independent paired T-test, with the difference WQ score as dependent and the conditions as independent variables was used to assess the effect of the treatment.

Secondary analyses

The scores on the WQ subscales 'navigation & orientation', 'distance estimation' and 'spatial anxiety' were analysed using a repeated-measures MANOVA with 'time' (T-screening, T2, T3) as within participant factor and 'condition' (experimental vs. control) as between-participant factor. Paired t-tests with correction for multi-comparisons (Bonferroni) were used for post-hoc analysis. Gender, age and education level were included as covariates in the analysis.

Subtasks of the VT test was assessed using the repeated measures MANOVA with 'condition' as between subject factor and 'time' (T0, T2) as within subject factor. Gender, age and education level were included as covariates in the analysis. The subtask 'map recognition' was analysed separately using a Chi-square test as the score was a binary variable.

The scores on the USER-P subscales 'frequency', 'restriction' and 'satisfaction' were analysed using a repeated measures MANOVA with 'condition' as between subject factor and 'time' (T0, T2, T3) as within subject factor. Paired t-tests with correction for multi-comparisons (Bonferroni) were used for post-hoc analysis. Gender, age and education measures were included as covariates in the repeated measures MANOVA analyses. Additionally, 14 items of the questionnaire (1B1 – 1B5, 2.3 – 2.6, 2.9, 3.3 – 3.6, 3.10) were selected because of their relevance for navigation and were analysed separately using a repeated measures MANOVA.

GAS scores were assessed using a repeated measures ANOVA using 'time' (T1, T2, T3) as within-subjects factor and gender, age and education as covariates.

Additional analyses

Independent T-tests and Chi-square tests were performed to compare demographic statistics, computer experience and neuropsychological assessment scores between the control and the experimental groups.

Data availability

Anonymized data not published within this article will be made available upon reasonable request from any qualified investigator for purposes of replicating procedures and results.

Results

Sample

A total of 42 participant were included in the experiment (**Supplementary document C**). In total, 38 participants completed T0, T1 and T2 (Table 2). The follow-up T3 was completed by 36 participants. Four participants withdrew from the experiment. Two participants experienced dizziness during the experiment. One participant withdrew stating the study was too intensive. Contact with one participant was lost after T1. Three participants that withdrew were assigned to the experimental condition, one participant was not yet assigned to a condition.

Independent T-tests were performed to assess age and education differences between the control and experimental group (**Table 8.2**). No significant difference for age (t (36) = -1.518, p = .138) and education (t (36) = 0.623, p = .539) were found between groups. A chi-square test revealed no proportional difference of gender between conditions (X^2 (1, N = 38) = 0.78, p = .782).

Independent T-test were performed on the scales of the CUSE to assess differences in computer ability between the two conditions. No significant differences for Self-efficacy (t (36) = 1.076, p = .328), familiarity (t (36) = 1.431, p = .161) and computer experience (t (36) = 0.992, p = .289) was found between groups.

Table 8.2 Patient characteristics

	Control	Experimental	Total Sample
N	20	18	38
Gender (% male)	40	44.44	42.11
Age (years)	49.65 (13.45)	56.17 (12.95)	52.74 (13.45)
Education (Verhage)	5.95 (0.83)	5.78 (0.88)	5.87 (0.84)
Type ABI*			
Stroke (% in group)	35.00	50.00	42.11
Traumatic brain injury (% in group)	30.00	27.78	28.95
Brain Tumour (% in group)	20.00	0.00	10.53
Other**(% in group)	15.00	22.22	18.42
ABI hemisphere			
Left (%)	5	16.67	10.53
Right (%)	30	22.22	26.32
No clear hemisphere (%)	65	61.11	63.16
ABI onset (months)†	136.45 (116.21)	117.44 (94.88)	127.45 (105.66)
Computer User Self Efficacy			
Self-efficacy	140.6 (27.18)	131.11 (27.08)	136.11 (27.19)
Experience	4.00 (0.79)	3.78 (0.55)	3.89(0.69)
Familiarity	3.85 (1.42)	3.22 (1.26)	3.55 (1.37)

*No official medical documents were available from 4 participants. Information provided by the participant was used.

**The category other includes the following cases (hypoxia, herpes encephalitis, 2 intracranial pressure, infection, rr ms, white matter degradation).

† The onset data in the table is an approximation. For 8 participants (1 experimental, 7 control), the exact onset date of ABI was unknown. The data for these participants was estimated based on information in medical records and participant reports.

Neuropsychological assessments

Several neuropsychological assessments were performed to inventory cognitive disability in patients. Independent T-tests were performed to assess whether differences were found in cognitive performance between the control and the experimental group (**Table 8.3**). No differences were found between control and experimental group on any of the cognitive tests.

Table 8.3 Performance on the cognitive tests in control and experimental groups

Cognitive test	Control	Experimental	t^*	p^*	Healthy Controls**
Corsi Block tapping task					
Forward (span x score)	46.90 (11.52)	45.11 (19.67)	0.346	.73	49.59 (13.48)
Backward (span x score)	49.50 (16.88)	43.78 (15.63)	0.108	.29	49.5 (17.37)
Digit Span (WAIS IV)					
Forward (score)	8.20 (1.82)	9.00 (2.02)	-1.264	.22	9.03 (2.04)
Backward (score)	7.90 (1.99)	7.72 (1.86)	0.272	79	7.91 (2.12)
Dutch Adult Reading Test (score)	86.50 (6.65)	87.11 (10.20)	-.221	.83	85.63 (9.31)
Raven APM set 1 (score)	8.95 (1.61)	8.56 (2.59)	0.577	.57	9.75 (2.02)
Trial Making Test					
Part A (seconds)	40.33 (12.76)	53.95 (36.01)	-1.159	.12	29.82 (8.67)
Part B (seconds)	71.91 (25.07)	93.60 (47.85)	-1.765	.09	58.34 (16.29)
Part B (B/A)	1.84 (0.53)	2.22 (1.26)	-1.228	.23	2.03 (0.61)

*T-test preformed between control and experimental groups

** Norm values based on data from healthy controls obtained from earlier study, N = 32, Age: M = 55.41 SD = 5.06, Gender: 50% female, Education: M = 5.78 SD = 1.74. Independent t-tests and chi-square test reveal that the healthy controls were comparable to the ABI patients in terms of age (p = .29), education (p = .85) and gender (p = .60).

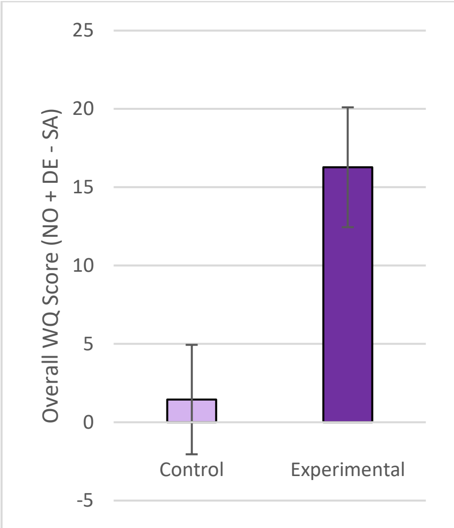
Subjective navigation ability

Primary analysis of the subjective navigation ability measured using the overall WQ score, revealed a significant effect of condition, $t = 2.87$, $p < 0.01$, Cohen's $d = 0.93$. WQ differences scores were significantly higher in the experimental group compared to the control group (M =16.28 SD = 16.23 *vs.* M = 1.45 SD = 15.62), indicating a positive effect of the intervention of subjective navigation ability (**Fig 8.2 A**).

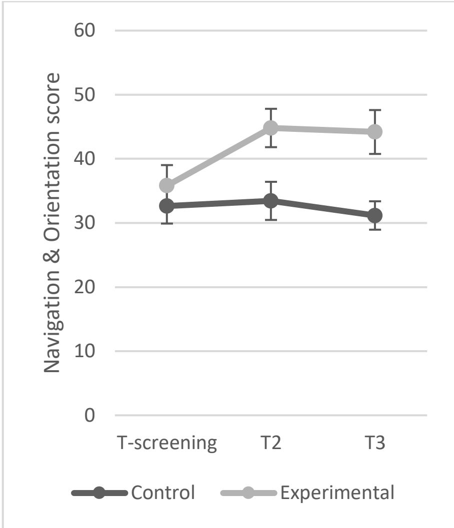
Analysis of individual subscales of the WQ (including the follow-up T3 measurement) using a repeated measures MANOVA revealed an interaction effect between 'condition and 'time', F (6, 24) = 3.44, p = .014; *Wilk's Λ* = 0.538, *partial η2* = 0.462. Univariate tests with the Greenhouse-Geisser correction showed a significant effect of ‘condition * time’ for the subscale ‘Navigation & Orientation’, *F* (1.932, 56.02) = 7.138, *p* = .002, *partial η2* = 0.198, and the subscale ‘Distance Estimation’, *F* (1.955, 56.694) = 4.133, *p* = .022, *partial η2* = 0.125 (**Fig 8.2 B, C & D**).

Post-hoc T-test showed that within the experimental condition, ‘Navigation & Orientation’ score at T-screening was significantly lower than at T2 (*M* = 35.81 *SD* = 12.84 *vs. M* = 44.81 *SD* = 11.97) and T3 (*M* = 35.813 *SD* = 12.84 *vs. M* = 44.19 *SD* = 13.69). Furthermore ‘Distance Estimation’ at T-screening was significantly lower than at T2 (*M* = 9.69 *SD* = 14.98 *vs. M* = 12.56 *SD* = 4.32), and a trend-level difference was found between T-screening and T3 (*M*= 9.69 *SD* = 14.98 *vs. M* = 11.19 *SD* = 4.32). No effects of ‘time’ were found in the control condition.

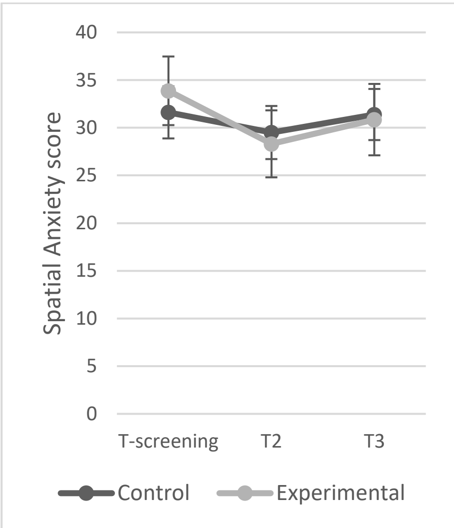
Contrasting the WQ scales for between the condition indicated that ‘Navigation & Orientation’ scale was significantly higher in the experimental condition compared to the control condition at T3 (*M* = 44.19 *SD* = 13.69 *vs. M* = 31.17 *SD* = 9.40). Furthermore, at trend-level, T2 score was higher in the experimental condition compared to the control group (*M* = 44.81 *SD* = 11.97 vs. *M* = 33.44 *SD* = 12.64) (*p* = .088). Similarly, ‘Distance Estimation’ score was significantly higher in the experimental group that the control group at T2 (M= 12.56 SD = 4.32 vs. M = 7.56 SD = 4.69).



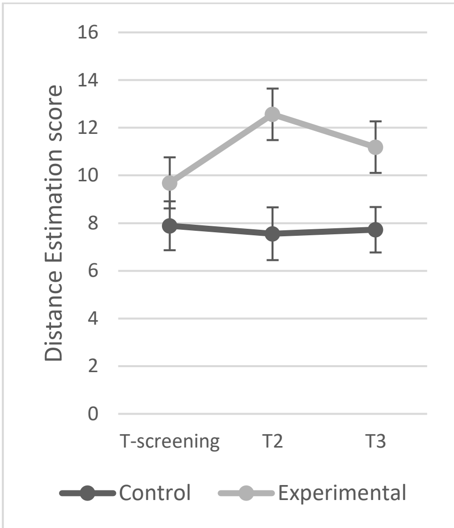
A. Overall WQ score T2-T-Screening



B. WQ subscale: navigation & orientation



C. WQ subscale: spatial anxiety



D. WQ subscale: distance estimation

Fig 8.2 Subjective navigation measure.

Objective navigation ability

Navigation ability measured with the VT testing battery was assessed using the repeated measures MANOVA with 'condition' as between subject factor and 'time' as within subject factor. No main effect was found for ‘time’ (F (8, 26) = 0.772, *Wilk's Λ* = 0.88, p = .631), ‘condition’ (F (8, 26) = 0.433, *Wilk's Λ* = 0.88, p = .89) or the interaction ‘time * condition’ (F (8, 26) = 1.102, *Wilk's Λ* = 0.762, p = .448). As ‘map recognition’ was a binary measure, it was measured separately using a chi-square test. No effects of ‘time’ (X^2 (1, N = 38) = 0.12, p = .73).and ‘condition’ (X^2 (1, N = 38) = 0.12, p = .73) were found on the ‘map recognition’ tests (**Table 8.4**).

Table 8.4 Performance on the Virtual Tübingen testing battery, functional measure of navigation

	Control		Experimental		Healthy Controls
	T0	T2	T0	T2	*
Scene Recognition, score	12.7 (1.69)	12.25 (1.83)	12.44 (2.33)	13 (1.68)	13.78 (1.36)
Route Sequence, score	4.2 (1.99)	4.15 (1.9)	3.28 (1.74)	4.83 (1.58)	4.81 (1.97)
Route Continuation, score	5.3 (1.3)	4.7 (1.75)	5.06 (1.86)	5.83 (1.69)	6.06 (1.27)
Route Order, score	14.1 (4.28)	13.4 (5.03)	14.44 (4.37)	14.94 (4.9)	18.00 (4.69)
Pointing to Start, pointing deviation	57.76 (19.57)	52.69 (21.06)	63.85 (24.98)	62.28 (23.93)	44.16 (19.96)
Distance Estimation, score	4.85 (1.9)	4.7 (1.98)	4.5 (2.12)	5.17 (1.82)	5.47 (1.67)
Direction Estimation, score	4.25 (1.59)	4.35 (1.14)	4.22 (1.17)	4.78 (1.4)	4.19 (1.31)
Location on Map, pixel deviation	236.23 (89.23)	220.39 (98.36)	237.85 (111.75)	204.28 (86.99)	134.38 (72.89)
Map Recognition, % correct	50.00	50.00	44.44	55.56	68.75

* Norm values based on data from healthy controls obtained from earlier study, N = 32, Age: M = 55.41 SD = 5.06, Gender: 50% female, Education: M = 5.78 SD = 1.74. Independent t-tests and chi-square test reveal that the healthy controls were comparable to the ABI patients in terms of age (p = .29), education (p = .85) and gender (p = .60).

User-P

USER-P questionnaire was used an outcome measure of societal participation. A repeated measures MANOVA with 'condition' as between subject factor and 'time' as within subject factor. The analysis showed that there was no significant effect of 'time', F (3, 26) = 2.28, *Wilk's* Λ = 0.627, p = .072, *partial* $\eta 2$ = .373, or 'time * condition', F (3, 26) = 2.44, *Wilk's* Λ = 0.61, p = .057, *partial* $\eta 2$ = .388. A separate repeated measures MANOVA of USER-P items relevant navigation did not reveal an effect of 'time * condition' F (28, 44) = .445, *Wilk's* Λ = 0.595, p = .984, *partial* $\eta 2$ = .229.

Goal Attainment Scaling

A repeated measures ANOVA was performed with 'time' as within subject factor and GAS score as dependent variable. A main effect of 'time' was found on GAS score F (1.87, 22.395) = 5.97, p < .009 η^2 = 0.332. Post-Hoc t-test revealed that T2 score was significantly higher in the intervention group than T1 score (M = -0.19 SD = 0.75 *vs.* M = -1.5 SD = 0.52). Similarly, T3 score was significantly higher than T1 score (M = -0.19 SD = 0.84 *vs.* M = -1.5 SD = 0.52), indicating that the intervention group attained self-determined goals at the post-treatment and maintained these goals at the follow-up assessment.

Training Adherence

Participants in the experimental condition would engage in one of the three training modules. Training time, challenges completed and average level obtained were recorded (Table 8.5).

Table 8.5 Training Adherence and performance

	Combination training	Allocentric training	Egocentric training	Total
N	6*	7	5	18
Training Time (minutes)	137.22 (90.91)	236.59 (108.97)	160.59 (80.52)	185.01 (101.016)
Challenges completed (*M*)	87.4 (36.94)	269.857 (221.88)	101.4 (49.69)	166.65 (165.45)
Average Level (range 0-9)	4.1 (1.71)	6.54 (1.87)	6.2 (2.18)	5.73 2.09)

* Training data of 1 participant is missing due to a logging error in the server

Discussion

The goal of this study was to assess the effectiveness of a rehabilitation training in a population of navigation impaired ABI patients. The intervention was designed to improve navigation ability by means of compensatory strategy training through blended care. Using an RCT design, we found that patients who engaged in the training improved significantly in perceived navigation ability compared to the control group. In addition, progress was made towards achieving self-set rehabilitation goals by patients in the experimental condition. No beneficial effects of the training were found with regard to objective navigation ability and the societal participation scores.

Perceived navigation ability was the target outcome measure of the intervention. While self-reported navigational ability improved in the experimental group, the subscale analysis revealed that the effect was driven by improvement of navigation & orientation and distance estimation subscales. Spatial anxiety levels were not affected by the training. Participants report that they became more adept at real life navigation, but they experienced similar levels of spatial anxiety. This result can be explained by the fact that the intervention explicitly targeted spatial processing strategies and did not include cognitive-behavioural-emotional regulation component often employed in anxiety treatments (Behar, DiMarco, Hekler, Mohlman, & Staples, 2009). This improvement of navigation ability was further demonstrated by the significant improvements on the personal real-life goals participants had stated at the beginning of the intervention period. Most patients who engaged in the training achieved their personal rehabilitation goals, or made clear progress towards their goal.

Contrary to expectations, the use of a novel navigation strategy did not result in an improvement of objective navigation abilities. In an earlier concept study in which 6 participants engaged in the training, performance differences were found before and after the intervention (Claessen, van der Ham, et al., 2016). In this study, no clear improvement was found, but rather, a change in performance patterns over the different tasks. A similar phenomenon might have taken place in the current study. However, likely due to nature of the group analysis, changes in individual patterns were not observed. The current finding is in line with earlier results in which this training was tested on a healthy group of participants (van der Kuil et al., 2020). In this study, a change in preferred navigation strategy was observed, whilst the objective navigation ability scores did not change. It has been suggested that navigation strategy selection does not correlate strongly with objective navigation abilities measured in the VT (Prestopnik & Roskos-Ewoldsen, 2000; van der Kuil et al., 2020). As such, the use of a novel navigation strategy is not reflected in VT task performance. This can be explained by the nature of the VT testing battery. In the current VT task, participants watched a route through an environment and were asked questions about the environment. As such, no active navigation was involved. Earlier research has shown that active or passive learning of an environment might affect how spatial representation are formed (Carassa, Geminiani, Morganti, & Varotto, 2002; Chrastil & Warren, 2012). While passive environment learning allows for a more standardized comparison between participants, we might not observe the utilization of novel strategies and techniques employed by patients after training.

No improvement of societal participation as measured on the USER-P scales was observed. Additionally, the analysis with only items relevant for navigation did not reveal an interaction effect of time and condition. While patients report that their navigation abilities improve, they did not seem to change their daily activities. Possibly, further encouragement by therapists is required for patients to improve participation and change habits. Alternatively, the four week period between the intervention and the follow-up measurements might have been too brief to induce a measurable change in societal participation.

Treatment adherence is considered a pitfall for home-based training interventions (Jurkiewicz, Marzolini, & Oh, 2011; Wentink et al., 2018). Home training often involves high level of attrition among participants or low levels of training time. In the current study, measured intervention adherence by tracking active training time and performance. Participants were asked to train for 360 minutes over the period of 6 weeks. An active average game time of 185 minutes was observed. This game time does not include time in menu screens, reading instructions, inspecting results or practising with the application of strategies in real life. While there is a degree of uncertainty in this data, we observed an acceptable level of time investment by the participants.

While the results of the intervention are promising, the lack of improvements in objective abilities and societal participation levels indicate that optimization of the treatment programme is warranted. The current intervention was designed to optimize training results whilst minimizing time and effort required from therapists. Only one hour of psychoeducation, face-to-face treatment time, was employed in this study. We expect that additional face-to face therapy sessions would be beneficial to the training success. In these sessions, there should be more attention to psycho-emotive factors underlying the impairments. There exist a variety of effective cognitive behavioural therapies (CBT) that help patients manage anxiety (Hofmann & Smits, 2008). Depending on the severity of spatial anxiety (as measured using the WQ) and characteristics of the patient (e.g. level of cognitive functioning), CBT can be integrated in the therapy sessions to help reduce the levels of spatial anxiety in patients. Furthermore, further elaboration on and specification of the goal attainment component of the intervention can be employed to help participants integrate the training in their daily lives. If therapists take a more active role in guiding and planning the attainment of rehabilitation goals set by the patient, societal participation might improve.

Several limitations also need to be discussed. First, due to the nature of the design, the study was not fully blinded. Patients who received the training understood that they were in the experimental condition, while patients in the control group noted that they did not receive training before the second measurement. We opted not to include a placebo training as no believable placebo navigation training was available and alternative brain training treatments as placebo's will have led to undesired side effects. Furthermore, as the training was offered to patients after completion of the study, occupying patients with a sham training might have taken away their incentive to partake in this. As such, the most realistic comparison with treatment was care-as-usual. Second, the study was terminated early due to low inclusion rates nearing the end of the study time. Respondents often reported difficulty traveling to the testing location. The study description, which stated that three visits were required, might have been deterred respondents from participation. However, given the large effect size on the main measures, the sample size was adequate. Third, while care was taken to minimize the effect of simulation sickness (usability tests, choosing to use desktop VR instead of immersive VR), several patients reported simulation sickness and a few of these patients resigned from participations. As no simulation sickness was reported in a study in which healthy participants used this intervention, this result suggests that the population of ABI are particularly susceptible to simulation sickness.

The results of this study reveal a promising intervention that can be applied patients with a wide array of navigation problems. It should be stressed that this study was performed in an experimental setting and was conducted by researchers with a background in spatial cognition who managed the technical component of the intervention. It is important that the results of this intervention are validated in clinical setting: guided by healthcare practitioners in an ambulatory care setting. This poses challenges concerning education of healthcare practitioners on the topic and the technical components of the interventions.

In conclusion, the compensatory, blended-care, strategy training for navigation impaired ABI patients significantly improved perceived navigation ability. While self-reported navigation abilities improved, no beneficial effect on objective navigation ability and improvements on social participation was observed here. The intervention is promising for clinical practise and should be validated in ambulatory care with healthcare practitioners as therapists.

Sponsor information:

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Author’s role:

MK, IH AV & AE developed the study’s concept and theories. MK & IH developed the tasks and intervention software. MK and IH conducted the study. MK performed statistical analysis. MK, IH, AV & AE interpreted the study’s results. MK, IH, AV & AE drafted the paper.

List of disclosures:

None of the authors report disclosures.

Supplementary Material

Strengths and weakness profile (supplementary A)

Participants in the experimental condition were allocated to the egocentric, allocentric or combination strategy training based on their strengths and weaknesses. During T0, before allocation to a condition, participants completed the Virtual Tubingen testing battery. Results of the Virtual Tubingen test were analyzed to determine the performance levels on different domains of navigation ability. Relative performance on each sub-tasks of the VT testing battery was determined by calculating a participant's Z-score in comparison to results provided by a healthy group of 32 participants (dataset acquired in an earlier experiment). The cut-off criteria set for impairments in each task is a Z score below -1.65 SD of the mean. The allocation of the training type was determined by the following steps:

1. Patients impaired on the scene/landmark recognition task would receive the combination strategy training.
2. Participant with selective impairments on one or more of the egocentric sub-tasks would receive the allocentric training and vice versa.
3. Participants with impairments on both egocentric and allocentric sub-tasks, will receive strategy training corresponding to domain (allocentric or egocentric) with the highest mean Z-scores over the 4 tasks in the respective domains.
4. Participants without impairments on egocentric or allocentric sub-tasks, will receive strategy training corresponding to domain (allocentric or egocentric) with the highest mean Z-scores over the 4 tasks in the respective domains.

Psycho-education procedure (supplementary document B)

Procedure

1. The experimenter and participants are seated at a table.
2. The experimenter summarized the content of the psycho-education session.
3. All images and texts placed on the table. The participants receives a copy of the documents so they can read along. The participant is encouraged to take notes.
4. The experimenter reads the text with the patients
5. After each paragraph, the experimenter asks if he should elaborate on the topic and questions can be asked.

6. The following topics are explained using the images:
   A. Landmarks

      Discuss if the participant can give examples of landmarks he or she uses in their daily life. Discuss the properties and characteristics of informative landmarks with the participants Discuss how a scene (configuration) of an environment can also be used as a landmark (e.g. a specific intersection). Ask participants to give examples.

   B. Perspectives
      Discuss the images regarding egocentric and allocentric perspectives. Discuss the concept of perspectives using the example of objects on a table and a map of the participant's room vs. a photo of their room.
   C. Navigation strategies

      Discuss the results of the Virtual Tubingen task. Explain the concepts of the sub-task of the Virtual Tubingen test and relate this to a patient's score. Use examples to explain these topics. Discuss if the participant can relate to the score. Discuss how a participant impairments experienced in daily life relate to the educative text. Introduce the compensation strategy.

   D. Navigation training software

      Install the software on the participant's computer or show how this can be done. Explain how a participant can log in using the password and username. Explain the menu screens of the software (where to find the training, education and progress). Go over each training module and explain its purpose and how the module relates to a participant's impairment. Discuss how participants can apply the exercises in the software in daily life.

Original psycho-education text and images.

1.1 Introductie

Onder navigatie verstaan we het vinden van de weg. We gebruiken ons navigatievermogen iedere dag. We navigeren wanneer we grote afstanden afleggen, bijvoorbeeld wanneer we op weg zijn naar de supermarkt of wanneer we naar ons werk reizen. Ook op kortere afstanden, wanneer we binnen een gebouw de weg moeten vinden, spreken we van navigatie. Denk bijvoorbeeld aan het vinden van de polikliniek wanneer u zich in een ziekenhuis bevindt.

Het navigatievermogen is complexe functie. Uiteenlopende denkprocessen maken het vinden van de weg mogelijk. Zo voorziet de visuele waarneming ons van informatie over waar we zijn en stelt het geheugen ons in staat om informatie over de omgeving op een later moment weer op te halen. Bovendien wordt er een beroep gedaan op onze planningsvaardigheden wanneer we een route moeten uitstippelen.

We kunnen verschillende strategieën gebruiken om naar een andere locatie te reizen. Dit biedt mogelijkheden voor revalidatie. In deze training gaan we onderzoeken welke manier van navigatie goed bij u past en krijgt u een programma mee naar huis om met deze manier van navigeren te oefenen. Om beter te worden in navigatie is het belangrijk dat u goed begrijpt hoe u met ruimtelijke informatie om kunt gaan.

1.2 Herkenningspunten

Herkenningspunten zijn voorwerpen of onderdelen van de omgeving die opvallen en makkelijk te onthouden zijn. Enkele voorbeelden van herkenningspunten zijn gebouwen, bepaalde kruispunten, straatnaambordjes of opvallende voorwerpen zoals treinsporen of zendmasten.

Het onthouden van herkenningspunten is een belangrijk onderdeel van het navigatievermogen. Herkenningspunten kunnen gebruikt worden om de omgeving te structureren. Zij kunnen dienen als referentiepunt en kunnen gebruikt worden om te bepalen waar in een route we ons bevinden.

Tijdens het navigeren is het onthouden van de identiteit van de herkenningspunten een eerste stap (wat is het?). De twee stap is het koppelen van de herkenningspunten aan de locaties in de omgeving (waar is het?). We kunnen dit op verschillende manieren doen.

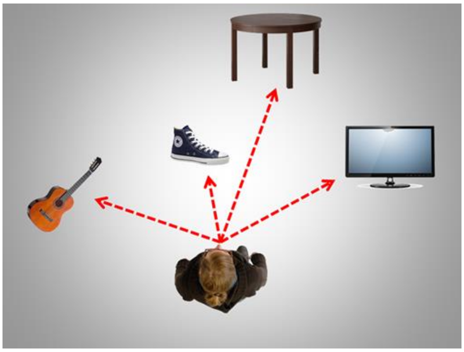
1.3 Perspectieven

We kunnen de koppeling tussen een herkenningspunt en de bijbehorende locatie op twee manieren onthouden: vanuit een eigen-perspectief of vanuit een helikopter-perspectief. Het eigen-perspectief wordt ook wel egocentrisch genoemd (ego betekent ik in het Grieks). Het helikopter-perspectief wordt allocentrisch genoemd (allo betekent anders in het Grieks). Wij zullen beide perspectieven bespreken.

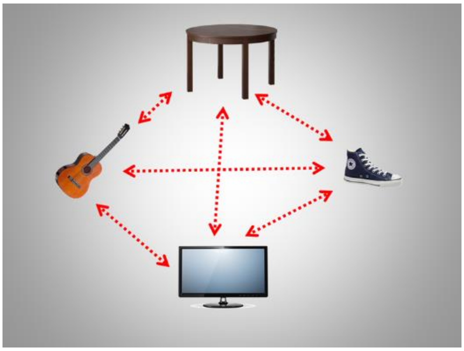
1.3.1. Eigen-perspectief

Een eigen-perspectief is gekoppeld aan het beeld dat u heeft wanneer u zelf in de omgeving staat (**Supplementary Figure 8.1**). Bij het koppelen van een herkenningspunt aan een locatie vanuit het eigen-perspectief maken we dus gebruik van beschrijvingen als "links van mij", "rechts van mij" of "recht voor mij".

Als u iemand hoort zeggen: "De slager zit links van de groenteboer" of "mijn huis ligt achter het spoor". Dan weet u dat deze persoon de locatie van de herkenningspunten benoemt vanuit een eigen-perspectief.



Supplementary Figure 8.1 Egocentric reference frame handout



Supplementary Figure 8.2 Allocentric reference frame handout

1.3.2. Helikopter-perspectief

Een helikopter-perspectief is juist niet gekoppeld aan een bepaalde positie in de omgeving, maar omvat informatie over hoe locaties zich ten opzichte van elkaar verhouden. U kunt de locaties en de herkenningspunten dus onthouden als een soort plattegrond (**Supplementary Figure 8.2**).

Stelt u zich de landkaart van Nederland eens voor. U weet dan dat Amsterdam noordelijk ligt van Rotterdam. Ook weet u dat dat de stad Utrecht ten oosten ligt van beide steden. U kunt de afstanden en richtingen tussen de steden onthouden.

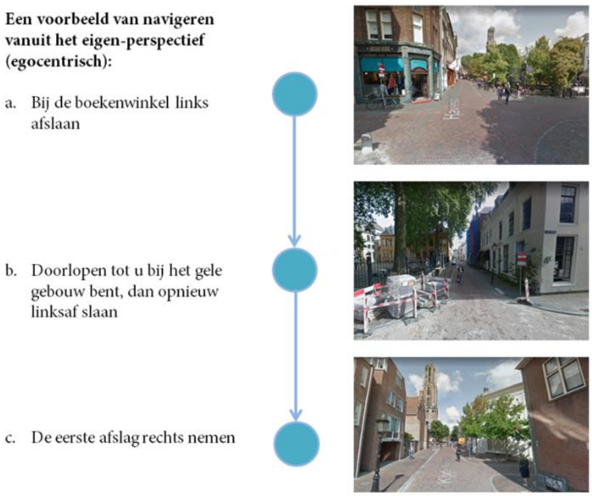
Een dergelijk helikopter-perspectief kunt u ook gebruiken op een veel kleinere schaal. Bijvoorbeeld wanneer u bedenkt waar de meubels in uw huis staan. Mogelijk heeft u hiervan een "mentale plattegrond" in uw hoofd. Wanneer we de locaties van herkenningspunten onthouden in een mentale plattegrond spreken we dus van een helikopter-perspectief.

1.3 Navigatiestrategieën

We hebben het nu gehad over herkenningspunten en de perspectieven waarmee we de locaties van herkenningspunten kunnen onthouden. Wanneer we navigeren hebben we een doel voor ogen: We willen van punt A naar punt B. Hiervoor hebben we informatie over herkenningspunten en hun locaties nodig. In grote lijnen onderscheiden we twee strategieën waarmee we dit kunnen doen: Navigeren vanuit het eigen-perspectief (ook wel egocentrische navigatie genoemd) en navigeren vanuit het helikopter-perspectief (ook wel allocentrisch navigatie genoemd).

1.3.2. Navigatie vanuit het eigen-perspectief

Mensen die navigeren vanuit het eigen-perspectief maken vooral gebruik van (vaste) routes. Een route kan gezien worden als een volgorde van afslagen en herkenningspunten door een omgeving die locaties met elkaar verbindt. Als u zich een route voorstelt zult u dit waarschijnlijk doen vanuit een eigen-perspectief. Denkt u bijvoorbeeld eens aan de route vanaf uw huis naar de dichtstbijzijnde supermarkt (**Supplementary Figure 8.3**).



Supplementary Figure 8.3. Egocentric strategy handout

Een manier om een route te onthouden is aan de hand van een reeks afslagen. Bijvoorbeeld: “De eerste afslag links, vervolgens de tweede afslag rechts”. Op deze manier kunt u een reeks van afslagen onthouden zonder dat u kennis over herkenningspunten nodig hebt.

Een andere manier om een route te onthouden is door koppelingen te maken tussen afslagen en herkenningspunten. Bijvoorbeeld: “bij de supermarkt rechts, dan bij de slager links en daarna doorlopen tot u bij het plein aankomt”. In dat geval koppelt iemand een specifieke locatie (bijvoorbeeld het postkantoor) aan een specifieke actie (namelijk rechtsaf slaan).

Mensen die navigeren vanuit het eigen-perspectief onthouden voornamelijk een volgorde van locaties en welke actie daar genomen moet worden. Andere aspecten van de omgeving (zoals precieze afstanden) hoeven voor deze navigatiestrategie vaak niet onthouden te worden.

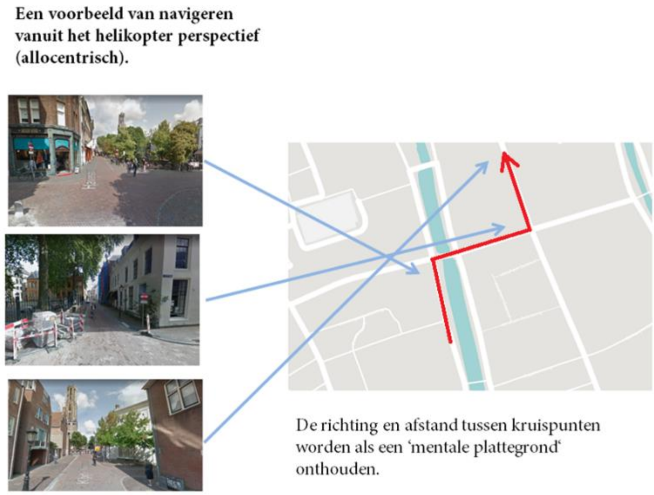
Een andere manier waarop we vanuit het eigen-perspectief kunnen navigeren is door het behouden van het richtingsgevoel. U kunt het richtingsgevoel voorstellen als een kompas dat altijd naar een bepaalde locatie wijst (bijvoorbeeld de ingang van een gebouw). Als u door een omgeving loopt en in de gaten houdt waar het kompas heen wijst, kunt u altijd teruglopen.

1.4.3. Navigatie vanuit het helikopter-perspectief

Zoals eerder genoemd is een helikopter-perspectief niet afhankelijk van een bepaalde positie in de omgeving. Kennis van een omgeving vanuit het helikopter-perspectief lijkt op het hebben van een mentale plattegrond.

Het meest aansprekende voorbeeld van navigeren vanuit dit perspectief is dan ook het gebruiken van een landkaart. Navigeren kan aan de hand van een papieren landkaart, maar ook met modernere technieken zoals Google Maps op de telefoon. U koppelt dan abstracte kennis over de omgeving van een 2D landkaart naar uw eigen-perspectief.

U heeft niet altijd een landkaart voor handen. Toch kunt u, wanneer u door een omgeving loopt, zelf ook herkenningspunten in een mentale plattegrond zetten en gebruiken. Als u de onderlinge richtingen en afstanden bedenkt tussen bijvoorbeeld de supermarkt, de bakker en de kerk, dan kunt u bepalen waar u zich op de kaart zou bevinden. U bouwt op deze manier vanuit een eigen-perspectief een helikopter-perspectief om uw plaats te bepalen.



Supplementary Figure 8.4 Allocentric strategy handout

Ook kunt u opvallende herkenningspunten in een stad gebruiken. Op verschillende plekken in de binnenstad van Utrecht is de Domtoren te zien. We kunnen navigeren door onze plaats te bepalen aan de hand van de Domtoren. U kunt bijvoorbeeld bedenken: Ik loop langs de gracht en de Domtoren is aan mijn linkerzijde, ik loop nu dus richting het zuiden (**Supplementary Figure 8.4**).

Beide perspectieven en navigatiestrategieën dragen bij aan het behoud van de oriëntatie. Er is niet een strategie beter dan de andere. Het ligt aan de omgeving en de situatie welke navigatiestrategie effectiever is.

Om een voorbeeld van te geven:

Als u in een gebouw bent met smalle gangen die op elkaar lijken en er zijn weinig herkenningspunten aanwezig, dan kan het verstandig zijn om vanuit het eigen-perspectief te navigeren en een reeks afslagen (links, rechts, links) te onthouden. Immers, zonder herkenningspunten is het moeilijk om een mentale plattegrond te maken.

Anderzijds, wanneer u uw auto parkeert op een grote open parkeerplaats (bijvoorbeeld aan het strand), dan kunt u moeilijk een route onthouden naar de auto. U bent dan beter af als u tijdens het parkeren bedenkt hoe de parkeerplaats ervan bovenaf uitziet en waar u ongeveer geparkeerd staat.

1.5 Toepassen van nieuwe navigatiestrategieën.

We hebben zojuist de achtergrondinformatie over navigatie doorgenomen. U zult in de loop van deze training gaan oefenen met nieuwe navigatiestrategieën en perspectieven.
Enkele algemene tips over het aanleren en training van nieuwe navigatievaardigheden:

- Het is belangrijk om u te beseffen dat navigeren al begint voordat u de deur uit gaat. Maak een plan van aanpak: waar gaat u op letten?
- Bekijk uw omgeving, bedenk welke informatie u heeft en wat u hier mee kunt. Bedenk rustig welke opties u heeft.
- Reflecteer na afloop op uw prestatie tijdens het navigeren, wat werkte goed voor u? Wat was moeilijk?
- Probeer uw nieuwe navigatiestrategie eens uit te leggen aan een vriend(in) of kennis. Wanneer u de nieuwe strategie onder woorden moet brengen kunt u tot nieuwe inzichten komen.

Screening Results (supplementary document C)

The study was advertised using social media, local newspapers and magazines, folders and an online platform for people interested brain research (hersenonderzoek.nl). Respondents contacted the experimenters by mailing, calling by phone or by directly visiting the study's website. All respondents were directed to the website to initiate the screening procedure could be initiated. The screening procedures consisted out of a questionnaire and a telephone interview.

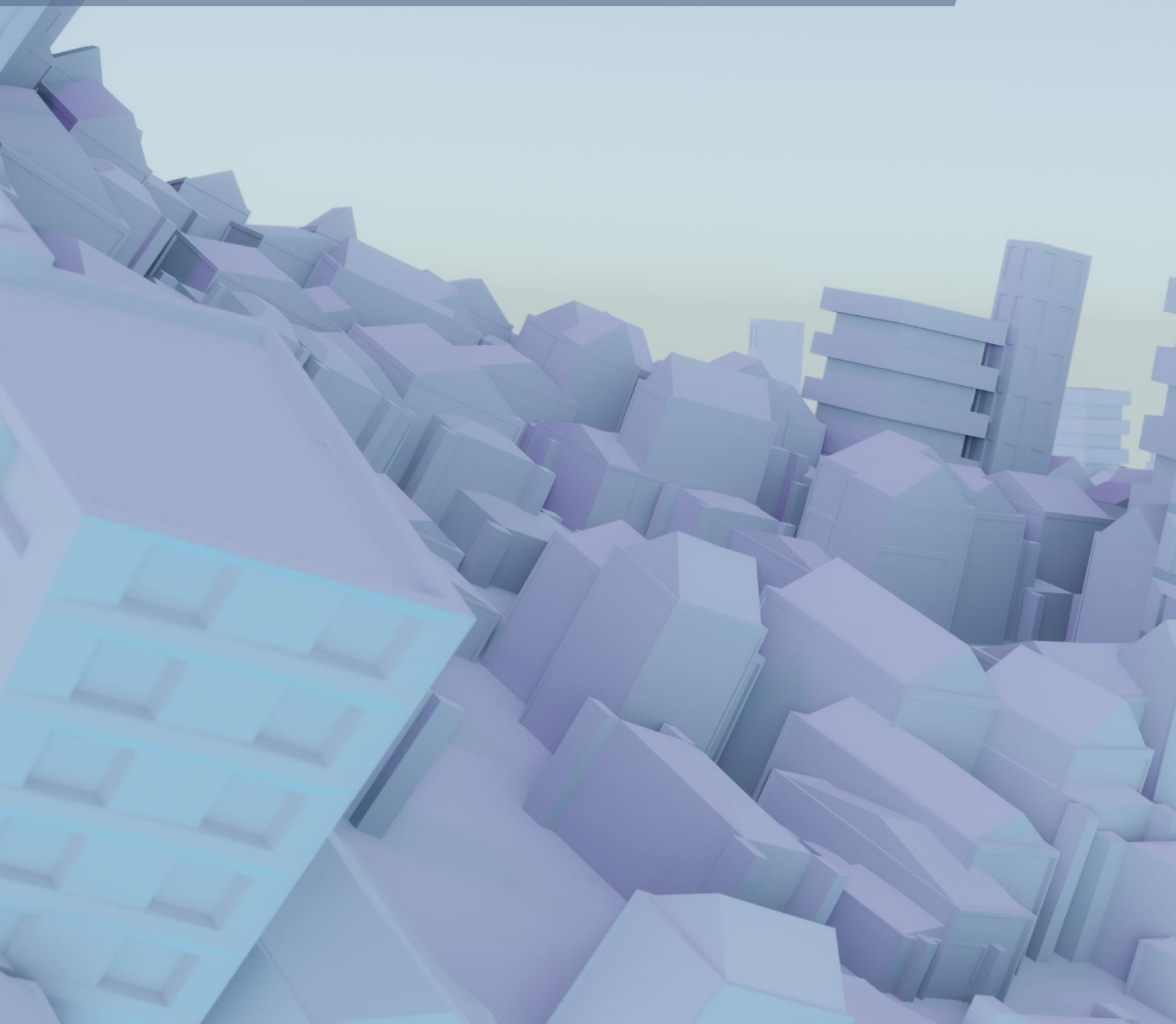
A total of 122 respondents expressed interest in the study. Contact with 17 of the respondents was lost after filing in the questionnaire or after providing direct information (**Supplementary Table 8.1**).. A telephone interview was held with the remaining 105 respondents. Of this group of participants, 10 responders were not diagnosed with acquired brain injury (mostly people directed via the online platform). Thirty-one participants were excluded as they reported no navigation impairments in their daily life. Many people in this category were interested in furthering research, but did not experience problems themselves. Five respondents were excluded as they suffered from addition neurological or psychiatric conditions (e.g. autism, major depression). Five respondents were excluded as they reported neglect. Five respondents were excluded as they were unable to travel to the lab at T0 and T2 (and potentially T1). Three participants withdrew from the recruitment phase after they perceived the experiment as being too intensive. Two participants did not have access to a computer that was required to use the training software. Two participants withdrew from the recruitment phase without stating a clear reason.

Supplementary Table 8.1 Recruitment process

Description	Nr. of respondents
Expressed interest	122
No contact after receiving information/filling in questionnaire	17
Telephone interview exclusion:	63
No navigation impairments	31
No acquired brain injury	10
Neglect	5
Psychiatric and/or neurological problems	5
No travel options	5
Study protocol perceived as too intense	3
No computer available at home	2
Lost interest (no clear reason given)	2
Telephone interview inclusion:	42

Chapter 9

General discussion



There currently is no standardized treatment for ABI patients who experience navigation problems. The general objective of this dissertation was to develop and evaluate a treatment, suitable for patients with navigation impairments. Four principles were incorporated in the approach to achieve this goal. Compensatory strategy training was designated as method of rehabilitation. The treatment had to be generalizable in order for it to be applicable to patients with a variety of navigation problems and cognitive abilities. Innovative technologies such as virtual environments and serious gaming elements were explored for use in the treatment. Lastly, a blended-care approach was taken with this treatment. The project was carried out in three phases that correspond to the parts in this dissertation: I) Problem assessment, II) Development of the treatment and III) Evaluation of the treatment.

Main findings

Problem assessment

Chapter 2 of this dissertation describes a nationwide online navigation experiment that was conducted among healthy participants and ABI patients. The study showed that the prevalence of self-reported navigation problems is higher (39%) among this population than previously estimated (29%). The study demonstrates that navigation problems are prominent in all types of ABI and are observed in patients with left, right and bilateral brain injuries. An assessment of objective navigation performance indicated that the performance on landmark recognition, route continuation and allocentric location knowledge are significantly lower compared to scores of matched healthy participants. The results of the study emphasize the importance of clinician's recognition of navigation problems among ABI patients and the need for adequate diagnosis and rehabilitation methods.

Development of the treatment

Chapter 3 is an inquiry into the underlying theoretical concept of the compensatory navigation strategies. The relation between learning perspectives (first-person or map perspectives) and the resulting mental representation of space was investigated. Evidence was found that supported the model of a partially independent representation of space. Specifically, route knowledge seems to depend on the perspective in which information was obtained. Survey knowledge seems to be less effected by the perspective in which information was obtained. For the purposes of content development for the treatment, this has important implications: People with impairment with egocentric knowledge acquisition, should be trained to obtain route knowledge by studying maps or by using GPS-like tools. In addition, these people should be trained to become adept at using maps to understand the environment from a birds-eye perspective. Perspective switching between map and first-person perspectives might be a useful skill for these patients. People with impairments relating to allocentric knowledge acquisition, should strictly focus on egocentric information acquisition for route knowledge. Metric spatial information such as distances and directions should be obtained through egocentric updating, rather than from birds-eye view perspectives. These insights led to the development of six specific training modules.

The home-training component of the treatment consists of exercises that educate patients on the use of novel navigation strategies and allow patients to practice with a novel approach to navigation. These modules were designed after experimental paradigms used in the field of spatial cognition. In Chapter 4, I present how these modules were constructed and what components of navigation were trained.

Chapter 5 and 6 describe a series of studies that were performed to give direction to the design and development of the treatment. Chapter 5 focusses on design choices that ensure effective interaction for ABI patients with the treatment software. In this usability study, we were concerned with design decisions regarding three critical gaming attributes: movement control in 3D virtual environments, instruction modality and feedback timing. Results showed that mouse-controlled interaction in 3D environments is more effective than keyboard-controlled interaction. Patients clearly preferred video-based instructions over text-based instructions, even though video-based instructions were not more effective in context of knowledge acquisition and comprehension. No effect of feedback timing was found on performance and motivation in games designed to train navigation abilities.

We investigated healthcare provider's attitudes towards digital tools in cognitive rehabilitation in Chapter 6. A broad sample of healthcare providers, including occupational therapists, psychologists, healthcare psychologists, cognitive therapists and others completed an online technology acceptance questionnaire survey regarding the use of digital cognitive rehabilitation therapies. Overall, healthcare specialists in cognitive rehabilitation have a positive attitude towards future digital interventions. The healthcare providers showed high levels of agreement with regard to perceived usefulness, perceived ease-of-use and intention to use. Levels on the subjective norm subscale were neutral, indicating a point of consideration for the implementation process of such interventions.

Evaluation of the treatment

The studies in the third part of this dissertation were conducted to evaluate the validity and effectiveness of the treatment. Chapter 7 was a pre-post study in which a group of healthy participants used the treatment at home over a period of 4 weeks, whereas a control group was passive. In this study, navigation strategy preferences were assessed prior and after the intervention period. The study showed that 50% of participants in the egocentric training version of the treatment adopted a different strategic preference. Conversely, 19% of the participants in the control condition shifted strategy. The allocentric training versions was not effective in changing navigation strategy, as the proportion of strategy shifters was comparable to that in the control group. These results for the first-time show, that in an ambivalent environment, navigation strategy preference can be shifted by using an external training. The intervention developed in this dissertation was, at least partially, capable of inducing a change in strategic preference.

Chapter 8 describes an RCT in which the effectiveness of the final version of the treatment was assessed in a group of navigation impaired ABI patients. Patients in the experimental condition showed a significant reduction in self-reported navigation problems compared to their baseline levels and the levels of the control group. In addition, the participants in the experimental condition made significant process in achieving their personally set rehabilitation goals, as measured with goal attainment scaling. No significant effect of the treatment was found on objective navigation abilities and societal participation levels. The treatment proved promising in this experimental setting. In the future, the treatment should be validated in a clinical setting.

Discussion of main finding

In the following section, I will discuss the findings of this dissertation in context of four topics: prevalence & diagnosis of navigation impairments, compensation in navigation rehabilitation, development of the treatment and implementation & future directions.

Prevalence and diagnosis of navigation impairments

Neuropsychological research published over the last 30 years, shows a wide variety of navigation problems associated with brain injuries (Claessen & van der Ham, 2017). As most of these accounts are case studies, little was known about the prevalence of the types of navigation impairments that can be distinguished. The nationwide navigation survey performed in chapter 2 sheds light on the pervasiveness of these type of problems in the ABI population at large. A considerable proportion (39%) of ABI patients reported navigation impairments, regardless of the type of ABI and location of the lesion. Admittedly, this study provides a rough estimate because of its inherent limitations: the study was performed unsupervised and data gathering was anonymous. Even considering these limitations, it is can be assumed that many accounts of navigation problems remain undetected and untreated.

This lack of detection can be attributed to both the anatomical and cognitive complexity of these impairments. Many neuropsychological impairments can be identified and to some degree understood by inspecting the location of the lesion in the brain by means of anatomical imaging (e.g. aphasia, motor impairments, hemispherical neglect, Gottesman & Hillis, 2010). The structure-function relation of these brain areas are well described in the literature (Cumming, Marshall, & Lazar, 2013). In context of navigation problems, the relation between impairments and brain injuries is less clear. PET and fMRI studies indicate large networks of neural substrates underlying spatial cognition (Cona & Scarpazza, 2019). Lesions that disrupt these networks can result in varied and diverse manifestations of impairments (Claessen & van der Ham, 2017). Chapter 2 stresses the complexity of navigation problems, as no clear relations were found between hemispherical injury location or types of brain injury and the type of navigation problems that are reported. As such, the location of a lesion might not lead a neuropsychologist to anticipate navigation problems in patients whom they treat, as might be the case with more well-known lesion related impairments such as aphasia and left hemispherical damage.

Navigation ability is supported by multiple cognitive functions, contributing to its cognitive complexity. As such, reported difficulties during navigation are likely to be regarded as components of more fundamental cognitive impairments by healthcare professionals. For example, landmark-recognition problems might be ascribed to memory problems, whereas allocentric location processing might be interpreted as impairments in executive functioning. However, navigation impairments can occur in isolation, without problems in other cognitive domains (de Rooij et al., 2019). It is recommended to diagnose navigation problems in a category of its own, rather than as side-effects of impairments of more fundamental cognitive functions.

Patients and professionals often have difficulty pinpointing the nature of cognitive problems (Schiehser et al., 2011). ABI patients are often not fully aware of their impairments, making the diagnostic process more difficult (Toglia & Kirk, 2000). Patients that partook in our studies (chapter 5, 8) remarked that navigation was notably more difficult, but found it hard to give an accurate description of their disabilities. This inability to describe the nature of navigation problems is understandable given the complex nature of navigation ability (Arne D Ekstrom, Huffman, & Starrett, 2017; Li et al., 2021). Effective navigation relies on a selection of relevant spatial information, encoding information in a mental framework, and processing this information to make the correct decisions. Having little understanding of the mechanisms underlying navigation, makes it difficult to reflect on one's disabilities, aside from the observation that one is often disorientated. In addition, few healthcare practitioners, including neuropsychologists and occupational therapist, are sufficiently knowledgeable on the topic of navigation to recognize and categorize problems patients might be reporting.

Another obstacle with navigation problems is that for many patients, impairments only become apparent in the chronic phase of brain injury. Patients first notice their impairments when they return to their pre-injury daily routines and try to live an independent life (Rasquin et al., 2010). As such, disabilities often go undetected by therapists for a longer period, potentially making rehabilitation more difficult.

Several patients in our studies reported that their navigation problems were non-consistent. For these patients, the experience of impairments can be determined or amplified by environmental factors. For example, navigation problems might only manifest in conjunction with mental fatigue (e.g. after an eventful afternoon), stress (e.g. a time-bound appointment) or overwhelming environments (crowded city centre). Patients tend to avoid these situations, thereby sacrificing a degree of autonomy, instead of discussing this with their rehabilitation specialists.

Overall, there are few diagnostic tools and no standardized treatment options available for these patients. Especially when compared to other cognitive impairments such as executive functioning (Chavez-Arana et al., 2018), memory defects (Elliott & Parente, 2014), or visuo-spatial neglect (Liu, Hanly, Fahey, Fong, & Bye, 2019; Luauté, Halligan, Rode, Rossetti, & Boisson, 2006). Currently, the Wayfinding questionnaire is the only standardized clinical tool than can be used to screen for navigation problems (de Rooij et al., 2019). This instrument indicates the presence or absence of navigational problems, but does not offer insight into the type of impairments (e.g. landmark recognition, route continuation, distance estimation).

There is high need for short and effective screening and diagnostic tools for different types of impairments. A first step in this endeavour is to develop a diagnostic method that is easy to use and understandable for practitioners. The large amount of data gathered in Chapter 2 can be used to develop such a tool. Data from healthy and ABI patients allowed us to develop norm-scores for each subtask. These scores can be used to develop a rapid screening tool for navigation impairments that can be used by healthcare providers that suspect navigation impairments in ABI patients they are treating. Such a tool will provide a fast, easy-to-understand and well-substantiated method to allow healthcare providers to screen patients for navigation impairments. Work on this tool has already begun, as a prototype is available online (https://lnt.navigatietraining.com/).

Recommendations

The prevalence of navigation problems among ABI patients warrants the adaptation of screening and diagnosis options in cognitive rehabilitation protocols. In the Netherlands, there currently is no standardized uniform approach employed for screening cognitive impairments at hospitals and rehabilitation centres. There are however, guidelines proposed by the Dutch Neurology Association that many healthcare centres adhere too (Nederlandse Vereniging voor Neurologie, 2019). These guidelines recommend that each stroke patient is at least screened with the MOCA. The MOCA however, is a global tool that is not sensitive to navigation problems (Nasreddine et al., 2005). Healthcare providers might gain insights from discussing potential navigation problems during anamneses and during the chronic phase in which patients resume their daily-life activities. Healthcare providers could ask the following questions as part of a short screening routine (most predictive items of the Wayfinder Questionnaire, de Rooij et al., 2019):

- How well are you capable of finding your way in an unknown building?
- How well are you capable of finding way to a meeting in an unknown city or part of a city?
- Do you enjoy taking new routes (for example shortcuts) to known destinations?
- How well can you estimate how long it will take me to walk a route in an unknown city when I you the route on a map (with a legend and scale)?

Strongly negative answers to any of these items warrant a full screening using the complete Wayfinding Questionnaire. This questionnaire comes with cut-off scores that allow the healthcare professionals to determine whether a patient suffers from significant navigation impairments. The next step in the diagnostic process would be to determine in what domain navigation problems are present. The prototype of the diagnostic tool, which was created from the results of chapter 2, allows healthcare professionals to get an understanding of impairments in the following domains: landmark, egocentric location, allocentric location, egocentric path or allocentric path. The results of this tool should be discussed with the patient, to understand how the impairment affects their navigation in real-life situations and whether it limits the patients in his/her daily life. The healthcare practitioners should determine If the patient is capable of and helped by engaging in the cognitive rehabilitation treatment described in part III of this dissertation.

Compensation

Ask five people how to travel from the Eifel Tower to the Notre Dame and you will hear five different strategies. The complexity of navigation provides obstacles for patients and healthcare professionals in detection and diagnosis. However, we can take advantage of this property when developing a treatment for navigation problems. The possibility of solving navigation challenges using a wide variety of approaches opens up the possibility for compensation.

Different methods of navigation rely on (partially) distinct networks in the brain (Boccia et al., 2014; Luca Latini-Corazzini et al., 2010; Li et al., 2021). Two major denominators in the activation of these networks are strategies that rely on egocentric processes and strategies that rely on allocentric processing (Zhang et al., 2012). As such, compensation based on egocentric and allocentric navigation strategies seemed a promising concept for the development of a treatment for navigation impairments.

It is known that people employ multiple strategies and are able to shift between strategies flexibly (Byrne, Becker, & Burgess, 2007; de Condappa & Wiener, 2016). However, people typically display a preference for a specific navigational strategy (Iglói, Zaoui, Berthoz, & Rondi - Reig, 2009). Earlier studies have shown that this strategy preference can change depending on the navigation goal and the environment. Repeated exposure to environments, in which one strategy is clearly more effective than another, will lead to the adoption of a more suitable strategy ((de Condappa & Wiener, 2016; Wiener et al., 2013). However, the ability to shift between strategies is affected by factors such as age and presumably, damage to the underlying neural networks (Colombo et al., 2017). It is possible that ABI patients with impaired navigational abilities will select navigation strategies similar to those that were preferred before the injury and as such, rely on a maladaptive strategy.

Few studies have been directed at establishing that strategic preference can be shifted and maintained by external interventions unrelated to a specific task. The main evidence for this approach was provided by a study in which patients changed their performance pattern on navigational abilities after training strategies with a therapist (Claessen, van der Ham, et al., 2016). To understand whether navigation strategies can be influenced by an external intervention, a more direct approach was taken in chapter 7. The outcome measure of this study was direct observation of navigation strategy selection after the training period. We demonstrated that engagement with the intervention, an early version of the treatment, can lead to strategy shifts in a strategically ambivalent environment. Admittedly, the intervention only leads to a shift in strategy for people who initially preferred an allocentric strategy and adopted an egocentric strategy, not vice versa. Regardless, the possibility of inducing changes in navigation behaviour in a neutral environment is an indicator that compensation might be a suitable approach for rehabilitation in this domain.

Effectiveness of compensation

The effectiveness of the treatment as a compensatory strategy training was finally evaluated in a group of navigation impaired ABI patients in chapter 8. The results of this trial were positive in the domain of self-reported outcome measures. Objective navigation abilities did not improve because of the treatment. Our results demonstrate that patients benefit from the treatment, and that these benefits are reflected in their daily lives.

Patients achieved ecologically valid rehabilitation goals they had set for themselves at the start of the training period. The goal attainment scoring method provides a measure of transfer of the compensation strategies that were taught to real-life situations. The rehabilitation goals set by patients varied widely in their nature and difficulty. For example, one patient’s goal was: “being able to cycle to the nearby camping place independently, with the patients partner cycling behind him, but not aiding him”. Another patient stated the goal of “maintaining my orientation when I leave a room”. Yet another patient set the goal: “not to panic when I am disoriented during navigation”. Most of the goals set by the patients were related to individual challenges and not directly related to the exercises in the treatment. Achieving these goals could not have been the result of a restitution of damaged functions, but rather, must have been the result of a change in the approach to navigation. A toolset of general compensatory navigation techniques was taught, that prepared patients to solve multiple navigational challenges.

Remarks from patients near the end of the trial support the idea that compensation strategies were transferred. Patients reported that they are now much more aware of their limitations and capabilities during navigation. Patients remarked that they make more preparations before leaving home such as looking at a map, planning routes and being mindful of important landmarks and locations during navigation. Furthermore, patients reported to be much more confident during navigation: taking the lead when traveling with others, or remarking that they did not panic whenever they got lost.

The effect of the treatment seemed to be maintained at least four weeks, as the self-reported navigation abilities were significantly higher in the follow-up measurement compared to the baseline measurement. The result suggests that the trained approach to navigation is integrated in the daily routine of patients.

A weakness of the methodology was that the study did not include any field-based observation to directly measure shifts in navigation strategies. Including observations into the experimental design would have been too taxing on the participants. Solely patient reported outcomes provide support for the idea that compensatory strategies did emerge in patients that engaged in the training. As the training was always directed at advancing intact functions, whilst ignoring impaired functions, it seems likely that a compensative, rather than a restorative component lay at the fundament of the training success.

Generalizability of compensation

The holistic approach of the treatment has the advantage that it is generalizable and standardisable for clinical practice. Earlier successful treatments have been strongly tailored towards individual patients (Bouwmeester et al., 2015; S. J. C. Davis, 1999; Incoccia et al., 2009; Rivest et al., 2018) or have focus on errorless learning of a specific environment or route (Kober et al., 2013). While effective, these treatments are impractical to implement as standard clinical practise. A lot of effort would be required to conduct highly individualized route training or to construct virtual environments tailored to each patient's locations of interest. The compensatory approach proposed by Claessen, van der Ham, et al. (2016) that was continued and expanded upon here, makes the treatment suitable for a heterogeneous patient population. As long as patients maintain intact components of navigation ability, the treatment can be applied. It is important to note that while the overall approach was standardized, there was room for individualized adjustments. The psycho-education component and subsequent contact with patients during the training period was tailored to the individual. A standardized informational text was read, but examples and implications were always related to the individual patient in the treatment. In-depth conversations regarding a patient's problems, living situation and goals were conducted to aid in the transfer process.

Finally, the blended-care approach that was taken in this treatment has advantages for patients in terms of accessibility. Large parts of the training were designed to be simple, self-explanatory and could be conducted at home by the patients, saving commuting efforts. Especially for this patient population, travelling to a rehabilitation centre can be an important obstacle for engaging in a rehabilitation program. Other aspects of blended-care, such as the possibility to complete the exercises in a patient's own pace and time and the blending of therapy in a patient's private situation contributed to the viability of the treatment (Rosalie van der Vaart et al., 2014). A diverse group of patients engaged in the treatment, including people with different levels of cognitive functioning, levels of navigation impairments and phases of life (i.e. students, people with young children, people in retirement etc).

Limitations of compensation

During the trial, several limitations of the compensatory approach became apparent. First, it was not always possible to get a comprehensive profile of the impairments in patients. In some cases, the performance pattern resulting from the Virtual Tübingen testing battery, pointed towards severe impairments in all three domains (landmark, allocentric, egocentric). In other cases, patients noted that their navigational ability had deteriorated notably, but still scored comparable to healthy participants on all domains. In these situations, we established the strongest domains, by comparing Z-scores between tasks and provided the strategy training that complemented these domains. In these extreme cases, using the objective navigation assessment might not be the best method for assigning the type of compensatory strategy training. Rather, a more in-dept personal account of their daily challenges and a stronger focus on personal rehabilitation goals should be leading in assigning what strategy is most appropriate.

Second, two patients had such severe cognitive impairments, that the psycho-education and subsequent training modules were very challenging. In these cases, effort was taken to adjust the information to the level of the patient and rehabilitation goals were set to match realistic expectations. In some cases, these goals were so minor, that the clinical relevance of the intervention was questionable. In future applications of the treatment, we suggest providing the treatment to patients with sufficient levels of insight into their own functioning (i.e. attention and memory) and problem-solving abilities. Additionally, a supporting role of the social network, such as the involvement of informal caregivers (i.e. partner, family), can be further explored in context of this treatment. In severe cases, involvement of family during diagnosis and psychoeducation sessions, might facilitate communication, knowledge transfer, selecting strategies for training and goal-setting (Plant, Tyson, Kirk, & Parsons, 2016).

Computerized cognitive training in compensatory rehabilitation

Over the past decade, a wealth of commercial computerized cognitive training programs (popularly named 'brain training') have become available such as Cogmed, Luminocity, CogniFit (García-Betances, Cabrera-Umpiérrez, & Arredondo, 2018). These programs aim to improve attention, executive function, processing speed and working memory of patients and elder individuals. Many of these programs aim to take advantage of serious game-like elements to improve the effectiveness of a therapy by enhancing adherence through enjoyment, providing adaptive challenge-levels and to allow for unsupervised training (C. M. van Heugten et al., 2016). Neuroplasticity is proposed to be the underlying mechanism in the approaches these programs take. There has been a lot of controversy surrounding these computerized cognitive training programs. Strong commercial interests have been involved in the success of these brain games, leading to misleading claims and promises of effectiveness as part of marketing of these programs (Simons et al., 2016). However, there are doubts as to whether these type of training programs are effective at all. Meta-reviews have failed to find clear evidence supporting the effectiveness of brain training software. Studies are often reported to contain flaws such as a lack of theoretical reasoning behind its underlying mechanisms, inappropriate control groups and no real-world outcome measures that can indicate the effectiveness of the intervention (Simons et al., 2016).

Regardless, it would be unwise to write off the potential of serious games in cognitive rehabilitation based on brain training games. The concept of compensation in computerized training programs has scarcely been explored. The few computerized rehabilitation training programs that employ a (metacognitive) strategy training approach in ABI patients seem promising, especially in combination with VR simulation techniques (Borgnis et al., 2022).

For the purposes of compensatory strategy training, virtual reality opened up interesting possibilities related to navigation. As real-life situations were simulated, the challenges posed in the training were directly related to daily life impairments. As such, the training directly targeted the cognitive function in an applied situation. In most modules, the type of environment was exchangeable for environments that patients might encounter in their own living area. The goals were clear but the suggested approach was rather open-ended. The environments were designed in such a way, that the only available spatial information that was necessary to reach a goal was either egocentric or allocentric. Patients were able to discover for themselves how they could utilize these spatial cues. The different set of environments and navigational challenges provided in this treatment, should lead to an arsenal of potential approach within the egocentric or allocentric domain. As such, the transfer is determined by a patient's capability to apply the strategy that was trained in the module to a novel situation, rather than a restitution effect that is usually aimed for in brain training games (Simons et al., 2016; C. M. van Heugten et al., 2016).

In sum, navigation impairments should be treated using a compensatory approach. The approach builds of a clear theoretical framework which was further validated by our studies. Compensatory strategy training is generalizable to a diverse patient population and standardisable for clinical practice.

Several preconditions for this approach are to be taken into consideration. First, screening and diagnostic tools will need to become available to therapists to determine what strategy would be most beneficial to patients. Second, therapists should consider whether the training is suitable for a patient given their learning capability and potential for insight into their personal strengths and weaknesses. Third, therapists have an important role in helping patients master novel navigation strategies through psycho-education. A good understanding of the neuropsychological theory underlying this treatment is required to tailor these sessions to the personal situation of patients.

More general, our studies show a promising role for computerized compensation training in rehabilitation, especially in combination with virtual environments. Virtual environments offer countless options for designing exercises and simulations with the goal of introducing novel strategies. Importantly, training modules in virtual environments can be designed in such a manner as to leave room for patients to experiment and develop their own approaches. The ecological validity of virtual environments is likely to aid in the transfer of these strategies to real-life situations. Researchers who aim to develop novel compensatory strategy treatments should consider the use of VR technology.

Development of the treatment

The studies presented in chapter 5, 6 and 7 were part of the developmental process of the treatment. Throughout this process, lessons were learned regarding the conception of such a treatment, the translation of theory to a gamified training and the involvement of stakeholders during the developmental processes.

In the construction of the treatment, we have followed guidelines laid out in literature (Wilson, Gracey, Evans, & Bateman, 2009). Five elements have been incorporated in this treatment. Education: Patients need to have a level of understanding about navigation as cognitive function and the differences in behavioural components that make up navigational strategies. Personal insight: Patients need to form an understanding of their impairments and strengths regarding the function that is targeted in the treatment. Goal setting: Patients need to have a clear view of what they aim to achieve in the rehabilitation treatment. Practice: Patients need to practice using the novel strategy and become familiar with it. Transfer: The trained strategies need to be implemented in their daily life activities. A two-step approach was taken to implement these elements in the training: a psycho-educative session and a home-training component.

Within the psycho-education session, personal insight to a patient's impairments and strengths were addressed by discussing a patient's daily problems regarding navigation and conjunction with the results of a general navigation assessment battery. Education on the topic of navigation was provided by reading a standardized educative text followed by answering questions patients might have. Goal setting was done by utilizing a simplified Goal Attainment Scaling approach. The GAS provided a unique insight in the problems, capabilities and desires of patients with navigation problems. Using goal attainment scaling is a viable method to evaluate the effects of an intervention in real life. In the context of this study, it can be argued that GAS evaluation contains information regarding the 'transfer' of the training to real-life situations. It was sometimes difficult to formulate SMART goals with patients, along the lines of the GAS method. Patients were encouraged to formulate a goal and together with the researcher, set the range of success (and failures). Some patients had difficulty coming up with reasonable goals, or formulated goals that were hard to quantify in levels of achievement. In these cases, the researcher was required to take a more active role in guiding the patients towards a realistic goal. Transfer was addressed by introducing the home-training software and by discussing how the exercises in the modules might be interpreted in light of daily life activities such as shopping or visiting relatives. While the psycho-education component of the treatment was rather conventional, therapists might include the Goal Attainment Scaling method in future treatments. Aside from establishing real-life goals, discussing these goals gave further insight into the nature of problems, that could be further expanded upon in providing information.

Gamification

The goals of the home-training component were to allow patients to practise and develop novel navigation approaches, to educate patients on navigation by means of practical exercises and to help in the transfer of difficult concepts of navigation that were explained in the psycho-education sessions. We were presented with several challenges in developing this software.

There was little precedence regarding the design of computerized exercises to train compensatory strategies. Consequently, we set out to design the exercises along three principles. Each module 1) encapsulated complex concepts of a behavioural approach (i.e. strategy) into simple exercises, 2) allowed patients to gain experience with and become better at using the strategy, 3) taught patients to recognize what strategy should be selected in real life situations.

Navigational challenges can often be completed by using a variety of approaches. To convey the benefit of the strategy to be trained to the patients, we sought examples of scenario's that clearly favoured to use of either egocentric or allocentric navigation. Navigation has been studied extensively in the more fundamental field of spatial cognition. A variety of experimental paradigms are published in papers that are concerned with isolated navigational abilities. As such, we modelled the training modules after existing experimental paradigms. For example, the Moris Water maze is a famous paradigm used to assess the navigational abilities of rats (Morris, 1981). In this paradigm, a circular area is filled with water. A platform is placed just underneath the water surface for the rats to rest on. Spatial cues in the form of red lights are placed alongside of the walls of the circular area. Rats are placed in the water, and will explore the environment to find the hidden platform. Over time, rats will learn to use the spatial cues to find a path to the hidden platform, utilizing allocentric spatial reference frames. The 'local and distant landmark' module in our training is a gamified virtual version of this paradigm. A grass plain, bordered by a circular wooded fence is used as a virtual reconstruction of the maze. The spatial cues in the Moris water maze are represented by plausible buildings in the distance surrounding the fence. In a cover story, patients learn that they have lost their mobile phone somewhere on the grass plain. The location of the mobile phone is the analogy of the platform in the Moris water maze. As in the original paradigm, the only method of finding the location of the mobile phone is by using an allocentric strategy. This exercise forced patients to become familiar with using allocentric cues. However, the exact method of utilizing the cues were left open for the patient to discover.

Modelling exercises after well-established experimental paradigms proved to be an excellent starting point for the development of serious games for rehabilitation. Researchers and developers might benefit from taking inspiration from experiments that isolate specific functions and to build game-like elements around these tasks.

In order to allowed patients to become more adapt in utilizing a strategy, we implemented game-like elements in which the difficulty of the challenges was gradually increased. Exercises were to be presented on a level that is always challenging to the user to optimize the learning process and increase motivation (Csikszentmihalyi & Csikszentmihalyi, 1992). In the current design, we opted for (simple) adaptive difficulty adjustments (Brassel, Power, Campbell, Brunner, & Togher, 2021; Zohaib, 2018). Nine difficulty levels were constructed for each exercise. The difficulty levels ranged from 'very easy' to 'challenging' even for high performing (healthy) navigators. More difficult levels were only accessible when a user demonstrated mastery over levels of lower difficulty. Note that patients were free to select their difficulty for each trial (and were not obligated to train on their highest difficulty setting). We experimented with the presentation of these difficulty levels. In the study with healthy participants, blocks containing difficulty levels were presented during a session (i.e. a session could consist out of levels 1, 2 and 3). However, in consultation with these participants and with patients, we concluded that the difficulty range within sessions was too steep. We have decided on a singular difficulty level per session (3,3,3). A more fine-grained distinction between sessions gave participants more opportunities to become accustomed to a higher challenge level. During informal testing, this adjustment led to lower levels of frustration and a smoother learning experience, as reported by participants.

In developing home-training computerized treatments, care should be taken in providing a suitable difficulty level. Rigorous testing of settings is required to understand the range of difficulty settings required. Constructing a broad range of difficulty settings, with fine-grained distinctions between levels can therefore be recommended. Depending on the nature of the training, a truly dynamic difficulty adjustment system can be used, in which the levels of difficulties are rapidly modulated by the system depending on the patient's performance during play (Zohaib, 2018). However, given that the layout of the environments in the exercised provided the challenge, a stepwise method was used.

The transfer of the trained strategy to real-life situations was the main goal of the treatment. As the effectiveness of this element of the treatment could only be established after a controlled experiment, components that improved transfer were hard to finetune during development. Informal interviews with patients and rehabilitation specialists did allow us to get a grasp of the patient's understanding of the exercises and how they related to real life navigation. We asked whether patients could give examples of real-life situations in which the demonstrated strategy could be used and we adjusted elements of the training accordingly. Several changes to the software were made as a result of these interviews. For example, the prototype of the treatment used in chapter 4 and 6 had a narrative theme designed to increase the enjoyment of using the treatment (Naul & Liu, 2020). The modules contained a background story revolving around Greek and Egyptian mythology. In the egocentric 'landmark direction association' module, patients traversed King Minos labyrinth in which golden coins could be found when heading in the correct corridors and wrong corridors would lead to the minotaur. In the 'local and distant landmark' module described above, participants would use landmarks of the old world to find a treasure in the desert. It turned out that while enjoyable, these cover stories distracted from the original goal of the exercise and interfered with the transfer. Upon recommendation of patients and rehabilitation specialist, the mythological theme was removed and replaced with realistic modern environments and objectives.

Cocreation

Patients stakeholders

The last decade has seen a surge in digital interventions and tools in healthcare in the forms of E-health, serious games and health related apps (Abd-Alrazaq et al., 2022; Lau, Smit, Fleming, & Riper, 2017; Paglialonga, Lugo, & Santoro, 2018). These digital tools have been implemented with varying levels of success. The success of digital interventions is determined by a multitude of factors. Some of these factors are determined by design of the intervention itself, such as an intervention's personalization, usability, acceptability and the level of engagement it evokes with the target audience (Arnold, Williams, & Thomas, 2020; Oakley-Girvan, Yunis, Longmire, & Ouillon, 2022; Topaloglu, Gumussoy, Bayraktaroglu, & Calisir, 2013). Other success factors are determined by the perceptions of healthcare personnel that are required to adopt the intervention and support their patients in using the intervention (Dünnebeil, Sunyaev, Blohm, Leimeister, & Krcmar, 2012). Involving stakeholders in an early stage of development is generally thought to contribute to a digital intervention's success (Kip, Wentzel, & Kelders, 2020; Nilsen, Stendal, & Gullslett, 2020; van Limburg, Wentzel, Sanderman, & van Gemert-Pijnen, 2015). To this end, ABI patients and rehabilitation specialists, neuropsychologists and occupational therapists were contacted in the early phase of the developmental process.

The first interactions with these groups were largely explorative and informal. Patients in the waiting room of the UMC Utrecht's rehabilitation department were approached and shown early versions of the modules and software as a whole to gauge whether the software was appealing, understandable and inviting to patients. Patients would try out sections of the modules and browse through the games early menu screen while giving feedback. Researchers would observe how patients used the program and ask questions regarding their experience with the software. Healthcare professionals were also shown early versions of the software and asked for feedback. Furthermore, perceived conditions and prerequisites for the intervention to be of use in a clinical setting were formulated. Using the input of these informal meetings, a preliminary version of the software was created. Using this version of the software, a formal usability study was designed in which qualitative and quantitative feedback of patients could be gathered.

An important component of the usability study was to ensure that the software was applicable to a heterogenous group with varying cognitive capacities. Different capabilities should be taken into consideration throughout the design process: from the installation process, the menu screens, the instruction texts to the difficulty of the exercises. The former elements should be tailored to the capabilities of patients with the highest levels of impairment. To determine these parameters, we conducted a usability study with a relatively large and diverse group of ABI patients (chapter 4). A clear advantage was found with regard to the control schema for movement in the 3D environment. Patients preferred the mouse control scheme and navigated more effectively. This control schema was implemented in the final version of the software. The learning modality assessment revealed more nuanced results. Participants preferred video-based information over text-based information, but video-based information did not lead to better comprehension. Post-experiment interviews gave some insight into this finding. Patients reported that spatial concepts were better explained with use of visual imagery, but many found it hard to keep focussed during the playtime of the video. It is likely many ABI patients lacked the cognitive capacity to effectively retain all information provided in the video. We therefore chose to implement an instruction format that relied heavily on visual imagery and involved as little text as possible, similar to comic-book-like formats with image panels. This way, patients could learn visually while controlling their own pacing of information.

Healthcare specialist stakeholders

Consultations with therapists was more directed at the acceptance of computerized components and the blended-care format of the treatment. Having a large part of training take place at a patient's home has potential advantages. First, navigation impaired patients will not have to travel to a therapist's accommodation as often. Second, as patients train independently, there is a substantial decrease in therapy time required from the healthcare professional compared to a fully supervised training (Claessen, van der Ham, et al., 2016). In addition, all data generated in training sessions are recorded in an online database that is accessible to the therapist, allowing for more fine-grained monitoring of training adherence and training progress.

However, the benefits of a blended-care approach are in part determined by the level of acceptance and endorsement by healthcare professionals (Kalayou, Endehabtu, & Tilahun, 2020). In practise, there are still reservations and barriers to the use of digital interventions by healthcare professionals in different fields (Hennemann, Beutel, & Zwerenz, 2017). In a survey study, psychologists expressed low levels of endorsement of online therapies (Mora et al., 2008) and barriers such as the lack of digital competence in healthcare professionals, the perceived lack of effectiveness compared to face-to-face intervention and concerns regarding privacy and data safety have been expressed (Bucci, Schwannauer, & Berry, 2019).

While there have been many studies regarding the use of digital intervention by general practitioners and psychologists, little is known about the attitude towards digital intervention of healthcare providers in the field of cognitive rehabilitation. The field of rehabilitation has a tradition of embracing novel and innovative technologies in their practise as evidenced by the extensive use of robotics, virtual reality, driving simulators, fitness games (excergames) and serious games designed to enhance cognitive and physical abilities (Q. Wang et al., 2021). However, most of these tools are used under direct supervision of the healthcare personnel. In chapter 6 we report a study on the attitude of healthcare providers to digital interventions in the field of cognitive rehabilitation. The healthcare providers showed high levels of agreement with regard to perceived usefulness, perceived ease of use and intention to use. Levels on the subjective norm subscale were neutral, indicating a point of consideration for the implementation process of such interventions. The subjective norm in the Technology Acceptance Model represents the encouragement to use digital rehabilitation treatments by patients, peers and superiors. The results revealed that especially encouragement by peers was low. As the concept of digital cognitive rehabilitation therapies is novel, it is possible that healthcare providers are not yet familiar with such therapies. Therefore, their estimation of peer's attitude towards the technology might not be known by respondents. Alternatively, respondents might reflect on their colleague's evaluation of 'older' digital therapies, such as restorative brain training games, which have proved ineffective in the past (C. M. van Heugten et al., 2016).

Intermediary between developers and co-creators

A large part of the treatment software was developed by an external software developing company. Because the research team had experience in developing VR applications from earlier projects, we had the opportunity to directly contribute to the development of the software alongside the external developers. This double role had proven serviceable during the development of this treatment. Feedback obtained through interviews and studies with co-creators could accurately be translated to game developers for integration. Minor changes to the software could be made swiftly, without requiring a new development cycle. This led to a shorter duration of the developmental period. Finally, iterative software development is expensive. Budgeting challenges surrounding the project could on many occasions be solved by implementing features ourselves. Overall. in this working arrangement, researchers had more control over the software they were developing. When conducting projects in which software need to be developed in close collaboration with co-creators on a tight budget, an intermediary role for a researcher in both the technical and medical domains might be desired.

Implementation and future directions

The clinical trial of the navigation training provided promising results as a rehabilitation program for ABI patients with navigation problems. It is important to note that the trial was conducted in an experimental setting, by spatial cognition researchers rather than healthcare professionals. The researchers were already familiar with the navigation literature and were able to identify complex spatial problems. Additionally, the researchers conducting the trials were the developers of the software and therefore familiar with the inner workings of the software that was used: training data could be easily accessed and inspected to monitor progress and problems experienced by patients could easily be tackled.

During the clinical trial, it became apparent that the treatment would benefit from the addition of features before use by healthcare specialists. In this chapter, we will address what adjustments should be made to prepare the treatment for clinical use. Furthermore, we will discuss the opportunities and risks regarding the training once it is implemented in a clinical setting.

Recommendation for further development

As a derivate of the MoSCoW prioritization approach system (Waters, 2009), 'must have' (required) and 'could have (recommended)' components are proposed as recommendations for further development to ensure the treatments success in clinical settings

Required improvements

User-friendly control centre for healthcare specialists

The user experience of the intervention has only been investigated for the patient's side of interacting with the software (chapter 4). To use the intervention at home, patients will have to download the software and log in once with a personal code provided by the researcher/healthcare specialists. All communication with the server is from that point on working in the background. The clinical trial proved that patients could interact with the software on an acceptable level.

In order to use the intervention in a clinical setting, healthcare specialists will be required to set up accounts for patients, send the intervention and inspect the progress of patients by inspecting databases. An intuitive and easy to use control environment is currently not available for the intervention. It is recommended that healthcare specialists are closely involved in the construction of such an online platform to ensure engagement and usability with the software (Kip et al., 2020).

Related to this, it might be important that healthcare specialists monitor the training progress closely. This will provide the healthcare specialist with information regarding the adoption of the strategy and potential ceilling effects regarding the completion of the exercises. For example, a patient unable to complete the second level of challenges after 2 weeks is not likely to master the strategy that was assigned to them with six weeks of training.

Finally, care should be taken to implement a suitable storage and management system for patient data. In the clinical trial, all digital interaction with the patients relied on pseudonymized codes (participant codes). It is likely that healthcare specialists working with the intervention will require further identification of patients using medical registration codes or name abbreviation. Many healthcare centres in the Netherlands have their own digital patient registration systems. The training's backend system should be adjusted to be compatible with existing systems already in use. Regardless, the control environment requires a secured data storage system that is in line with Dutch privacy laws (General Data Protections Regulation).

Healthcare specialists' theoretical knowledge

Diagnosing navigation problems, preparing a suitable training and evaluating navigation strategies employed over time requires in-depth knowledge of spatial cognition. Understanding navigation impairments is especially important in providing psycho-education. Patients often have difficulties explaining navigation problems they experience. Patients often focus on anecdotal and emotional experiences rather than consistent impairments that are easy to categorize. For example, a patient might indicate that he panics when he is disoriented or that he 'mixes everything (geographical features) up' and gets lost. Further diagnosis by means of objective measurements and an in-depth interview might reveal that this patient specifically has problems with ordering landmarks along a route.

During the psycho-education sessions, we found that in explaining how novel strategies should be employed, it is important to relate the aspects of the training to the navigation problems expressed by patients. Similarly, understanding whether a correct strategy had been adopted after the training required us to carefully listen to the scenarios described by patients.

Having a firm understanding of egocentric and allocentric representations as well as understanding the Landmark, Route and Survey model is helpful in providing the right information to patients. A short theoretic course on spatial cognition is recommended to be provided to all healthcare professionals who will work with the training.

Recommended improvements

An integrated notebook-feature

In the clinical trial, patients were asked to keep a paper diary of their experiences during the training. Both for themselves, as a reflection tool, as for the researcher, to gain insight into the learning process. These notes provided interesting takes on the thought processes of patients using the training. Unfortunately, many patients stopped using the diary after a few sessions. I recommend implementing a digital form in the software that prompts patients to write comments after each training session (optionally). This might lead to further adherence by the patients regarding the diary, as well as additional treatment information that is easily stored and accessible by therapists. These notes could be used by therapists to aid in the transfer process when evaluating the progress of the training.

A sandbox feature with simple navigation challenges to increase transfer

All the components of the training in the virtual environment of the software are directed at adopting a novel strategy. Training of components of this strategy took place in three short and specific modules. The actual adoption of the strategy as a whole is reserved for real-life navigation. We recommend introducing an intermediary phase to this learning process by adding a sandbox feature to the training. This sandbox should be a simple, randomly generated urban environment in which participants can move around freely without having to complete a prescribed task that is linked to a score. A target location can be provided, but the method of locating this location should be left to the patient to decide. This will allow patients to further experiment with the novel strategy before venturing outside. We expect this feature will aid in the transfer process.

Integrated goal attainment scoring

In the clinical trial, participants were reinvited to the lab after the training period was completed to complete tasks meant to evaluate the training success. It is possible to present patients with a short re-evaluation of the GAS and Wayfinder questionnaires on a weekly or 2-weekly basis. This can be easily done from home by the patients, rather than taking up time during a therapy session. In addition, obtaining this information upfront will allow healthcare specialists to adequately prepare for the session.

Opportunities

The blended-care approach taken with this training has revealed that ABI patients are capable of using complex home-training treatments that employ virtual environments. This finding opens up new avenues for treatment development for this population. It might be possible to adapt virtual reality treatments for other impairments, such as executive functions, memory and attention into a blended-care format (Alashram, Annino, Padua, Romagnoli, & Mercuri, 2019).

With regards to navigation rehabilitation, the compensation approach might be extended beyond the ABI population. Navigation problems have been described in other patient groups, such as people with dementia, schizophrenia or ADHD (Cogne et al., 2017; Descloux, Ruffieux, Gasser, & Maurer, 2022). Moreover, aging has been shown to negatively affect allocentric navigation in healthy elderly. Training elderly individuals to develop their egocentric navigation abilities might contribute to autonomy and independence in daily live activities (Colombo et al., 2017).

Another opportunity that has arisen during the development of the training is the construction of an easy to use diagnostic system for navigation impairments. The Wayfinder questionnaire has of course been used as a reliable tool to assess subjective complaints. The study in chapter 2 provided a tool to compare objective navigation abilities between patients and a cohort of healthy participants that is matched on factors such as gender, age and education level. This task can be developed to serve as an initial screening tool for objective navigation problems alongside the Wayfinding questionnaire. Once the treatment can be coupled to a diagnostic method that is easy to use and interpret, the implementation process will likely be less complex.

The Covid-19 pandemic has led to an abrupt transition to healthcare at distance in most healthcare domains. This event had brought forth different attitudes towards hybrid care in patients, medical staff and policy makers (Almog & Gilboa, 2022; Anthony, 2020; Guinart, Marcy, Hauser, Dwyer, & Kane, 2021; Hamlin et al., 2020). In the Netherlands, the ministry of public health has recently presented a covenant (Integraal zorgakkoord), that included a vision, plans and agreements with healthcare partners regarding the future of healthcare (Ministry of Health, 2022). Within the document, the Dutch government advocates the use and implementation of digital and blended-care treatments in the upcoming years. The approach taken with the current intervention fits within the vision of the Dutch government and its healthcare partners.

Barriers

We have identified several potential barriers for the success of the training in an implementation tract. Overall, these risk factors are largely organizational in their nature.

First, therapists will require knowledge and experience relating to spatial cognition to utilize the training. While we expect most therapists will be willing to learn more about these topics to increase their treatment arsenal, resources must be made free for this to happen. As per 2023, (Dutch) medical staff at hospitals and health centres face a high working load. This might place restrictions on time and motivation required to engage in such a course.

In Chapter 5 we show that the subjective norm amongst healthcare specialist in the field of cognitive rehabilitation is an element that might hinder adoption of digital health intervention. Heightening the subjective norm within an organization might lead to a more effective adoption rate of digital health interventions in general. Including users in the implementation process, appointing stakeholders, knowledge brokers and involving enthusiastic individuals might benefit the adoption of this treatment.

Finally, the treatment software and the underlying infrastructure (website and servers) needs to be maintained for it to function reliably in the future. Funding or potential commercial collaborations will need to be ensured.

Conclusion

Navigation impairments in the ABI population are common, complex and manifestations of problems vary between patients. In this dissertation we developed and evaluated a treatment that was applicable for ABI patients with a variety of navigation problems. The compensatory approach to rehabilitation taken proved to be effective in increase patients self-reported navigation abilities and helped patients in achieving rehabilitation goals. Compensation in navigation rehabilitation allows for flexibility when determining what strategy is beneficial for specific impairments. As such, the treatment is suitable for a broad range of patients. However, for the approach to be effective, patients are required to have a degree of insight into their own impairments and the capability to learn metacognitive concepts.

Central to the treatment was the combination between face-to-face interaction and home-based exercises in virtual environments. Usability and feasibility studies allowed us to optimize the software for unsupervised training by patients. The early involvement of patients and healthcare professionals during the development of the software allowed us to make substantiated design decisions regarding interaction, instruction modality, motivational elements and the transfer of therapeutic concepts. Eventually, a digital treatment was developed that was deemed easy-to-use by a diverse population of ABI patients.

Compensatory strategy training in virtual environments is an exciting development for cognitive rehabilitation. Exercises in virtual environments can be constructed to train complex behaviour and cognitive functions in an ecologically valid setting. Patients can practise in controlled and safe environment whilst the difficulty of the exercises can easily be adapted to a patient's abilities. Importantly, our results suggest that patients are capable of perform this training individually at home.

Given the demands on healthcare systems in many countries, it is likely that blended-care approaches to cognitive rehabilitation will become more prevalent in the future. In this dissertation we have established that healthcare professionals in this field are open to these digital interventions, although they currently do not feel encouraged by peers and superiors to use digital intervention. Implementation strategies must be employed to improve the subjective norm regarding digital interventions.

At the end of this project, a standardized, blended-care navigation rehabilitation treatment was presented that proved effective in an experimental setting. In the future, this intervention should be validated in a clinical setting, in which healthcare professionals provide the treatment.

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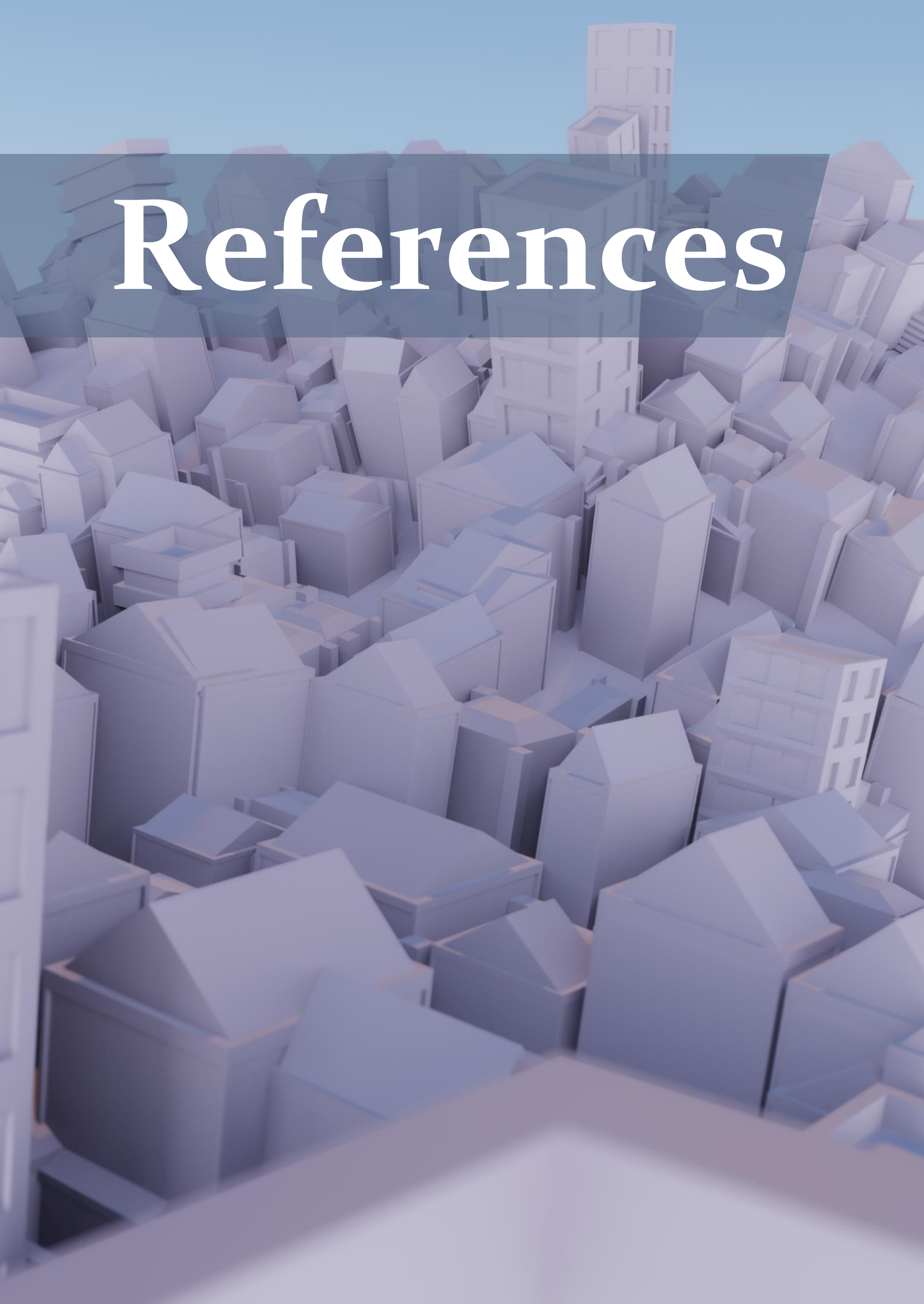

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Nederlandse samenvatting

Aanleiding

Iedereen die ooit is verdwaald, weet dat dit een frustrerende en stressvolle ervaring kan zijn. Voor sommige mensen is verdwalen, of de angst om te verdwalen, een dagelijkse realiteit. Een aanzienlijk deel van mensen met niet-aangeboren hersenletsel (NAH) rapporteert navigatieproblemen. Deze klachten hebben een grote impact op het dagelijks leven van deze patiënten. Navigatieproblemen houden verband met een verminderde kwaliteit van leven, sociale isolatie, het verlies van autonomie en verminderde mobiliteit.

Vanuit een neuropsychologisch perspectief typeren navigatieproblemen zich doordat deze zich op uiteenlopende manieren manifesteren. In de literatuur worden patiënten beschreven die moeite hebben met het herkennen en het onthouden van belangrijke punten in de omgeving (zoals kruispunten, gebouwen of monumenten). Anderen zijn niet in staat een volgorde van herkenningspunten langs een route te onthouden, terwijl een ander juist wel een volgorde kan onthouden, maar geen afslag kan koppelen aan een herkenningspunt. Ook zijn er patiënten beschreven die bijzonder veel moeite hebben met het gebruik van landkaarten. Zo kunnen zij hun eigen locatie op een landkaart niet bepalen.

De complexiteit van navigatieproblemen heeft ertoe geleid dat er lange tijd geen instrumenten beschikbaar waren om navigatieproblemen te diagnosticeren of tot een behandeling te komen. De afgelopen jaren is er meer aandacht voor dit onderwerp. Casestudies, neuroimaging studies en experimenten binnen de cognitieve neurowetenschap hebben geleid tot een beter begrip van neuropsychologische mechanismen onderliggend aan het navigatievermogen. Deze inzichten zijn vastgelegd in nieuwe modellen van navigatieproblematiek. Op zijn beurt leidde dit tot inspiratie voor het ontwikkelen van nieuwe diagnostische instrumenten en behandelingen.

In 2016 hebben Claessen en collega's een voorstel gedaan voor een revalidatie aanpak voor navigatieproblemen. Zij stelden een aanpak voor waarin mensen met navigatiebeperkingen een alternatieve navigatiestrategie aanleren die in lijn was met intacte navigatievaardigheden: een compensatiestrategie. Om de navigatievaardigheden van patiënten in kaart te brengen werd een neuropsychologische test afgenomen in een virtuele stad. Naar aanleiding van het navigatieprofiel dat hieruit volgde, werd in samenspraak met de patiënt een navigatiestrategie uitgewerkt, waarna er hiermee geoefend werd in de virtuele stad. De resultaten van deze pilot waren veelbelovend. Deze holistische aanpak maakt het mogelijk deze training in te zetten voor een breed scala aan navigatieproblemen. Hiernaast leent deze behandeling zich ervoor om doorontwikkeld te worden als 'blended-care' interventie.

In dit proefschrift is de pilot van Claessen en collega's als uitgangspunt genomen om tot een gestandaardiseerde behandeling te komen voor navigatieproblemen als gevolg van NAH. In de ontwikkeling van deze behandeling zijn vier uitgangspunten vastgesteld.

Ten eerste moet de werking van de therapie gebaseerd zijn op het compensatieprincipe. Kennis van navigatiestrategieën, ruimtelijke referentiekaders en de onderliggende neuronale netwerken staan aan de basis van de oefeningen die onderdeel zijn van de behandeling.

Een tweede uitgangspunt was dat de behandeling generaliseerbaar moet zijn naar een brede patiëntenpopulatie. Hieronder wordt verstaan dat de therapie geschikt moet zijn voor verschillende navigatieproblemen en bruikbaar is voor patiënten met uiteenlopende cognitieve vaardigheden.

Het derde uitgangspunt was dat de behandeling als blended-care therapie ontwikkeld werd. Waar mogelijk worden oefeningen door patiënten thuis uitgevoerd. Het reizen van patiënten naar revalidatiecentra wordt hiermee tot een minimum beperkt en de behandelintensiteit kan door patiënten zelf bepaald worden.

Het laatste uitgangspunt was de inzet van moderne digitale technieken in de behandeling. Verkend wordt in hoeverre virtuele omgevingen en serious game-elementen gebruikt kunnen worden om een effectieve cognitieve revalidatie therapie te ontwikkelen.

Opbouw

Dit proefschrift bestaat uit drie onderdelen. In het eerste deel van het proefschrift onderzochten wij het voorkomen van navigatieproblemen in de Nederlandse populatie van mensen met NAH. In dit onderdeel is getracht antwoord te geven op de vraag: hoe prevalent zijn navigatieproblemen en welke type navigatieproblemen zijn het meest voorkomend?

In het tweede deel van het proefschrift wordt de ontwikkeling van de therapie beschreven. Om de uitgangspunten van de therapie te waarborgen zijn studies uitgevoerd naar de theoretische validiteit van de behandeling, de vormgeving van de trainingscomponenten, de gebruiksvriendelijkheid van de software voor NAH-patiënten en de bereidheid van behandelaars om digitale behandelingen in te zetten voor cognitieve revalidatie.

In het derde deel van het proefschrift werd de effectiviteit van de behandeling onderzocht. Uit eerder onderzoek was bekend dat mensen flexibel zijn in het gebruik van navigatiestrategieën. De selectie van een strategie heeft te maken met de voorkeur van de persoon, de omgeving en de navigatietaak (bijvoorbeeld verkenning of het terugkeren naar een locatie). In dit onderdeel is onderzocht of een geprefereerde navigatiestrategie te beïnvloeden is door gebruik te maken van een *externe* interventie: een training die niet gerelateerd is aan de omgeving en taak. Tot slot werd de effectiviteit van de behandeling bepaald in een klinisch onderzoek onder mensen met navigatieproblemen als gevolg van NAH. Onderzocht werd of de behandeling leidde tot een verbetering van het subjectieve navigatievermogen, objectieve navigatievermogen en de mate van sociale participatie.

Belangrijkste bevindingen

In **hoofdstuk 2** van dit proefschrift wordt een landelijk online navigatieonderzoek besproken dat uitgevoerd was als onderdeel van de Week van de Wetenschap in 2018. In deze studie werd een navigatietaak uitgevoerd waarin participanten een route door een omgeving moesten leren. De route slingerde door een onbekende omgeving en op belangrijke punten werden markante herkenningspunten geplaatst. Na afloop werden vragen gesteld die betrekking hadden op de vijf domeinen van navigatie volgens het model van Claessen en van der Ham: geheugen voor herkenningspunten, allocentrische[1] en egocentrische[2] locatiekennis, kennis van de route en kennis van de configuratie van de omgeving. Daarnaast werd de Wayfinding questionnaire afgenomen, een vragenlijst waarmee het subjectief navigatievermogen werd beoordeeld. Aan deze studie namen 7474 gezonde participanten en 435 participanten met NAH deel. De resultaten toonden aan dat zelf gerapporteerde navigatieproblemen nog meer voorkomen (39%) in de NAH-populatie dan eerder was vastgesteld (29%). Bovendien werd aangetoond dat navigatieproblemen prominent zijn in alle typen NAH, niet enkel na een beroerte of traumatisch hersenletsel, zoals in veel casestudies wordt beschreven. Prestatiescore op de objectieve navigatiematen

[1] Allocentrische kennis van een omgeving omvat het begrip van de ruimtelijke relaties in een omgeving los van het eigen perspectief. Voorbeelden hiervan zijn afstanden tussen objecten en de hoeken die zij vormen in de omgeving. Allocentrische kennis kan gezien worden als een mentale landkaart.

[2] Egocentrische kennis omvat het begrip van een omgeving wanneer het gezichtspunt van de persoon centraal staat. Het gaat hierbij om de afstanden en richtingen tussen een object en de persoon in de omgeving. Ook categorische elementen van een omgeving vallen hieronder: ‘links van mij’, ‘achter het huis’.

suggereert dat met name het geheugen voor herkenningspunten, route kennis en allocentrische locatiekennis kwetsbaar zijn bij NAH. De studie benadrukt het belang om aandacht te hebben voor en te screenen op navigatieklachten bij mensen met NAH, door revalidatiespecialisten. Hiernaast wordt duidelijk dat er voor deze groep patiënten adequate diagnose-instrumenten en behandelingen van belang zijn.

In **hoofdstuk 3** werd onderzocht in hoeverre het perspectief waarop ruimtelijke informatie opgedaan wordt invloed heeft op de mentale representatie van deze omgeving. Kennis van een omgeving kan opgedaan worden vanuit een ik-perspectief (first-person), door bijvoorbeeld een route te bewandelen. Anderzijds kunnen wij een beeld van de omgeving vormen door een landkaart te bestuderen: een vogelperspectief (birds-eye perspective). Binnen de literatuur bestaan twee modellen die de invloed van het leerperspectief op ruimtelijke kennis beschrijven. Het eerste model stelt dat alle ruimtelijke kennis, ongeacht het leerperspectief, in eenzelfde vorm gerepresenteerd wordt. Het tweede model stelt dat ruimtelijke kennis, ten minste gedeeltelijk, afhankelijk is van het perspectief waarop het geleerd wordt.

In deze studie hebben we onderzocht welke cognitieve mechanismen onderliggend zijn aan het vormen van deze mentale representaties en in hoeverre deze mechanismen afhangen van het leerperspectief. Wanneer dezelfde cognitieve mechanismen bijdragen aan het vormen van ruimtelijke kennis, ongeacht het leerperspectief, is dit een argument voor het eerste model. Wanneer ruimtelijke kennis opgedaan in het ik-perspectief rust op andere cognitieve mechanismen dan de kennis opgedaan in het vogelperspectief, is het aannemelijk dat mentale representaties gebonden zijn aan het leerperspectief.

In deze studie hebben participanten twee delen van een virtuele stad bezocht. Een deel werd verkend door hierdoor heen te lopen terwijl een ander deel middels een dynamische landkaart (gps-visualisatie) verkend werd. Vervolgens is getoetst hoe goed de ruimtelijke kennis van deze omgevingen was. Tevens werden cognitieve vaardigheden van deze participanten in kaart gebracht (o.a. visueel-ruimtelijk werkgeheugen, mentale rotatie en transformatie). Er is onderzocht welke cognitieve vaardigheden de opgedane ruimtelijke kennis voorspelden en of dit afhing van het leerperspectief.

Onze resultaten suggereren dat configuratie kennis (survey knowledge) niet afhankelijk is van het leerperspectief. Kennis van de genomen paden in de omgeving (route knowledge) lijkt daarentegen wél afhankelijk te zijn van het perspectief waarop het geleerd is. Hiermee ondersteunen de resultaten het model dat stelt dat ruimtelijke kennis gedeeltelijk afhankelijk is van het perspectief waarin het geleerd is.

Deze inzichten zijn gebruikt bij het vormgeven van de oefeningen van de revalidatietherapie. Patiënten die beperkingen hebben in het egocentrische domein en moeite hebben met het vergaren van kennis vanuit het ik-perspectief zullen trainen in het gebruik van landkaarten en gps-navigatie. Belangrijk is dat het uitstippelen van routes door een omgeving zeker zinvol kan zijn, maar deze routes moeten middels een vogelperspectief aangeleerd worden. Patiënten met beperkingen in het allocentrisch domein (vogelperspectief) en moeite hebben met het begrip van een configuratie van de omgeving, zullen zich moeten richten op het aanleren van de routes, vergezichten en volgorden geleerd vanuit het ik-perspectief. Ook metrische eigenschappen van een omgeving zoals afstanden en richtingen zullen vanuit dit perspectief aangeleerd moeten worden. Het trainen met abstracte representaties van omgevingen (landkaarten en gps-navigatie) zal naar verwachting veel minder effectief zijn.

Deze inzichten zijn gebruikt om zes oefenmodules te ontwikkelen die beschikbaar zijn binnen de training software. Voor mensen met beperkingen op het gebied van allocentrische navigatie zijn de modules *egocentrisch updaten*, *herkenningspunt-actie associaties* en *spatio-temporele volgorde reeksen* ontwikkeld. Voor patiënten met beperkingen op het gebied van egocentrische navigatie zijn de modules *landkaart gebruik*, *plaatsbepaling* en *landkaarten en volgorden* ontwikkeld. In **hoofdstuk 4** wordt de theoretische achtergrond van deze modules verder beschreven.

In **hoofdstuk 5** is de gebruiksvriendelijkheid van de interventie onderzocht om richting te geven aan praktische ontwerpbeslissingen. In deze studie is onderzocht op welke manier patiënten het beste om kunnen gaan met beweging (rondlopen) in virtuele omgevingen. Ook is onderzocht wat voor deze patiëntenpopulatie het beste medium is om relatief complexe informatie op een beknopte manier over te brengen. Er is onderzocht hoeverre de timing van feedback over prestaties tijdens het uitvoeren van oefeningen een rol speelt. Hierin is directe feedback vergeleken met uitgestelde feedback (aan het einde van een oefening). Tot slot zijn er in deze studie vragen gesteld over de algemene indruk van de training. Onze resultaten tonen aan dat patiënten het effectiefst door de omgeving bewegen gebruikmakend van de muis. Patiënten hadden een sterke voorkeur voor een video uitleg, maar scoorden niet beter op het begrip van de tekst vergeleken met een conditie waarin enkel tekst aangeboden werd. Tot slot werd geen invloed van de feedback timing gevonden op prestatie en motivatie.

In **hoofdstuk 6** is de houding van zorgmedewerkers ten aanzien van digitale hulpmiddelen in cognitieve revalidatie onderzocht. Voor dit onderzoek is een vragenlijst uitgezet onder een brede groep zorgmedewerkers werkzaam op het gebied van revalidatie: o.a. ergotherapeuten, (gezondheids-) psychologen, cognitieve behandelaars. Over het algemeen waren zorgmedewerkers positief over de toepassing van digitale interventies in de cognitieve revalidatiezorg. Zorgmedewerkers gaven aan dat dergelijke interventies zinvol geacht worden, makkelijk te gebruiken zijn en men staat open voor het gebruik hiervan. De scores op de subjectieve norm sub schaal waren neutraal. Dit suggereert dat zorgmedewerkers niet het gevoel hebben dat collega's, die zij hoog hebben zitten, vinden dat digitale interventies gebruikt moeten worden. De relatief lage score op de subjectieve norm is een potentieel obstakel voor de implementatie van digitale interventies in cognitieve revalidatie. Tijdens implementatieprocessen kan hier rekening mee gehouden te worden door kartrekkers en enthousiaste medewerkers te betrekken bij de adoptie van nieuwe technologieën. Positieve ervaringen van deze groep kunnen de subjectieve norm van andere medewerkers positief beïnvloeden.

In het derde deel van dit proefschrift beschrijf ik twee studies die zijn uitgevoerd om de validiteit en de effectiviteit van de behandeling te toetsen. In **hoofdstuk 7** is middels een pre-post studie onderzocht of het gebruik van de interventie bij gezonde participanten leidt tot een verandering in navigatiegedrag. In deze studie zijn de preferenties voor navigatiestrategieën (egocentrisch, allocentrisch of een mix hiervan) bepaald tijdens de voormeting. Een groep participanten trainde 4 weken met de interventie, terwijl de controlegroep dit niet deed. Tijdens de nameting is voor participanten van beide groepen opnieuw bepaald welke navigatiestrategie ze prefereerden. Uit de resultaten bleek dat 50% van de participanten die de egocentrische navigatietraining volgden, een alternatieve navigatiestrategie vertoonde tijdens de nameting. In de controlegroep liet 19% van de participanten een spontane verandering van de navigatiestrategie zien. Ook liet 19% van de participanten die de allocentrische training gebruikt hadden een andere navigatiestrategie zien in de nameting. De belangrijkste bevinding van deze studie was dat het mogelijk is om middels een externe training de geprefereerde navigatiestrategie van participanten te beïnvloeden. Deze bevinding suggereert dat het concept van de training, het aanpassen van strategieën door de interventie te gebruiken, theoretisch haalbaar is. Opvallend is echter dat dit alleen geobserveerd werd bij participanten die begonnen met een allocentrische strategie en getraind waren om een egocentrische strategie te gebruiken. In context van gezonde participanten kan dit verklaard worden door dat het gebruik van de allocentrische strategie tijdens de voormeting, cognitief intensiever was dan de egocentrische strategie die getraind werd met de software. Overstappen naar een minder belastende strategie is aantrekkelijk in een situatie waarin het gebruik van beide strategieën mogelijk is.

In **hoofdstuk 8** van dit proefschrift werd de effectiviteit van de training onderzocht bij een groep patiënten doormiddel van een klinisch onderzoek. Ons onderzoek toonde een significante verbetering aan op zelf gerapporteerd navigatievermogen en het behalen van persoonlijk gestelde revalidatiedoelen binnen de experimentele groep. Er werd geen effect van de interventie gevonden op objectieve navigatie vaardigheden en sociale participatie. De studie toont aan dat de behandeling effectief is in het verbeteren van het navigatievermogen zoals ervaren door patiënten. In deze context was de behandeling geschikt voor alle patiënten, ongeacht het type navigatieprobleem. De blended-care aanpak was geschikt voor de patiëntenpopulatie en de software werd correct gebruikt. Toch is het mogelijk de behandeling verder te verbeteren. Zo wordt aangeraden een specifiek therapieonderdeel toe te voegen aan de behandeling voor patiënten die hoge mate van "spatial anxiety" ervaren. De begeleiding van patiënten door de behandelaar was in deze studie minimaal. Mogelijk kan er verdere winst geboekt worden door meer contact momenten op te nemen in de behandeling. We concluderen dat de compensatieaanpak in cognitieve revalidatie van navigatieproblemen effectief is. Een volgende stap is de validatie van de therapie in de praktijk.

Conclusie

In dit proefschrift is een behandeling voor navigatieproblemen als gevolg van NAH ontwikkeld en getoetst. Het resultaat van dit project is een blended-care therapie, die met enkele kleine aanpassingen ingezet kan worden in de revalidatiezorg. Dit proefschrift heeft geleid tot verschillende nieuwe inzichten.

Allereerst wordt geconstateerd dat compensatie een effectieve aanpak is voor de revalidatie van navigatieproblemen bij mensen met niet-aangeboren hersenletsel. Patiënten kunnen zich alternatieve navigatiestrategieën aanleren die aansluiten bij hun intacte cognitieve vaardigheden. De therapie die in dit proefschrift ontwikkeld is leidt tot een verbetering op het gebied van zelf gerapporteerd navigatievermogen en het behalen van revalidatiedoelen. De therapie is geschikt voor patiënten met een breed scala aan navigatieproblemen en cognitieve vaardigheden. De therapie kan hierdoor gestandaardiseerd aangeboden worden. Echter, een zekere mate van inzicht in iemands eigen kunnen en beperkingen, alsmede de capaciteit om meta-cognitieve concepten te kunnen leren is een vereiste om effectief met de behandeling om te gaan.

In de genomen aanpak is gebruik gemaakt van virtuele omgevingen en serious gaming elementen. Virtuele omgevingen bieden bijzonder veel flexibiliteit voor het ontwikkelen van oefeningen en het vormgeven van leerprocessen. Omgevingen kunnen weergegeven worden met een hoge ecologische validiteit, maar kunnen tegelijkertijd simpel gehouden worden door afleidende elementen te verwijderen. Dit maakt de technologie veelbelovend voor revalidatie van complexe cognitieve vaardigheden waarin de context of omgeving een belangrijke rol speelt (navigatie, sociale interactie, executieve functies). Hiernaast is het mogelijk om mechanismen te introduceren waarmee patiënten op een gepaste moeilijkheidsgraad kunnen oefenen. In de virtuele omgevingen kunnen patiënten op een veilige manier, zelfstandig experimenteren met nieuwe strategieën.

Gerelateerd hieraan is de inzet van blended-care. Gezien de toenemende druk op de zorg in vele westerse landen zal er in de toekomst meer zorg op afstand gegeven moeten worden. In dit proefschrift laten wij zien dat revalidatiebehandelingen voor complexe cognitieve functies, zoals het navigatievermogen, aangeboden kunnen worden middels een blended-care aanpak. Belangrijk hierbij is dat deze behandeling aansluit bij de doelgroep. Hiertoe is het belangrijk om de doelgroep bij de ontwikkeling van de software te betrekken. Een combinatie van kwalitatieve en kwantitatieve onderzoeksmethoden kan ingezet worden om te bepalen of de interactie met de software toereikend is, of de presentatie van de leerdoelen helder is en of de oefeningen van geschikt niveau zijn.

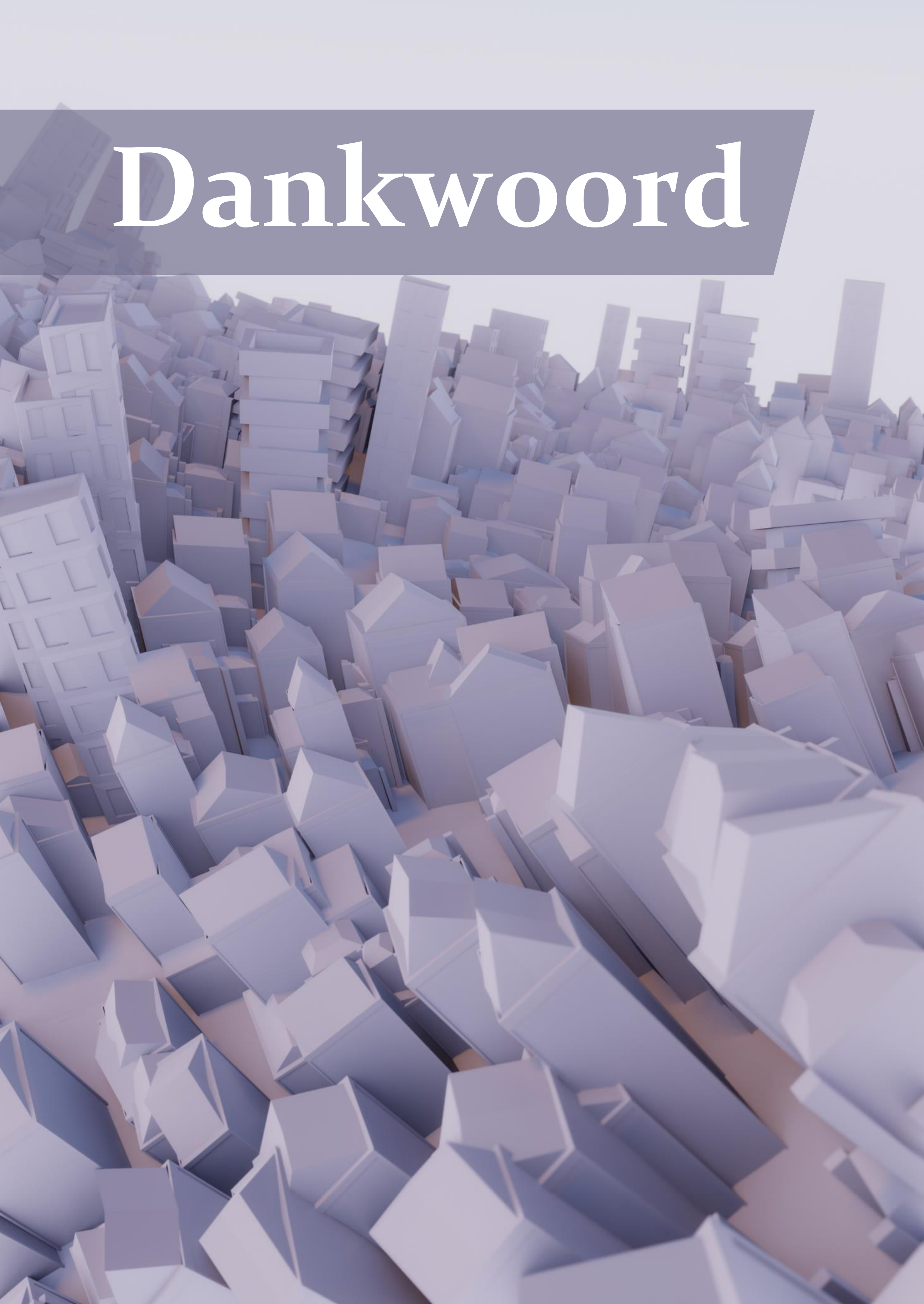
Zorgmedewerkers die werkzaam zijn binnen de cognitieve revalidatiezorg staan open om met digitale interventies te werken. Zij zien het nut van deze behandelingen en verwachten dat het werken met deze technologie makkelijk te integreren is. Er heerst echter nog geen sociale norm waardoor zorgmedewerkers op het werk niet aangemoedigd worden om dergelijke interventies in te zetten.

In dit proefschrift wordt aangetoond dat de navigatietraining veelbelovende effecten heeft voor de revalidatie van navigatieproblemen bij mensen met NAH. Dit onderzoek werd echter uitgevoerd in een experimentele context, door onderzoekers met een achtergrond in ruimtelijke cognitie. Onderzocht moet worden of de behandeling ook effectief blijkt in een klinische context, wanneer deze gegeven wordt door zorgprofessionals.

Voor de adoptie van de training in de zorg plaatsvindt doen wij enkele suggesties voor de doorontwikkeling van de behandeling. Ten eerste is het aan te raden om een 'dagboek' systeem te integreren in de software, waarin patiënten hun ideeën, aantekeningen en leermomenten kunnen opschrijven (ter vervanging van een papieren dagboek). Hiernaast raden wij de toevoeging van een oefenomgeving (sandbox) in de software aan. Deze omgeving kan een virtuele stad zijn, waarin geen oefeningen of opdrachten gegeven worden. Patiënten zijn vrij te experimenteren met nieuw aangeleerde navigatie strategieën. Hiernaast moet er een portal ontwikkeld worden waarin behandelaars op een gebruiksvriendelijke manier inzicht krijgen in de voortgang van de patiënten met de software en idealiter, ook het dagboek in kunnen zien. Tot slot moet er lesmateriaal ontwikkeld worden voor zorgprofessionals die willen werken met deze behandeling, zodat zij genoeg kennis van ruimtelijke cognitie en navigatie hebben om de psycho-educatie te kunnen verzorgen.

Veel patiënten met niet-aangeboren hersenletsel bevinden zich na het incident in een andere wereld waarin zij opnieuw een weg moeten vinden. Mijn hoop is dat de revalidatietherapie die ontwikkeld is tijdens dit promotietraject hen zal helpen om zelfstandigheid, zelfsturing en mobiliteit terug te krijgen en hun persoonlijke doelen te behalen.

Dankwoord



Dit promotieonderzoek is voor mij een fantastische reis geweest. Ik heb in de afgelopen jaren met interessante mensen mogen samenwerken, mooie plekken bezocht en uitdagingen overwonnen. Het afronden van dit project was niet mogelijk geweest zonder de steun van collega's, vrienden en familie.

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Curriculum Vitae

Milan van der Kuil was born on 22 September 1987 in Vlaardingen, the Netherlands. He finished his secondary school at Spieringshoek, Schiedam in 2006. In 2006, he enrolled in the Bachelor's program Biology at the University of Utrecht. After obtaining his degree, he started the Master's program Neuroscience & Cognition at the same university. Under the supervision of dr. Ineke van der Ham, he wrote his masterthesis on the use of auditory and multimodal landmarks during navigation, which sparked his interest in spatial cognition and virtual reality. After obtaining his Master's degree in 2013, he worked as a research assistant on several short-running projects at the University of Utrecht and the Rotterdam School of Management. In 2014, he started working as a fMRI flowmanager at the UMC Utrecht where he facilitated research on 3T and 7T MRI scanners. In 2016, he was admitted as a PhD student at Leiden University under the shared supervision of Andrea Evers, Anne Visser-Meily and Ineke van der Ham. In 2020, he started as a researcher at the Trimbos-instituut where he focusses on dementia, aging and mental health policies.

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