Can Navigation Research Employ Virtual Reality Techniques Without Reducing External Validity?

Master Thesis Applied Cognitive Psychology

Annemarie Faber - 3507483

Utrecht University, July 2014

Supervisor:

dr. Ineke van der Ham

Second reviewer:

dr. Stella Donker

Abstract

Desktop Virtual Reality is on the rise in human navigation studies. The high controllability of stimuli and the increased possibilities for measurements seem to make it useful addition to navigation research. A major difference between traditional, real world navigation studies and desktop VR studies is the lack of locomotion in desktop VR, which results in reduced sensory input. The consequences this might have on human navigation are not fully known. The aim of this study is to conclude whether VR is a valid research method for navigation studies by comparing navigation performances between navigation with and without locomotion. Additionally, two new types of VR display were tested to study how these displays influence navigation performances.

We assessed route memory performance in four conditions: a real world environment, a desktop virtual environment, a desktop virtual environment with additional directional information (compass) and a hybrid condition, in which participants used locomotion to follow a virtual route.

The results confirmed that locomotion is important for acquiring navigational information, and survey knowledge in particular. When choosing to apply VR methods in a navigation study, the implications of this decision therefore have to be considered. Providing additional bearing information in virtual environments does not help to overcome the defunct in survey knowledge acquisition. The hybrid condition, which combines high controllability and measurability with real world locomotion, showed a high validity to real world navigation, indicating it might be a useful navigation research method worthy of additional research and development.

Introduction

Desktop Virtual Reality (VR) is used more and more often in navigation research. A major difference between traditional, real world navigation studies and desktop VR studies is the lack of locomotion in desktop VR, which results in reduced sensory input (Richardson, Montello, & Hegarty, 1999). The consequences this might have on human navigation are not fully known. The aim of this study is to conclude whether VR is a valid research method for navigation studies by comparing navigation performances between navigation with and without locomotion. Additionally, two new types of VR display are tested to study how these displays influence navigation performances.

Traditionally, most navigation research is carried out in real world environments. Convenience is often a considerable factor in selecting a suitable real world environment for research (Waller, Beall, & Loomis, 2004). When carrying out research in the real world, there are a number of challenges that researchers face. Influencing and constraining a real world environment can be challenging. Enforcing identical conditions for all participants or specifically controlling the stimuli between participant groups to aid the study is difficult to realize in real-world experiments. Intervening stimuli in the real world, e.g. weather, noise and other possible disturbances, are difficult to control, which impedes the analysis of the results (Gillner & Mallot, 1998; Rey & Alcañiz, 2010). In the real world, either a topographical layout that is available in the area is used, or an environment needs to be constructed, which can be rather time and money consuming. Participants having prior knowledge of the test environment might influence the results, and is therefore undesirable. However, in cases where locals are participating in a study, it can be difficult to find a suitable real world environment which is reachable for both participants and researchers, yet is still unknown to participants (Sandstrom, Kaufman, & Huettel, 1998).

During the last decade, VR has been in the rise on several areas of application and research (Maguire, Burgess, & O'Keefe, 1999; Thiruvengada, Derby, Foslien, Beane, & Tharanathan, 2011; Waller, Loomis, & Steck, 2003). VR is a technique in which people are placed into a three-dimensional, simulated environment. While the real environment is no longer clearly visible, the virtual environment can be manipulated by the user and is updated in real time (Azuma, 1997; Bouvier, de Sorbier, Chaudeyrac, & Biri, 2008; Mills & Noyes, 1999; Schuemie, van der Straaten, Krijn, & van der Mast, 2001). Virtual locomotion allows participants to move over distances in a virtual environment, while remaining in a smaller physical space (Templeman, Denbrook, & Sibert, 1999).

VR seems to have some promising features, which could make it a useful and versatile navigation research tool (Waller, Beall, et al., 2004). Nowadays, virtual environments can be constructed with relative ease and little resources are necessary to run the required software (Mills & Noyes, 1999). The main advantage of virtual environments is their ability to be modeled and controlled to the precise wishes of the researcher (Dombeck & Reiser, 2012; Sauzéon et al., 2011). Secondarily, VR allows studies to be conducted in a lab setting, which means the conditions can be much further constrained and remain comparable for all participants. This high level of control improves the validity of the navigation studies (Schultheis, Himelstein, & Rizzo, 2002). The lack of contextual factors however, makes a laboratory setting less realistic (Rey & Alcañiz, 2010). An additional advantage of VR is that it enables easy capture of precise data, for example a participant's movement pattern over time. Thus research data becomes more readily available and more precise (Dombeck & Reiser, 2012; Rey & Alcañiz, 2010).

An important characteristic of a VR condition is immersion. Immersion is defined as *"… a description of a technology, and describes the extent to which the computer displays* *are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant*' (Slater & Wilbur, 1997, p. 3). In more immersed virtual conditions, participants show an improved navigation performance to less immersive conditions (Taube, Valerio, & Yoder, 2013). Immersion is influenced by several factors, including visual fidelity, field of view, how the environment is controlled and the range of sensory modalities accommodated, for example sound (Bouvier et al., 2008; Slater, 2009; Tan, Gergle, Scupelli, & Pausch, 2006).

There are several types of VR technologies and ways to control them. Two main types of visual display of the environment can be distinguished, differing in the degree of immersion they offer (Mills & Noyes, 1999; Schmelter, Jansen, & Heil, 2009).

In the first type is desktop VR, where the VR is displayed on a simple screen while the participant is situated behind the desk. As there are still several aspects of reality visible and present, desktop VR is not fully immersive. The main source of information to navigate through the environment is visual input. Additionally, the field of view is often narrower and visual details are reduced (Burgess, 2008; Maguire, Burgess, & O'Keefe, 1999; Roupé, Bosch-Sijtsema, & Johansson, 2014). Desktop VR allows no physical movements, except for controlling the environment. Generally, a joystick, keyboard and/or mouse are used to control the environment (Roupé et al., 2014).

In the second type of VR, participants wear a head mounted display (HMD) on which the virtual world is displayed. More advanced implementations of HMD allow participants to move around freely. Their physical movements are tracked by tracking equipment, which in turn interacts with the virtual world (Azuma, 1997; Schultheis et al., 2002). As more influences from the outside world are removed, this type of VR is much more immersive than desktop VR (Mills & Noyes, 1999; Péruch, Belingard, & Thinus-Blanc, 2000).

The different types of VR harbor a tradeoff between ease of use and availability, and to what extent they resemble real world navigation. Navigation in VRs with a higher degree of immersion is more similar to real world navigation, as they include more natural forms of locomotion. However, using these methods will also require additional resources (Riecke et al., 2010; Waller, Hunt, & Knapp, 1998). Whereas desktop VR is more readily available, the lack of locomotion might influence the extent to which the results can be generalized to real world navigation. The tradeoff occurs where the increased expenses of more advanced VR technologies outweigh the improved fidelity of the VR technology.

The advantages of VR, including increased experimental control and measurability, implicate that VR would be an improved alternative to traditional navigation research. However, the question remains if the results obtained in VR studies are valid in comparison with traditional navigation research methods and if the results can be generalized to real world navigation. Whether or not this is the case, would determine if VR methods are suitable for navigation research. To conclude whether VR navigation is comparable to real world, first must be studied how human navigation works.

In order to navigate successfully, humans acquire several types of information about the environment. The first type is landmark knowledge, which consists of knowledge of notable items in an environment. These landmarks act as place markers. The second type of information is route knowledge, which contains sequential information about which turns are taken at decision points to complete a route. The final type of information is survey knowledge. In this case, objects are regarded in terms of their position and distance relative to other objects. This knowledge is more global oriented and world-centered (Chrastil & Warren, 2013; Wallet et al., 2011; Wolbers & Hegarty, 2010). The three different types of information are combined in order to allow for successful navigation. Research suggests that humans make mental representations of space, which is often called a cognitive map (Gillner & Mallot, 1998; Hartley, Maguire, Spiers, & Burgess, 2003).

Landmark and route knowledge are based on an egocentric frame of reference, where the body is used a reference point. A person compares oneself to the objects in space and determines his own position, distance and bearing with respect to the object. Survey knowledge in turn, uses an allocentric frame of reference and determines positions and distances between objects. In practice, both the egocentric and allocentric system operate in parallel and are used together to aid successful navigation (Burgess, 2008; Maguire, Burgess, & Donnett, 1998; Roupé et al., 2014; Wolbers & Hegarty, 2010).

There are three major types of sensory input that contribute to navigation. The first is visual information, which includes seeing the changing relative position of landmarks and optic flow during movement. The second type of sensory input is podokinetic information, which can be described as the collaboration of motor commands and proprioceptive information. It entails knowing where and how one’s body parts are located and what muscle commands have been executed to move them. The final type is vestibular information, which collects information about motion and balance from head movements (Chrastil & Warren, 2013; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Rey & Alcañiz, 2010). Both podokinetic and vestibular information are body-based inputs (Chrastil & Warren, 2013; Taube et al., 2013; Waller, Loomis, & Haun, 2004).

The most common way to gather spatial knowledge about an environment is through experiencing it directly by locomoting through said environment (Richardson et al., 1999; Waller & Greenauer, 2007). Locomotion can be described as the active movement of oneself, which is usually performed on foot (Templeman et al., 1999). Spatial navigation is a multisensory process, which constantly integrates all sensory knowledge over space and time to reconstruct one’s trajectory (Wolbers & Hegarty, 2010) . This process is called path integration (Chance, Gaunet, Beall, & Loomis, 1998; Klatzky et al., 1998; Philbeck, Klatzky, Berhmann, Loomis, & Goodridge, 2001). Another important process is wayfinding, which deals with developing and correctly using a representation of the environment, combining memory of object locations and the direction in which a route is traveled (Janzen, 2006; Wallet et al., 2011).

In short, the combined sensory input of visual, podokinetic and vestibular information contribute to navigation. However, in a common desktop VR situation. where participants sit behind a desk. participants solely acquire visual information from the virtual environment displayed. The body-based information they receive while sitting down, does not match their virtual movements through the environment and is therefore unreliable (Azuma, 1997; Burgess, 2008; Richardson et al., 1999). The lack of locomotion-based sensory input might limit the external validity of VR studies towards real-world navigation (Driscoll, Hamilton, Yeo, Brooks, & Sutherland, 2005; Waller, Loomis, et al., 2004). Now we have established an overview of the factors contributing to successful navigation, we must consider how this influences navigation in VR and the external validity of navigation research in VR.

Current literature displays no general consensus on the level of external validity of VR in navigation studies. Two types of literature can be distinguished. Some simply use VR in navigation studies and barely question the external validity of their results (Janzen, 2006; Spiers, Sakamoto, Elliott, & Baumann, 2008; Wallet et al., 2011). Others studies specifically try to understand the influence of all three sensory inputs on navigation, often with mixed results (Richardson et al., 1999). Some of these studies are rather positive about the possibilities of VR in this aspect, while others have a more negative attitude towards the subject. The next paragraphs will give a short synopsis of the ongoing debate in literature.

Several studies have used VR in navigation studies and have a positive outlook on the possibilities. They often perform a navigation study in both virtual and real environments and compare the results between groups. When similar results or similar patterns between subgroups (e.g. males/females, age groups) are found, they theorize that this indicates that VR navigation is similar to real world navigation. Additionally, they find that participants are able to effectively navigate through virtual environments and are able to learn spatial relations in the virtual environment. This, combined with the promising features VR offers, like high controllability of stimuli and precise measurements, urges them to conclude that VR can be successfully used in navigation studies (Gillner & Mallot, 1998; Sandstrom et al., 1998; Schmelter et al., 2009).

Waller and Greenauer (2007) had participants study locations along a short route in three conditions; either while walking (access to all sensory information), sitting in a wheelchair (access to visual and podokinetic information) or while watching a video of the route (only visual information). Participants then pointed to the locations, estimated the distances between the locations and drew maps of the environment. They found very few differences in accuracy of spatial memories acquired between the conditions. This supports the idea that visual information alone can be enough for the acquisition of survey knowledge, which is a positive indicator for the usefulness of VR as a navigation research tool.

On the other hand, several studies indicate that even though participants are indeed able to acquire some navigational knowledge from a virtual environment, navigation performance and spatial learning simply do not reach the same level as real world conditions. Their opinion about the application of VR are often more nuanced. Correlations between how well participants were able to learn virtual and real environments are found, as well as similar biases between the two groups. This seems to suggest that similar cognitive mechanisms are being used in virtual learning. Despite these promising findings, these studies also indicate that virtual environment learners simply showed the poorer learning, than real world learners (Richardson et al., 1999; Schmelter et al., 2009; Waller, Loomis, et al., 2004).

The previously mentioned studies indicate that virtual environments, in which solely visual information is presented, often do not yield to similar performances as real world navigation, with access to all relevant sensory input. This indicates that podokinetic and vestibular information are important components to successful navigation.

Several studies investigate the individual importance of visual, podokinetic and vestibular information to successful navigation, with mixed results. Some mention that visual input alone might sufficient information for survey learning and spatial updating in a simple environment (Chrastil & Warren, 2013; Waller et al., 2003), while others mention that body-based information alone might be sufficient (Waller & Greenauer, 2007).

Furthermore, Riecke and colleagues (2010) mentioned spatial orientation specifically as a yet unsolved challenge in VR. They found that adding vestibular information to visual information in virtual environments seems to improve the overall performance of participants, which makes a case for the importance of vestibular information. Opposed to this, Waller and Greenauer (2007) did not find any difference in navigation performance between a wheelchair condition (both visual and vestibular input) and a video condition (only visual), which seems to indicate that vestibular information contributes little to navigation .

Chrastil and Warren (2013) studied the influences of vestibular, podokinetic and visual information and decision making in navigation. According to their study, decision making and vestibular information contribute little to navigation performance, while visual and podokinetic information contribute significantly to survey knowledge. They argue that vestibular information might be important to spatial updating, while podokinetic information is more important to path integration. With these sometimes contradictory findings, literature so far remains inconclusive about the individual importance of vestibular and podokinetic information.

A frequently found problem is difficulties with spatial orientation and bearing. Klatzky and colleagues define bearing as: “The bearing from a navigator (or other object) to a target object is the angle between a reference direction (e.g., north) and a line originating at the navigator and directed toward the target” (1998, p. 294). Richardson and colleagues (1999) mention that participants in the VR condition seemed unable to correctly update their bearing while moving through eight 90° turns in a staircase. The disorientation might be caused by the lack of vestibular information in VR, as it no longer rely on vestibular information to keep track of turns made by the body. Riecke and colleagues (2010) mentioned a commonly found failure to update bearing chances, resulting in poor spatial orientation.

In summary, literature indicates that visual, podokinetic and vestibular input are all important components of navigation. In conditions where either of these are missing, navigation performance often drops significantly. Important to mention with this is that both proponents and opponents mention that even though performance is often worse, they often find similar patterns between groups, indicating that it is very likely similar cognitive processes underlie both virtual and real navigation (Maguire et al., 1999b; Péruch et al., 2000; Waller et al., 1998; Wallet et al., 2011).

The most significant differences are often found in survey tasks, like pointing to locations and drawing a map, whereas landmark and route tasks often yield similar results between conditions. This might indicate that podokinetic and vestibular information are more important to the allocentric frame of reference, whereas it influences the egocentric frame of reference less.

Present study

As literature indicates that visual, podokinetic and vestibular information are all important for navigation, it’s important to question how this influences the external validity of desktop VR. Are results found in VR-studies transferable to real world situations or are those results intrinsically different to real world conditions? Despite their being no overall agreement, the majority of studies seem to indicate a loss of performance in studies where one of the sensory inputs is missing, as well as additional disorientation in virtual environments. This indicates that the current limitations in VR do not allow for the results found in VR studies to be generalized to real world navigation (Driscoll et al., 2005; Maguire et al., 1999b; Waller, Loomis, et al., 2004). This is unfortunate, as the advantages and possibilities of the application of VR in navigation research, as mentioned before, are obvious. The increased controllability and measurability could be a great aid to improve navigation research. In an ideal situation, the advantages of VR can be applied to navigation research without impeding external validity or needed an exorbitant amount of resources.

To create the ideal situation, it is in the first place important to study whether there really is a performance difference between navigation with locomotion and navigation without locomotion, as is often found in literature. This is the first research question. By using locomotion as the discriminating factor, the importance of vestibular and podokinetic information is not studied separately. Instead the overall influence of locomotion is regarded, which naturally entails all major sensory inputs.

The second research question aims to find a solution in which the advantages of VR are accommodated without impeding the external validity of navigation research results to real world navigation. There is a wide range of possible improvements, including more realistic and complex VR environments, and the combination of VR with other technologies, like whole-body interfaces or GPS (Péruch et al., 2000). The best results are likely obtained by solving the current most important problems found in VR.

The first is the obvious lack of locomotion in desktop VR. Using locomotion in virtual navigation often requires pricy equipment and impractical and artificial test setups. This is not a suitable solution for most situations. Instead we tried to find a solution in which natural locomotion can be combined with the high controllability and measurability of VR. We found this in a Geoshooter application (Venselaar, 2014). The goal of the application is to create a game, which allows players to shoot at virtual targets in physical space, that are shown to them on a mobile device. The Geoshooter uses GPS and compass data from the mobile device to determine the players' position and bearing and displays this on a virtual map. The combination of real world position and bearing and a virtual map makes this a hybrid solution between real world and virtual navigation. Virtual targets of various shapes and sizes can be shown on the map. The map can be modelled in numerous ways, allowing a large controllability of the layout of the virtual environment. Because of the use of the mobile device, GPS and compass data, it becomes possible to log and measure a vast body of information. When applying this to navigation research, it has the potential to be a useful combination of virtual controllability and complete sensory input through locomotion.

Another problem that is identified is the disorientation after rotation that participants experience in conditions where they did not have access to body-based information. This problem might be overcome by supplementing the vestibular information they lack. Providing participants with constant access to correct bearing information might improve their performance and in turn, make their results more comparable to real world conditions. A compass is an instrument, which always points to the same direction, regardless of the participants bearing. Regarding the direction in which the compass points compared to one's own direction, would allow participants to compute their own bearing. Adding a compass to the virtual environment seems to be a suitable solution, as it allows participants to constantly compute their own bearing in situations where they lack the natural vestibular input.

In summary, this study aims to is to conclude whether VR is a valid research method for navigation studies by comparing navigation performances between navigation with and without locomotion. Additionally, two new types of VR display are tested to study how these displays influence navigation performances. The hypothesized results are firstly to be able to replicate the gap in performance between navigation with and without locomotion, which is often found in other literature. Secondly, we expect the proposed solutions to at the least improve performance when compared to normal desktop VR conditions. In the best-case scenario they would not significantly differ from the real world navigation results.

Methods

Participants

Participants were 78 student volunteers (36 females) between the ages of 17 and 30, with an average age of 21.74 years (*SD =* 2.420). Some additional characteristics of participants per condition can be found in Table 1. All participants gave informed consents. Psychology students received participation credits for their participation. Participants completed a Santa Barbara Sense of Direction Scale (SBSODS) questionnaire before completing the test. The SBSOD scale is a standardized self-report scale of spatial abilities with a high reliability and internal consistency (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). The questionnaire score were used to balance conditions on initial navigation skills. A one-way ANOVA did not show a significant difference in questionnaire scores between groups, $F(3,74) = 1.426$, $p = .242$, $\eta_p^2 = .054$. This indicates that the overall navigation skills between groups was equal, which eliminates any unfair advantages which might have influences the results. The overall average score was 66.73 points ($SD = 12.53$). The duration of a session was generally between 25 and 35 minutes.

Table 1

Overview of group characteristics. The number of participants in each condition, the male/female distribution, the average age and standard deviation, and the average Santa Barbara Sense of Direction Scale score and standard deviation are listed.

	Number	M/F	Age (*SD*)	SBSODS (*SD*)
RL	19	7/12	21.89 (2.60)	63.05 (3.03)
HY	20	12/8	23.20 (2.51)	64.90 (2.74)
VR	19	12/7	20.63 (1.74)	70.58 (2.50)
VR+	20	11/9	21.20 (2.09)	68.40 (2.95)

Design

The study was composed of four separate conditions and used a between-subjects design. The first condition was the real world condition (RL). In this condition, participants used locomotion to travel through a real world environment. This gave them access to all types of sensory information. This condition mimicked real world navigation as close as possible. The second condition was the hybrid condition (HY), where participants used locomotion to travel along a virtual route on an open field. This condition used the

Geoshooter application. Participants had access to visual, podokinetic and vestibular information. Their visual information was comprised of both what they saw in the real world, as what was displayed on the mobile device.

In the third and fourth condition participants moved through a VR environment in a desktop VR setting. Participants had access to visual information, but could not rely on podokinetic and vestibular information. Both conditions used the same virtual environment. The fourth condition gave participants additional bearing information, in the form of a compass (VR+).

Materials

Real world condition

A route was created through three connected buildings on the Utrecht University de Uithof campus. The route was approximately 260m in distance and consisted of ten 90° turns and one gradual shift to the right (see Figure 1). As most participants were students at the university, this particular route was selected on being an unusual route through campus. Students might be familiar with parts of the route, but not with the entire trajectory, which gave them no preliminary information about the layout of the route. All participants indicated no full prior knowledge with the entire route.

Hybrid condition

In the hybrid condition, participants walked a virtual route on an regulation field hockey field. The route was based on the real world route, which means it had the same number and order of turns, but with different proportions to fit within the rectangular field. The route was approximately 290m in distance and started and ended on opposite sides at the

Figure 1

Overview of the real world route. The route (red) starts at the bottom of the picture and ended at the top. The black lines represent the building outlines and the blue lines show encountered swing doors.

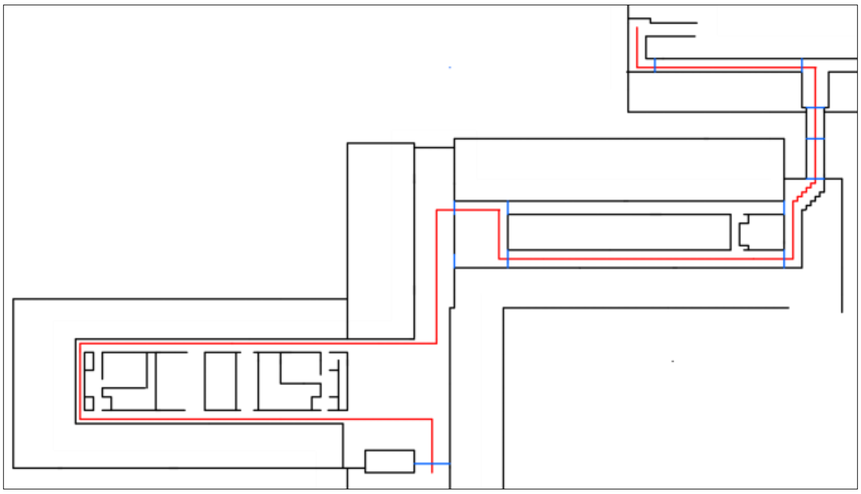
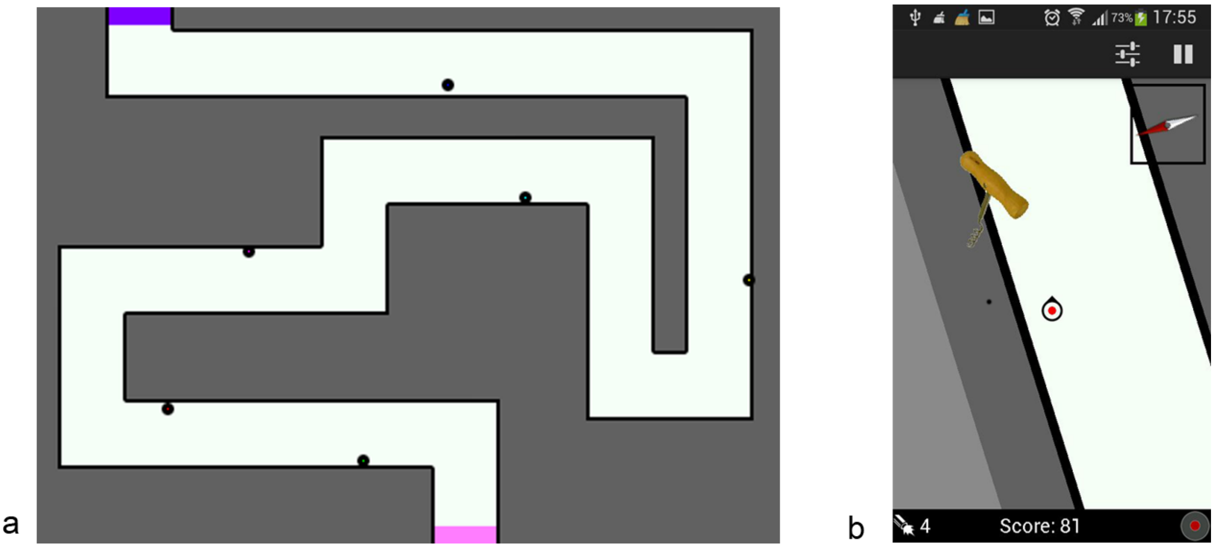


Figure 2

(a) Overview of the map in the hybrid condition. The pink area indicates the start position, the purple area the ending position. The black dots indicate landmark positions. (b) Screen capture of the Geoshooter application in use.



edge of the field (see

Figure 2a). The route was presented to participants in the Geoshooter application. The application showed them a small portion of the map, meaning they could see enough necessary to follow the route, but did not have a full overview of the entire route layout. A small marker in the middle of the screen indicated their own position and bearing on the map, while the map turned around them as they moved and turned (see

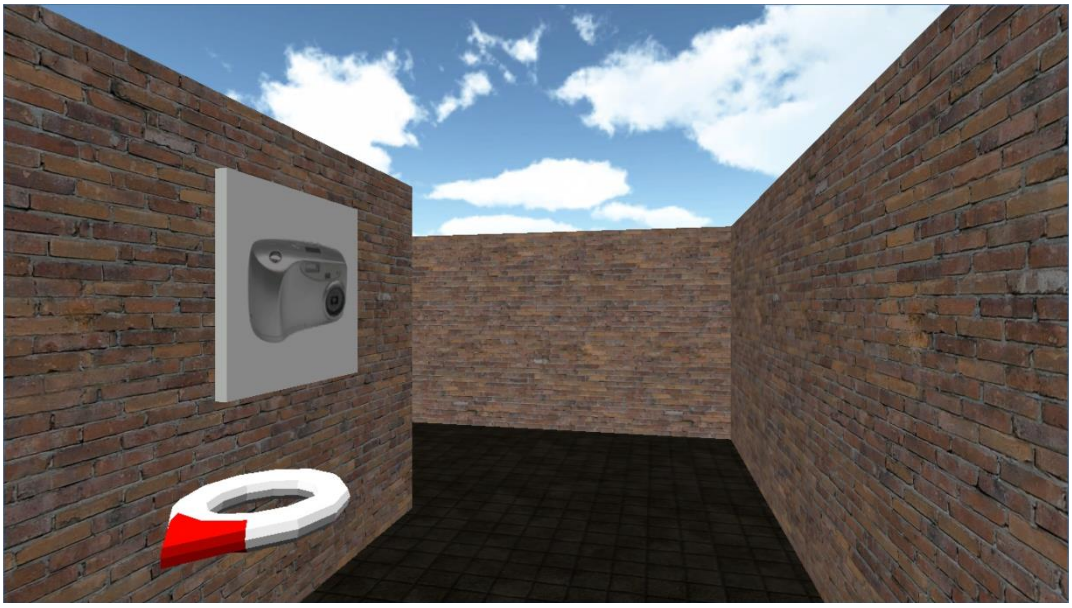
Figure 2b). This condition used a Samsung Galaxy Tab 1 device with a 10.1” screen and a resolution of 1280x800 pixels to run the application.

Virtual conditions

The virtual conditions used the same map layout as the hybrid condition. On scale to a real world environment, the route distance was approximately 320m. The virtual environment was built using Unity 3D software. The route followed a set of connected corridors with walls and no ceiling. The virtual environment was scaled to resemble the real world environment. The walls were of normal height and the camera was positioned

Figure 3

View from inside the virtual environment from a participant’s point of view, depicting the corridor, a landmark on the wall and the compass in the left bottom corner.



1.75m above ground, making it a proper viewpoint for a person of average length. There were several light sources, pointing in all directions, as to not allow participants to determine their bearing based on lighting. The movement speed was fixed and scaled to about 5.5km/h, to simulate walking speed. A participant moved through the environment by using the keyboard to incite motion and the mouse to look into a certain direction. Vertical mouse look and walking backwards was turned off, so participants could only follow the route in one direction.

The additional bearing information in the final VR+ condition was displayed as a floating compass ring. The compass was always visible in the left bottom corner of the screen. The red point always pointed to the same axis (similar to a virtual “north”) regardless of the participants orientation. The virtual environment was displayed on a 15.6” laptop screen with a 1366x768 resolution. The laptop keyboard and a separate mouse were used to control movement in the environment.

Landmarks

Six images were used to serve as landmarks in the conditions (see Figure 4). All images came from a standardized image set, in which images were normalized on, among others, familiarity, visual complexity and viewpoint (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010). The six landmarks were chosen as to be distinguishably different from one another and representing different object groups.

The images were distributed over the route. To compensate for the different proportions in the routes between conditions, their exact location was slightly different between conditions. Half of the landmarks showed on the left side and half on the right of the

Figure 4

The six landmarks used in all conditions.

path. In the real world and virtual environment, landmarks were displayed on the walls, either as printed A4 sheets or as digital images. In the hybrid condition they were displayed as icons on the virtual map. Each condition required participants to interact with the landmarks, to guarantee they had consciously seen all of them. In the real world condition they were asked to take photos of the landmarks, in the hybrid condition they were asked to shoot them as virtual targets and in the VR conditions they were asked to screen capture the landmarks.

Procedure

All participants were asked to follow the route and interact with the landmarks as specified for the conditions. In the real world condition the researcher walked with them to show them the route. In other conditions they could simply follow the route, as there were no decision points. In all conditions landmarks were pointed out to them, so they would not miss any by accident and would encounter all in the same order. All participants were tested individually.

Practice phase: The hybrid and virtual conditions all had a short practice phase to familiarize participants with the interfaces they were going to use. This also controlled the possible influence any experience with a similar system participants could have. For the hybrid condition this meant getting used to following the route on the tablet application and the way it displayed and updated ones position and bearing. During the practice round they walked a short route with one 90° turn and encountered two targets (landmarks) to shoot. In the virtual condition participants traveled a long a short route, while getting used to the navigation controls and making screen captures of the landmarks. At the end of the practice phase, all participants indicated they felt comfortable using the technologies, after which they moved on to the learning phase.

Learning phase: Participants were instructed to remember the route, the landmarks, and their position on the route to the best of their abilities. Participants then followed the route. In the real world condition, the researcher told them specifically where the route started and informed them when they had reached the end. In the hybrid condition the application showed them when they could start (which was triggered by standing in the right area on the field) and showed a message when they were finished. In the virtual condition they simply started at the beginning and the end of the route was clearly marked in the environment.

Tasks:

After reaching the end of the route in RL and HY conditions, the participants were taken to a quiet place where they could sit down to execute some tasks on a laptop. They could not see any part of the route from this location. This was unnecessary in the virtual conditions, as participants were already seating in a quiet place with a laptop. To control influence of the difference in the time necessary to switch from learning to tasks between conditions, all participants were asked to perform a cognitively demanding task for a minute. This way they were all equally distracted before performing tasks. Participants then performed five tasks. The answers on the first three tasks were recorded the laptop. The answers to the fourth and fifth task were written down.

(1) Landmark recognition: Participants were shown a set of 12 images in random order. The set contained the six landmarks, three images strongly resembling a landmark and three completely different images. For each image, they had to indicate within five seconds whether they had encountered the image in along the route or not. Response times were automatically measured.

(2) Route distance: Participants were asked to make an estimation of the distance they had traveled in meters. In the virtual conditions they were additionally instructed that the environment was built to scale to match a real world environment and they speed in which they moved through the environment simulated walking speed.

(3) Landmark position on route: Participants were shown all six landmarks in random order. They indicated on which part of the route they had encountered the landmark on a slider, which represented the entire route distance.

(4) Pointing: Participants were presented with a 360° pointing device and once again all landmarks were named in random order. They were then asked to envision themselves on the route next to the landmark, facing the direction they were walking in at the time. Then they tried to point the device to where the beginning of the route was in relation to their own position. This was then repeated by pointing to the end of the route. Participants were encouraged to make an educated guess when they had forgotten the landmark or could not orientate themselves.

(5) Maps: Participants were given a sheet of paper and asked to redraw the route they had traveled to the best of their abilities and place all landmarks they remembered on their corresponding positions in the map. When they were finished, their maps were put out of sight and they were presented with four possible maps (three distractors and the real one). They then picked the map, which they thought displayed the actual route.

The tasks were chosen to represent landmark knowledge, route knowledge and survey knowledge. As these three are important aspects of navigation, the combination of tasks should give a decent overview of overall navigation performance. This would provide us with information about navigation performances in these 3 areas. Together, the data would give an overall balanced overview of navigation performances in all four conditions. The order of the tasks was designed to minimalize the possibilities of participants gaining additional information from the tasks (e.g. the landmark position on route task was performed after the landmark recognition task, so the landmarks shown during the landmark position on route task would not influence participants' initial memory of the landmarks).

Results

Data transformation

Some data transformations were necessary before the task results could be statistically analyzed. As there were small differences in route layout between conditions, correct answers were determined for all conditions separately. The answers were compared to the correct answer for the specific condition The landmark recognition data was converted to a percentage of correct answers. Answers slower than five seconds were marked as incorrect. The response time of incorrect answers was disregarded in average response time. As the route distances were slightly different between the conditions, the estimated distance in meters could not be compared between conditions. The distance estimations were transformed to two variables. Firstly, the average absolute deviation from the correct answer in percentages was determined. Secondly, the average estimated distance as a percentage of the actual route distance was calculated. The landmark position on route answers on the slider were interpreted as percentages and compared to the actual percentage of the route a landmark was placed. The average absolute deviation over the six landmarks was used. The pointing answers were recorded as a number in a 360° radius. They were transformed to absolute deviation from the correct answer. The average over 12 answers (six landmarks to begin, six landmarks to end) was calculated. The drawn maps were judged on three factors: how well the route drawn resembled the actual route (max ten points, one for each correct turn), number of landmarks recalled (max six points, one for each correct landmark) and number of landmarks on correct position (max six points, one for each correctly positioned landmark). The scores were added up to form an overall map score. The highest possible score was 22 pts.

Analyses

The five tasks resulted in several main variables, as mentioned above, representing the navigation performance on specific tasks. In order to answer the research questions, the differences in navigation performances between the conditions will be studied. The performances of the five tasks will be looked at separately, to be able to distinguish possible performance difference on a landmark, route, or survey knowledge level.

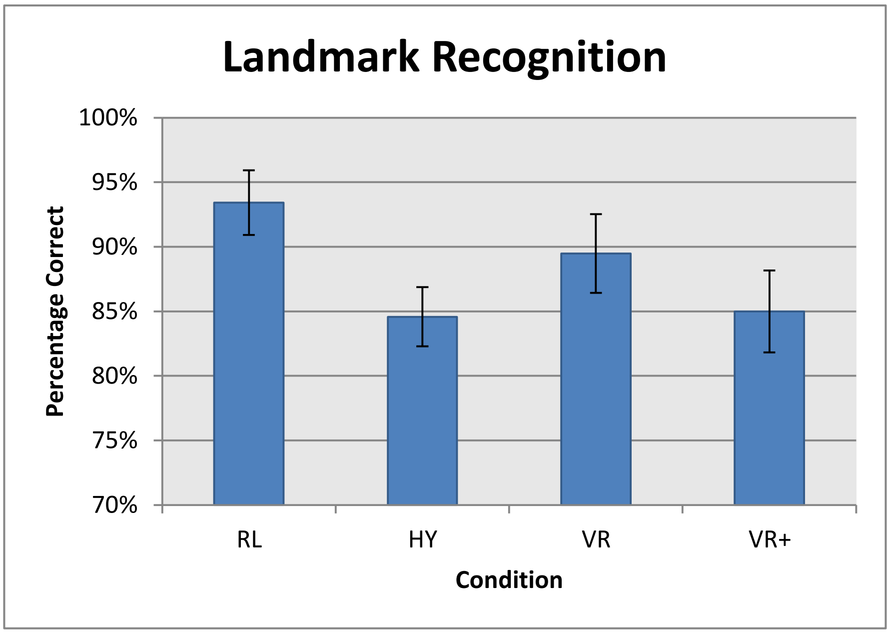
Several ANOVAs were performed to compare the results of participants' performance on all five tasks between conditions, using the condition as the independent variable and the task performance as the dependent variable.

Landmark Recognition

The landmark recognition data represents the landmark knowledge participants gained during their time in the environment. The mean scores for each condition are plotted in Figure 5. An ANOVA, comparing the landmark recognition performances between conditions, shows a trend *F* (3,74) = 2.241, p = .091, η_p^2 = .083. The RL condition scored better than the HY and VR+ conditions. The VR condition ranked in between the other conditions. The overall performance of correct recognition was relatively high, with roughly 30% of participants, receiving a full score. An ANOVA revealed no significant difference in response times between conditions, *F* (3,74) = .823, p = .486, η_p^2 = .032.

Figure 5

Landmark recognition scores for the four conditions, depicting the average percentage of correct answers. The error bars indicate standard error.



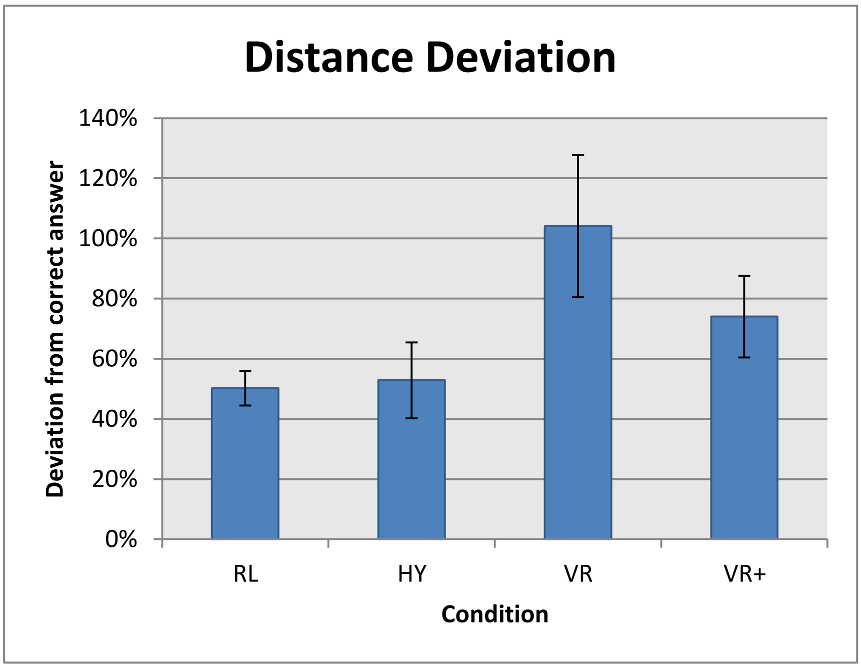
Route Distance Estimation

The route distance estimation represents the route knowledge gained by participants in the environment. There were relatively large differences in estimations between all participants, ranging from an estimation of 60m in the real world condition, to an estimation of 1700m in the virtual condition.

Two measures were derived from the data. The first is the average absolute deviation from the correct answer. The mean scores for each condition are plotted in Figure 6. An ANOVA, comparing the performances between conditions displayed a trend, *F* (3,74) = 2.645,, p = 0.55., η_p^2 = .097. The VR condition resulted in higher deviations from the correct answer than the RL and HY conditions. VR+ ranked in the middle. The average deviation in the best performing condition was already close to 50%, indicating that most participants had a relatively high difficulty answering this question correctly.

Figure 6

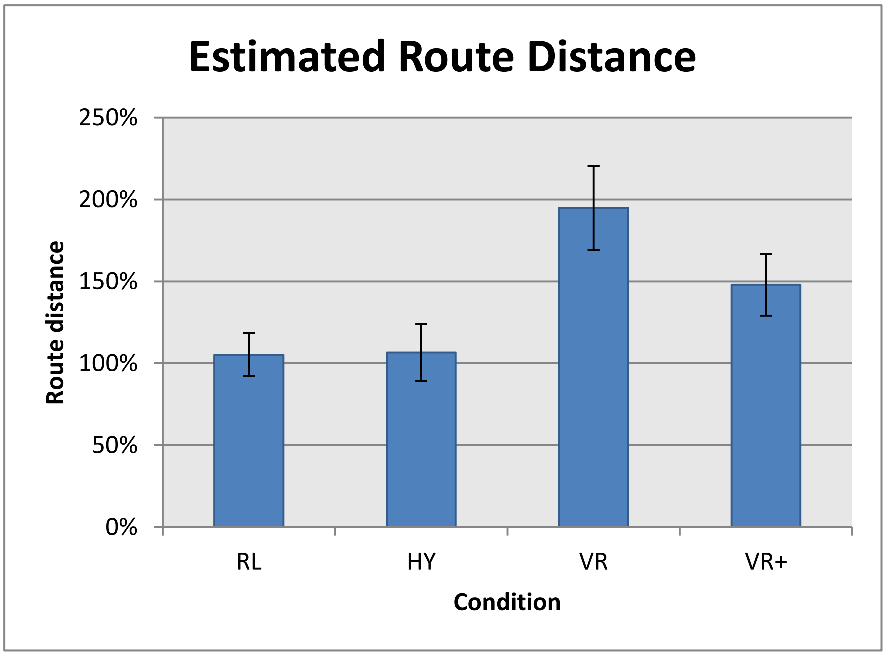
Average deviation from the correct answer as a percentage of the actual distance for each condition. The error bars indicate standard error.



The second measure shows how much the average estimation differs from the correct answer, expressed in a percentage of the correct answer. The mean scores for each condition are plotted in Figure 7. The ANOVA, comparing the results between conditions, revealed a significant difference between conditions, $F(3,74) = 4.771$, $p = .004$, $\eta_p^2 = .162$. Post hoc analyses with Tukey's HSD revealed that VR condition performed significantly worse than the RL and HY condition. The RL and HY condition's average estimate were just over 100%, which indicates that the route distance was only slightly overestimated in these conditions. The distances of the VR and VR+ condition were both overestimated, with respectively 95% and 38%.

Figure 7

The average estimated route distance for each condition as a percentage of the actual route distance, for each condition. The error bars indicate standard error.



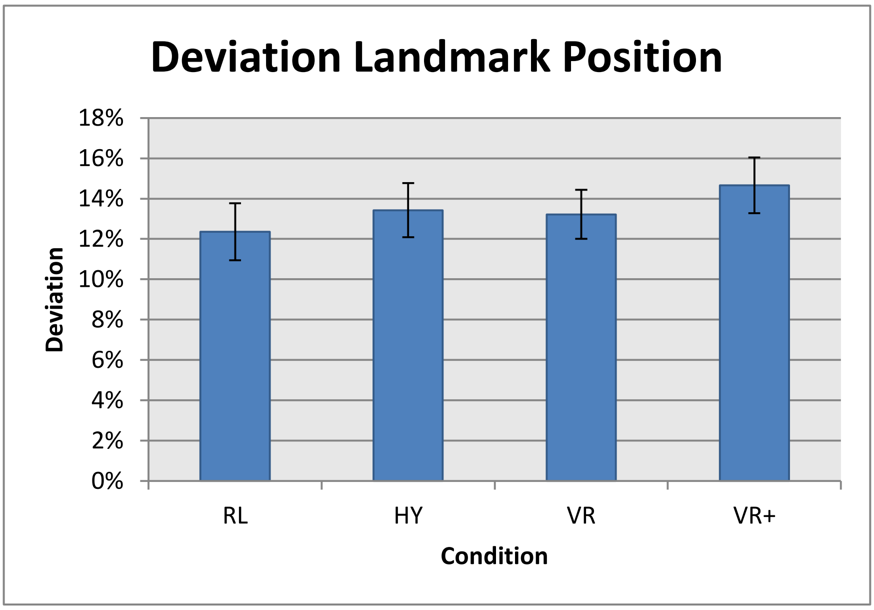
Landmark Position on route Deviation

The landmark position deviation also represents route knowledge and measures how well participants remembered on what part of the route a specific landmark was positioned. The mean scores for each condition are plotted in Figure 8.

The ANOVA on the landmark position deviation did not show a significant difference between groups, $F(3,74) = .504$, $p = .680$, $\eta_p^2 = .019$. The overall average deviation was 13.4% ($SD = .059$). The performance in all conditions was rather similar. A possible explanation for this is offered in the discussion.

Figure 8

The average deviation in percentage for correct answer for a landmark's position on the route, for each condition. The error bars indicate standard error.



Pointing

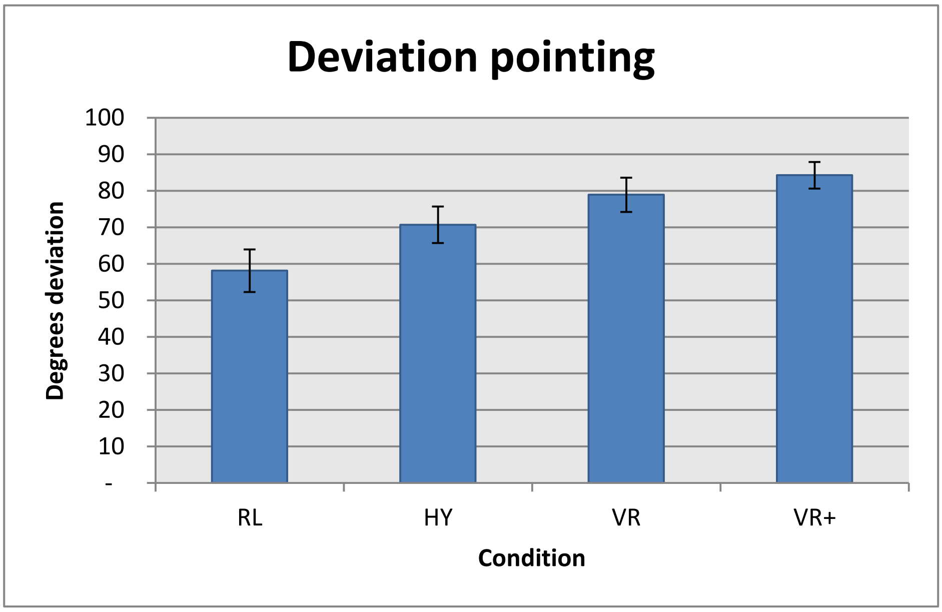
The pointing tasks represents survey knowledge, as in order to answer correctly, one needs to remember the position of landmarks in reference to each other. The biggest error possible during pointing is to point in the exact opposite direction, which would score as a 180° deviation. Therefore it can be assumed if a participant were to completely guess all their answers, their average deviation would be 90°, which will place the following results into perspective.

The mean pointing deviation scores for each condition are plotted in Figure 9. An ANOVA showed a significant difference in average absolute pointing error between the four conditions, *F* (3,74) = 5.539, p = .002, $\eta_p^2 = .183$. Post hoc analyses with Tukey's HSD revealed that the RL condition scored significantly better than both the VR and the VR+ condition. The HY condition scored in the middle. Overall performance was rather poor, which indicates that participants found this a difficult task in any condition.

A one sample *t*-test comparing the results of the VR+ condition to the hypothetical chance score of 90, was not significant, *t*(19) = -1.575, *p* = .132, indicating this group did not perform significantly different from chance. All other conditions did score better than chance.

Figure 9

The average deviation in degrees from the correct answer in the pointing task, for each condition. The error bars indicate standard error.



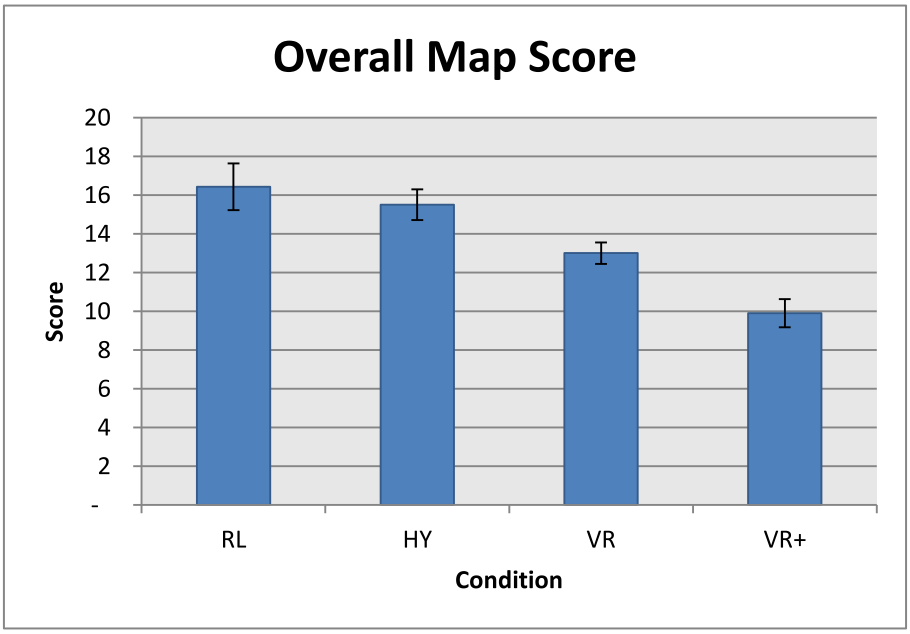
Map Drawing

The map drawing tasks resembles the survey knowledge participants acquired in the environment. Participants had first been asked to draw their own map and after this to pick a map from a selection. This ensured that even if the drawn maps would contain insufficient useful information to work with, data about their survey knowledge of the environment had still been gathered. The drawn maps proved to contain sufficient information to score them properly, and were different enough between participants, making the map choice data redundant. This was therefore not further analyzed.

The average map scores for each condition are plotted in Figure 10. An ANOVA, which compared the map scores between all four conditions. revealed a significant difference in overall map drawing scores $F(3,74) =$, $p = <.001$, $\eta_p^2 = .033$. A Tukey's HSD post hoc analysis reveals a higher map drawing score for RL when compared to VR and VR+. HY also scored higher than VR+. The comparison between VR and VR+ displayed a strong trend ($p = .057$).

Figure 10

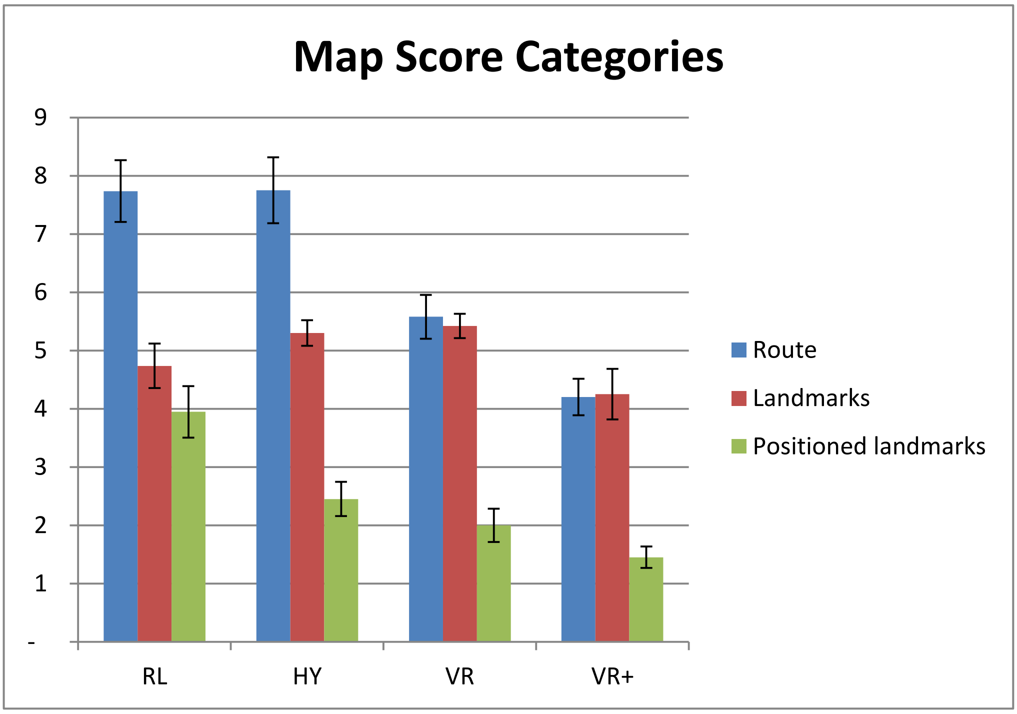
The average overall map scores for each condition. The error bars indicate standard error.



When taking a more detailed look into the three factors of which the overall score is comprised (route, correct landmarks and landmark position), similar results arise. The mean scores for the separate factors in all conditions are depicted in Figure 11. Separate ANOVAs on the three factors all show a significant difference between groups. A post hoc analysis of the route score, *F* (3,74) = 14.588, p = <.001, η_p^2 = .372, showed that the VR and VR+ conditions scored significantly lower than RL and HY. The number of landmarks mentioned was less variable between conditions, yet the difference was still significant, *F* (3,74) = 2.762, p = .048., η_p^2 = .101. The largest differences could be found between VR and VR+, with VR scoring better. In the landmark position scores, *F* (3,74) = 11.637, p = <.001, η_p^2 = .321, the RL was a clear winner with significantly higher scores than any other condition.

Figure 11

The average scores for each of the three factors on which drawn maps were judged for each condition. Points were given for the accuracy of the route, the amount of landmarks remembered and landmarks what were positioned on the correct position on the map.



Discussion and conclusion

To investigate whether VR can be a valid research method for navigation, two research questions were explored. Firstly, we investigated whether navigation performance in basic desktop VR is different from real world navigation. Secondly, two new types of VR display were tested, to study if commonly found problems in VR, who might impede the external validity of research results, could be overcome. Participants learned a similar route with six landmarks in one of four conditions and performed tasks afterwards, which tested their knowledge about the environment. We hypothesized to see a decrease in performance in desktop VR, consistent with most literature. The new types of VR display were developed to solve recurring problems in VR. Therefore we hypothesized to see increased performances in those conditions, compared to the normal desktop VR condition.

The results indicated that performance in a desktop VR environments, which lacked podokinetic and vestibular input as there was no locomotion, was indeed worse than in real world environments on several tasks. Additional bearing information in the form of a compass did not improve performances of a desktop VR condition. Performances in a hybrid condition, where participants used locomotion to traverse through a virtual environment, yielded similar results as the real world condition. The next paragraphs will elaborate further on the results, what might have influenced them and what conclusions can be drawn.

The tasks included one landmark task, two route tasks and two survey tasks. Participants over all four conditions scored quite similarly in the landmark recognition task. This seems to indicate that locomotion has no influence on how well landmarks are remembered, despite the differences in sensory input. This suggests that landmark knowledge is mainly acquired through visual input.

In the route tasks, only a difference in distance estimation was found, in which the VR condition scored worse than the RL and HY conditions. In both VR conditions, the route distance was grossly overestimated. This is in opposition to other literature, which claims that the distances in a virtual environment are often underestimated (Richardson et al., 1999). The higher scores of the RL and HY conditions, in which participants used locomotion, compared to the normal VR condition, suggests that locomotion improves distance estimations. Where the conditions with locomotion overestimated the distance on average by 5% or 6%, the VR and VR+ conditions overestimated the distance with 95% and 48%. In the virtual environment, participants would sometimes indicate they struggled with staying focused on the task, despite a clear instruction to pay attention to the best of their abilities. As the environment was rather barren and walking speed was simulated, it would take a while to walk through the halls while meanwhile nothing particularly engaging was happening. This might have caused participants to feel like they have spent much more time in the environment than they actually did, which in turn might have caused them to overestimate the route distance. No possible explanation has been identified for the difference between the two virtual conditions.

There was no difference in landmark position on route scores between conditions. The main characteristics participants seemed to consider while completing this task, was the order of the landmarks. This might have influenced the results. For example, when participants were shown the camera landmark (which was the third they encountered), they would try to remember the order of landmarks, instead of the individual landmark's position on the route. If they thought it was the third, they then seemed to mentally divide the slider in even parts and simply place slider on the point corresponding with 3/7th of the route. This meant that how correct their answers were, was likely more influenced by their ability to remember the correct order of the landmarks, than by their ability to judge how far on the route they thought a landmark was. In this case, the task is closer to measuring landmark knowledge than it is to route knowledge.

The most interesting results are found in survey knowledge, which was measured by a pointing and map drawing task. The RL condition scored significantly better than both virtual conditions in pointing to the beginning and ending of the route. The map drawing task lead to the same conclusion. When we look at the separate components of the map drawing score, some interesting observations can be made. The route score shows a similar pattern as the route distance estimation task did, with RL and HY scoring significantly better than the virtual conditions. The score for the amount of landmarks they remembered was similar amongst the groups, a result we also found in the landmark recognition task. The score for landmarks they placed on the correct position on the route shows similarities with the pointing results, where each consecutive condition showed worse performance.

The results indicate that access to locomotion significantly influences the acquiring of survey knowledge. In landmark knowledge and route knowledge no influence was found, with the exception of route distance estimation. These findings are in agreement with previous studies, who conclude worse performance on survey tasks in conditions without locomotion or the importance of podokinetic and vestibular information on acquiring survey knowledge (Chrastil & Warren, 2013; Richardson et al., 1999; Waller & Greenauer, 2007). It must be noted, however, that this study did not study vestibular and podokinetic information separately. Any conclusions are therefore only applicable on locomotion as a whole.

The second research question focused on two alternative VR displays and studied if these solutions make navigation performance results more similar to real world navigation results. The results from the hybrid condition are promising. Despite the Geoshooter application not being specifically designed for navigation research, the performance results are not significantly different from the real world condition on all tasks. This seems to indicate that the Geoshooter application can be applied to navigation research, while it retains the high measurability and controllability of VR, without compromising the external validity of the results. It implemented the best features of VR without reducing the amount of realism by forcing it into a lab environment.

The VR+ condition, which had the additional compass, did not have the hypothesized results. Instead of improving the performances when compared to the normal VR condition, statistical analysis found no significant differences between the two conditions. A trend is found in the overall map scores, in which VR+ performs worse than VR. Despite the results in the pointing task over all conditions was not high, VR+ scored not significantly better than chance, which indicates a particular poor performance. This might be caused by an overload of information. Participants were paying close attention to landmarks encountered and turns taken in the route. This already proved to be a significant cognitive load, as no participant managed to remember all landmarks and turns taken perfectly. The compass was a rather artificial solution, and an average person has little experience with translating what it sees on the compass to useful information. Paying attention to the compass, translating what it means, and remembering this might have been a too extensive cognitive load, which may have caused participants to forget things more easily and perform worse.

Some factors might have inadvertently influenced the study. The three different routes used in the conditions were designed to resemble each other as close as possible. However, due to practical constraints, they were not completely identical. The same applies to the position of the landmarks.

The landmarks used in the study were carefully selected. By definition, landmarks are notable features of an environment, which is how they were used in this study. However, participants were forced to focus on these specific landmarks and were not free to choose for themselves what they identified as notable features. As landmarks need to be realistic in order to be properly used, the landmarks used might not have been a fully equal substitution for natural landmarks in a real world environment (Maguire et al., 1999b).However, the way in which they were employed in this study is very common amongst other navigational studies.

It is worth emphasizing that this study only tested one particular type of desktop VR display. During the design processes, several decisions have been made to try to ensure an environment most suitable and valid for this research, resulting in a basic, and stereotypical virtual environment. However, as mentioned before, several aspects might affect the degree of immersion in an environment, including visual fidelity and controls.

There are several studies on the influence of visual fidelity (the degree to which visual elements of a virtual environment compare to visual elements in a real world environment (Mania, Wooldridge, Coxon, & Robinson, 2006)) on spatial cognition tasks. Some point out that enough information can be deduced from a simple virtual environment (Ruddle & Lessels, 2006; Waller et al., 1998) or even find an increased performance in less naturalistic environments (Mania et al., 2006). The virtual environment constructed for this study was relatively simple and based on the finding of these studies. However, in opposition of this are several studies who found increased spatial learning in more detailed environments (Meijer, Geudeke, & van den Broek, 2009; Wallet et al., 2011). This indicates that even though we cannot be sure how, the degree of visual fidelity used in this VR might have influenced the results, one way or another.

The controls employed for this virtual environment (mouse and keyboard) are one of the most commonly used controls for desktop VR. This allowed us to study the validity of a normal desktop VR. Some research has been done towards different type of VR controls, which are often more body-based and therefore allow for additional sensory inputs, with mixed results (Riecke et al., 2010; Roupé et al., 2014; Teixeira, Duarte, Teles, & Rebelo, 2011). The additional sensory input acquired from employing more advanced controls in this study might have improved performance. However, it would have defeated the purpose of this study in studying the validity of basic and affordable desktop VR.

Making different choices in the design process on other factors might have yielded different navigation performance results as well. For example, the virtual environment had no decision points (only turns), while the real world environment did. There is evidence that landmarks near decision points are remembered better than those on other locations (Janzen, 2006). The camera view height was fixed for all participants and virtual view motions were not allowed. The movement in the VR can be best described as a 'glide', and did not simulate head movement that would occur during natural locomotion. The current study did not use a large screen, which might have reduced immersion, and, in turn, performance (Tan et al., 2006). Lastly, the virtual environment in this study directly displayed a first person point of view and no avatar. However, there is evidence that displaying an avatar improves performance on spatial tasks (Mohler, Creem-Regehr, & Thompson, 2010; Ries, Interrante, Kaeding, & Phillips, 2009).

In summary, a number of display decisions made for this particular VR, might have influenced the navigation performance results. The results found in this study therefore are only applicable on this specific type of virtual environment. Designing a different type of desktop VR could yield to different results.

There were a few issues discovered in the use of the Geoshooter application during testing. The current application shows participants the route they have to follow in a top view style map. This is different from real world navigation, where no overview map is present. Despite the view being zoomed in enough as to not give participants access to the entire map, they still might acquire additional knowledge from the spatial layout. As the images of the landmarks had a transparent background, contrast with the landmark and the map background was in some cases inadequate. The size of the landmarks was modest and sometimes a sun glare on the tablet's screen further decreased visibility. This resulted in a decreased visibility of the landmarks and map under certain conditions. During the test, the participants' main instruction was focused on the navigation study. At the same time however, they tested the gameplay of the Geoshooter. As they could score points for shooting landmarks, this drew the attention of participants. This might have resulted in a decreased attention to the layout of the environment and participants being more engrossed by the game, which might have dented their performance.

There are some practical implications that need to be considered before using this method. To be able to use this type of application, a level and open field is required, in which participants can walk around while looking at a mobile device without injuring themselves. In order to use the GPS, a clear view of the sky is a necessity, which means that the research should preferably be performed outdoors (Bajaj, Ranaweera, & Agrawal, 2002). This in turn, means that good weather conditions are also preferable. However, it seems like a reasonable price to pay for valid navigation research in a highly controlled and measurable environment.

To continue exploring this hybrid method, the current application would need to be further developed to reach full potential. It would be interesting to test an augmented reality

3D view of the environment, instead of the 2D map. Augmented Reality is a mix between VR and reality, in which the display of reality is augmented with virtual additions (Azuma, 1997; Mills & Noyes, 1999). In the current solution, the virtual and real environment elements only interact on a basic level, allowing for neither full immersion in the real world, as in the virtual world. Augmented reality might improve the immersion in the hybrid world and further connect the virtual and real elements. The technical implications would need to be researched and discussed.

In summary, in this study we confirmed that locomotion is important for acquiring navigational information, and survey knowledge in particular. This indicates that the lack of locomotion in a basic desktop VR environment, as used in this study, results in a decreased external validity, in terms of acquired survey knowledge by participants. As a result, when choosing to apply VR methods in a navigation study, the implications of using desktop VR and how this might influence the results, have to be considered. However, this does not mean VR as a whole has to be written off as a useful research tool, as several other studies point out different applications for VR, for example trainings, in which they do find positive results (Waller, Beall, et al., 2004; Waller et al., 1998). Providing additional bearing information in virtual environments in the form of a compass to substitute the lack in sensory input, does not help to overcome the defunct in survey knowledge acquisition. The tested hybrid solution, which combines high controllability and measurability with real world locomotion, showed a high validity to real world navigation. These promising results indicate it might be a possible navigation research method, worthy of additional research and development.

Bibliography

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385.

Bajaj, R., Ranaweera, S., & Agrawal, D. (2002). GPS: location-tracking technology. *Computer*, *35*(4), 92–94.

Bouvier, P., de Sorbier, F., Chaudeyrac, P., & Biri, V. (2008). Cross-benefits between virtual reality and games. In *International Conference and Industry Symposium on Computer Games, Animation, Multimedia, IPTV, Edutainment and Security*. France.

Brodeur, M. B., Dionne-Dostie, E., Montreuil, T., & Lepage, M. (2010). The Bank of Standardized Stimuli (BOSS), a new set of 480 normative photos of objects to be used as visual stimuli in cognitive research. *PloS One*, *5*(5).

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*, 77–97.

Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998). Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration. *Presence: Teleoperators and Virtual Environments*, *7*(2), 168–178.

Chrastil, E. R., & Warren, W. H. (2013). Active and passive spatial learning in human navigation: acquisition of survey knowledge. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *39*(5), 1520–37.

Dombeck, D. a, & Reiser, M. B. (2012). Real neuroscience in virtual worlds. *Current Opinion in Neurobiology*, *22*(1), 3–10.

Driscoll, I., Hamilton, D. A., Yeo, R. A., Brooks, W. M., & Sutherland, R. J. (2005). Virtual navigation in humans: the impact of age, sex, and hormones on place learning. *Hormones and Behavior*, *47*(3), 326–35.

Gillner, S., & Mallot, H. a. (1998). Navigation and acquisition of spatial knowledge in a virtual maze. *Journal of Cognitive Neuroscience*, *10*(4), 445–63.

Hartley, T., Maguire, E. A., Spiers, H. J., & Burgess, N. (2003). The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. *Neuron*, *37*(5), 877–88.

Hegarty, M., Richardson, A., Montello, D., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence*, *30*, 425–447.

Janzen, G. (2006). Memory for object location and route direction in virtual large-scale space. *Quarterly Journal of Experimental Psychology (2006)*, *59*(3), 493–508.

Klatzky, R., Loomis, J., Beall, A., Chance, S., & Golledge, R. (1998). Spatial updating of self-position and orientation during real, imagined and virtual locomotion. *Psychological Science*, *9*(4), 293–298.

Maguire, E. A., Burgess, N., & Donnett, J. G. (1998). Knowing where and getting there: a human navigation network. *Science*, *280*(5365), 921–924.

Maguire, E. A., Burgess, N., & O'Keefe, J. (1999). Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates. *Current Opinion in Neurobiology*, *9*(2), 171–7.

Mania, K., Wooldridge, D., Coxon, M., & Robinson, A. (2006). The effect of visual and interaction fidelity on spatial cognition in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, *12*(3), 396–404.

Meijer, F., Geudeke, B. L., & van den Broek, E. L. (2009). Navigating through Virtual Environments : *Cyberpsychology & Behavior*, *12*(5), 517–521.

Mills, S., & Noyes, J. (1999). Virtual reality : an overview of User-related Design Issues Revised Paper for Special Issue on "Virtual reality : User Issues." *Interacting with Computers*, *11*, 375–386.

Mohler, B. J., Creem-Regehr, S. H., & Thompson, W. B. (2010). The Effect of Viewing a Self-Avatar on Distance Judgments in an HMD-Based. *Presence: Teleoperators and Virtual Environments*, *19*(3), 230–242.

Péruch, P., Belingard, L., & Thinus-Blanc, C. (2000). Transfer of spatial knowledge from virtual to real environments. *Spatial Cognition II*, (1998), 253–264.

Philbeck, J. W., Klatzky, R. L., Berhmann, M., Loomis, J. M., & Goodridge, J. (2001). Active control of locomotion facilitates nonvisual navigation. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 141–153.

Rey, B., & Alcañiz, M. (2010). Research in Neuroscience and Virtual Reality. In J.-J. Kim (Ed.), *Virtual Reality* (pp. 377–394). InTech.

Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*, *27*(4), 741–50.

Riecke, B. E., Bodenheimer, B., Mcnamara, T. P., Williams, B., Peng, P., & Feuerreissen, D. (2010). Do We Need to Walk for Effective Virtual Reality Navigation? Physical Rotations Alone May Suffice. In *International Conference, Spatial Cognition 2010* (pp. 234–247). Springer Berlin Heidelberg.

Ries, B., Interrante, V., Kaeding, M., & Phillips, L. (2009). Analyzing the Effect of a Virtual Avatar ' s Geometric and Motion Fidelity on Ego-Centric Spatial Perception in Immersive Virtual Environments, *1*(212), 59–66.

Roupé, M., Bosch-Sijtsema, P., & Johansson, M. (2014). Interactive navigation interface for Virtual Reality using the human body. *Computers, Environment and Urban Systems*, *43*, 42–50.

Ruddle, R. a, & Lessels, S. (2006). For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological Science*, *17*(6), 460–5.

Sandstrom, N. J., Kaufman, J., & Huettel, S. a. (1998). Males and females use different distal cues in a virtual environment navigation task. *Brain Research. Cognitive Brain Research*, *6*(4), 351–60.

Sauzéon, H., Arvind Pala, P., Larrue, F., Wallet, G., Déjos, M., Zheng, X., … N'Kaoua, B. (2011). The use of virtual reality for episodic memory assessment: effects of active navigation. *Experimental Psychology*, *59*(2), 99–108.

Schmelter, A., Jansen, P., & Heil, M. (2009). Empirical evaluation of virtual environment technology as an experimental tool in developmental spatial cognition research. *European Journal of Cognitive Psychology*, *21*(5), 724–739.

Schuemie, M. J., van der Straaten, P., Krijn, M., & van der Mast, C. a. (2001). Research on presence in virtual reality: a survey. *Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society*, *4*(2), 183–201.

Schultheis, M. T., Himelstein, J., & Rizzo, A. a. (2002). Virtual reality and neuropsychology: upgrading the current tools. *The Journal of Head Trauma Rehabilitation*, *17*(5), 378–94.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *364*(1535), 3549–57.

Slater, M., & Wilbur, S. (1997). A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence Teleoperators and Virtual Environments*, *6*(6), 603–616.

Spiers, M. V, Sakamoto, M., Elliott, R. J., & Baumann, S. (2008). Sex differences in spatial object-location memory in a virtual grocery store. *Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society*, *11*(4), 471–3.

Tan, D. S., Gergle, D., Scupelli, P., & Pausch, R. (2006). Physically large displays improve performance on spatial tasks. *ACM Transactions on Computer-Human Interaction*, *13*(1), 71–99.

Taube, J., Valerio, S., & Yoder, R. (2013). Is navigation in virtual reality with FMRI really navigation? *Journal of Cognitive Neuroscience*, *25*(7), 1008–1019.

Teixeira, L., Duarte, E., Teles, J., & Rebelo, F. (2011). Evaluation of human performance using two types of navigation interfaces in virtual reality. *Virtual and Mixed Reality,* 380–386.

Templeman, J., Denbrook, P., & Sibert, L. (1999). Virtual locomotion: Walking in place through virtual environments. *Presence*, *8*(6), 598–617.

Thiruvengada, H., Derby, P., Foslien, W., Beane, J., & Tharanathan, A. (2011). The Influence of Virtual World Interactions toward Driving Real World Behaviors. *Virtual and Mixed Reality*, 100–109.

Venselaar, M. (2014). *Towards location- and orientation-aware gaming: Research on Location-based Games with additional compass features*. Utrecht University.

Waller, D., Beall, A. C., & Loomis, J. M. (2004). Using virtual environments to assess directional knowledge. *Journal of Environmental Psychology*, *24*(1), 105–116.

Waller, D., & Greenauer, N. (2007). The role of body-based sensory information in the acquisition of enduring spatial representations. *Psychological Research*, *71*(3), 322–32.

Waller, D., Hunt, E., & Knapp, D. (1998). The Transfer of Spatial Knowledge in Virtual Environment Training. *Presence*, *7*(2), 129–143.

Waller, D., Loomis, J. M., & Haun, D. B. M. (2004). Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin & Review*, *11*(1), 157–63.

Waller, D., Loomis, J. M., & Steck, S. D. (2003). Inertial cues do not enhance knowledge of environmental layout. *Psychonomic Bulletin & Review*, *10*(4), 987–93.

Wallet, G., Sauzéon, H., Pala, P. A., Larrue, F., Zheng, X., & N'Kaoua, B. (2011). Virtual/real transfer of spatial knowledge: benefit from visual fidelity provided in a virtual environment and impact of active navigation. *Cyberpsychology, Behavior and Social Networking*, *14*(7-8), 417–23.

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences*, *14*(3), 138–46.