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Desktop versus immersive virtual environments: effects on spatial learning

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ABSTRACT
Although immersive virtual reality is attractive to users, we know relatively little about whether higher immersion levels increase or decrease spatial learning outcomes. In addition, questions remain about how different approaches to travel within a virtual environment affect spatial learning. In this paper, we investigated the role of immersion (desktop computer versus HTC Vive) and teleportation in spatial learning. Results showed few differences between conditions, favoring, if anything, the desktop environment. There seems to be no advantage of using continuous travel over teleportation, or using the Vive with teleportation compared to a desktop computer. Discussing the results, we look critically at the experimental design, identify potentially confounding variables, and suggest avenues for future research.

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1. Introduction

As the availability of immersive Virtual Reality (iVR) expands, so too do its potential applications and the breadth of virtual environments (VEs). We can give people access to a location in the past (e.g., *Ancient Rome* revived by Lithodomos VR)[1] or the future (e.g., *The Disappearing Oasis* by Contrast VR)[2] using technologies such as HTC Vive, Oculus Rift, or Google Daydream, all of which offer control of virtual cameras with at least three degrees of freedom (Ragan, Kopper, Schuchardt & Bowman, 2012). While it is possible on desktop screens to pan through a 360-degree view of the VE, access is confined to the screen. In addition, the frame of access uses the body of the viewer as

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[1]https://lithodomosvr.com/
[2]http://contrastvr.com/

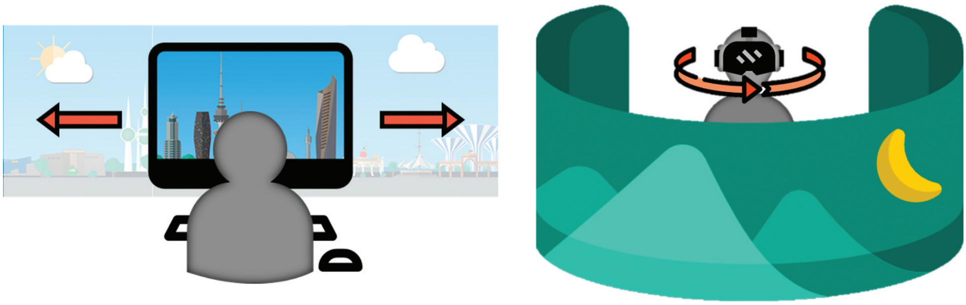

Figure 1. Desktop (left) and iVR (right) users apply different interactions to access VEs (modified from Klippel et al., 2019).

a constant point of reference rather than the environment (Figure 1, left). In contrast, iVR systems using Head-Mounted Displays (HMD) mimic how people access spatial information naturally; that is, at any particular location, the environment is the constant, and users are able to look over their shoulders and see the information they would expect in a natural physical environment (Figure 1, right; see also Balakrishnan & Sundar, 2011).

Users of the newest generation of iVR systems often react to their experience with enthusiasm and even awe (Chirico, Ferrise, Cordella & Gaggioli, 2017; Chirico, Yaden, Riva & Gaggioli, 2016; Quesnel & Riecke, 2017; Sundar, Tamul & Wu, 2014). However, limitations remain even with the most advanced consumer grade iVR systems, such as the persistent issue of simulator sickness (Porcino, Clua, Trevisan, Vasconcelos & Valente, 2017). One of the main limitations is rooted in the simple fact that many VEs are larger than the physical space possible in iVR systems. Even the Vive, with the latest generation of tracking systems, is limited to a physical space of 10 × 10 meters,[3] far smaller than most proposed historical or educational VEs.

There are numerous and often ingenious solutions to the problem of traveling in the digital world, freed from the constraints of its physical counterpart (see Boletsis, 2017 for an overview). Whereas traditional desktop-based computer games use a combination of mouse/joystick and arrow keys to effect changes in position (e.g., Creative Assembly, 2014), creating continuous visual change, using continuous travel in iVR can cause more serious simulator sickness (Guna et al., 2019; Sharples, Cobb, Moody & Wilson, 2008). This sickness stems from the incompatibility between visual movement information from virtual transitions and proprioceptive information specifying no movement (Rebenitsch & Owen, 2016).[4] Hence, designers and engineers have

[3]There is, though, anecdotal evidence to suggest the support of a 10 × 30 meter tracking area through the integration of multiple Vive base stations.
[4]Such incompatibility may be enhanced by the large projected field of view of the immersive display (Moss & Muth, 2011). Empirical studies suggest that the simulator sickness can be mitigated by, for example, limiting the travel speed to a relatively low level, or narrowing down the visual field to a small circle in front of the user during travel but relaxing the field of view when travel stops (e.g., Google Earth VR – https://vr.google.com/earth/).

created a variety of solutions for how users can change their position. One of the most widely used method is teleportation, also called *jumping* (Bowman, Koller & Hodges, 1997) or *Pointing & Teleport* (Bozgeyikli, Raij, Katkoori & Dubey, 2016). It is often paired with a discrete target selection technique in which users select a specific location in their surroundings and then “jump to” that location with infinite velocity (i.e. instantaneously).

The main question we address in this paper is whether different types of travel systems affect how well users learn an environment. Is it essential to maintain continuous viewpoint transitions even if this means missing out on highly immersive VEs (i.e., accessing an environment via a low-immersion desktop screen), or does the immersive VE provide an advantage even if we have to switch to a discrete form of travel? Empirical studies have shown that the cognitive processes that people rely on when navigating large-scale VEs are comparable to those that people employ in real-world settings, but with reduced efficiency (Wraga, Creem-regehr & Proffitt, 2004). In other words, people are able to eventually develop accurate spatial knowledge when they navigate VEs, but the rate at which knowledge develops is typically slow (Ruddle, Howes, Payne & Jones, 2000; Ruddle, Payne & Jones, 1997). As a result, there is much interest within the field of VEs how immersion levels and forms of travel affect spatial learning (Buttussi & Chittaro, 2018; Ruddle & Péruch, 2004).

2. Related work

In this section, we provide an overview of immersion and viewpoint transitions. First, we summarize the differences between immersive and desktop VEs, then discuss empirical studies to illustrate the role of immersion on spatial learning and to provide background for our studies. Second, we introduce some fundamental issues related to virtual travel and then give a representative sampling of research that has previously studied the effect of viewpoint transitions by comparing different travel approaches in VEs.

2.1. Immersion

Immersion is a term used in rather different ways. Some researchers use it to refer to psychological states, associating it with a lack of awareness of time and of the real world, as well as the sense of being physically present in a nonphysical world (i.e., spatial immersion; Freina & Ott, 2015; Shin, 2017). Others in the VR community regard immersion as a more technical term, using it to describe the characteristics of a VR system such as the field of regard (i.e., the measure for what can be seen by physically rotating eyes, head, and body; Buttussi & Chittaro, 2018; Jerald, 2016; Mestre, 2005; Ragan, 2010; Slater, 2003). We will be using immersion in this latter sense throughout the paper.

iVR systems use internal or external tracking sensors to enable 3D tracking of an HMD and render a virtual world by obtaining the users' head orientation and position in real time. Leveraging tracking sensors, physical rotation and translational movement are translated into the virtual world by physically walking and turning around, and bodily sensations are initiated from the coupling of visual changes and body actions. The advantage of this method is that iVR users are provided with a 360-degree field of regard and move in the world to apprehend it, meaning that the users are always able to receive a visual image if they turn their heads to look in any direction (Figure 1, right; Costello, 1997). Low-immersion desktop computers also allow users to access a VE in 360 degrees, but they move the world to apprehend it (Figure 1, left). Desktop users typically use more abstract navigation interfaces (e.g., keyboard, mouse, or joystick) to control their ability to look around, meaning that desktop users "pan" through the VE to change their viewing direction without moving their bodies or turning their heads. The coupling between panning and mouse-clicking affords active motor control and active decision making but fails to provide desktop users with idiothetic information associated with walking (Lan, Chen, Li & Grant, 2015). Studies that empirically examine the role of body-based senses (i.e., vestibular, proprioceptive, and efferent information) on acquiring spatial knowledge have yielded mixed results. Some show an advantage of body-based senses (Chrastil & Warren, 2013, 2015; Klatzky, 1998; Richardson, Montello & Hegarty, 1999; Riecke et al., 2010; Ruddle, Volkova & Bülthoff, 2011; Waller, Loomis & Haun, 2004). Some show a minimal effect (Ruddle & Péruch, 2004; Waller, Loomis & Steck, 2003). Which result is obtained may depend on the size of space (room-scale vs. large-scale, navigable spaces: Klatzky, 1998; Riecke et al., 2010; Ruddle & Péruch, 2004; Ruddle, Volkova, and Bülthoff; Ruddle et al., 2011; Waller et al., 2003), environmental complexity (e.g., simple, single floor vs. two floors of a complex building: Richardson et al., 1999), and the nature of the task (route vs. survey learning: Chrastil & Warren, 2013, 2015; Waller et al., 2004, 2003).

In addition to body-based senses, other potential differences between the iVR system and a low-immersion desktop computer lie in visual experiences on the HMD and 2D desktop screen. For example, there are variations in display quality and resolution (sometimes similar but often higher with desktop screen), physical field of view (larger for HMD),[5] and the availability of binocular depth cues (HMD only; Riecke et al., 2010). Specifically, for depth perception, conventional 2D computer screens do not provide stereopsis, and users must rely on monocular perception cues such as linear perspective, occlusion, texture gradients and motion parallax[6] to extract depth information (Sakata, Grove, Hill, Watson & Stevenson, 2017). In contrast, stereoscopic

[5]The physical field of view is set physically by the actual size of the display and viewing distance of the user.
[6]Motion parallax is a type of visual depth cue in which objects that are closer appear to move faster than objects that are farther away.

HMDs can provide rich monocular depth cues available on 2D computer screens and binocular disparity (McIntire & Liggett, 2014); the latter requires an individual image per eye and allows for the use of stereoscopic depth cues. According to previous studies, binocular stereopsis and monocular motion parallax are considered most important depth cues for building appropriate distance perception in complex environments (Gerig et al., 2018; Mikkola, Boev & Gotchev, 2010; Nawrot, 2003). Considering the essential role of distance relationships between landmarks in developing survey knowledge (according to the *landmark-route-survey* framework; Siegel & White, 1975), it is possible that iVR users would show better spatial learning performance than desktop users. However, it is important to note that the binocular vision is less effective as a depth cue for very long distances (about 30 meters or longer; Rousset, Bourdin, Goulon, Monnoyer & Vercher, 2018), because binocular disparity decreases with distance from the observer to the observed object (Rousset et al., 2018; Willemsen, Gooch, Thompson & Creem-regehr, 2008). Thus, the relative advantages of iVR over desktop computers in producing depth perception are not uniform across different size VEs.

In addition, iVR systems induce a higher sense of presence than low-immersion desktop computers, such that iVR users are able to experience a strong sensation of being inside the VE (Chirico et al., 2016; Shin, 2017; Slater & Wilbur, 1997). Therefore, one may assume that engaging with the iVR system gives rise to experiences of deep involvement with the VE and thus could be more effective than the low-immersion desktop computer for certain learning tasks (e.g., remote collaboration: Oprean, Simpson & Klippel, 2017; memory recall: Krokos, Plaisant & Varshney, 2019). However, Makransky, Terkildsen and Mayer (2017) indicate that immersion may not be positively correlated with users' learning performance. In their study, users felt a greater sense of presence when they used an iVR system to explore a virtual science laboratory, but they actually learned less compared to those experiencing the same lab simulation on a low-immersion desktop computer. This difference in learning is presumably due to the extraneous cognitive load imposed by the iVR system (Makransky et al., 2017).

Cognitive load can be described as a multidimensional construct that represents the load that is imposed on a learner's cognitive system while performing a particular task (Paas & van Merriënboer, 1994). According to cognitive load theory (Makransky et al., 2017; Sweller, 1988; Sweller, van Merrienboer & Paas, 1998), instruction can impose three types of cognitive load on a learner's cognitive system: intrinsic load–cognitive processing required to understand the essential material, determined by task complexity and the learner's prior knowledge; extraneous load–cognitive processing that does not support the learning goal, caused by poor instructional design or distractions during learning; and germane load–cognitive processing that is beneficial for learning, caused by the learner's motivation to exert effort. Given that human processing capacity is limited, one goal of instructional design is to reduce extraneous load and to allow learners to engage in activities imposing germane load (Leppink, Paas, van der Vleuten, van Gog & van Merriënboer, 2013). Regarding virtual learning simulations, from one perspective the cognitive load theory suggests that highly immersive VEs could foster germane load by providing a more realistic virtual experience, which would allow users to engage in activities and stimulate them to take the learning material seriously. On the other hand, the theory also suggests that any stimulus that is not absolutely necessary to understanding what needs to be learned should be eliminated in order to minimize extraneous load (Makransky et al., 2017). From this perspective, the added immersion of highly immersive VEs may not support learning goals directly but may instead impose extraneous load, and thus diminishing learning.

Several studies of navigation in VEs have addressed the effect of different levels of immersion on large-scale navigation tasks, in which users processed spatial and visual cues to search or navigate to targets within VEs (Li & Giudice, 2013; Ruddle & Lessels, 2006b; Ruddle, Payne & Jones, 1999; Santos et al., 2009). For instance, Ruddle et al. (1999) investigated the role of display types in which users navigated two virtual buildings to reach destinations on a standard desktop screen with mouse and keyboard or using an HMD with physical rotation. They found, compared to desktop users, that users with the HMD navigated quicker, spent less time stationary, and looked around more while traveling, but there was no significant difference in the absolute percentage error of users' straight-line distance estimates; also, there was no reliable difference in the accuracy of direction estimates between the two display types. Similarly, Li and Giudice (2013) tested the effects of immersion levels (low-immersion desktop computer vs. iVR) and vestibular feedback (rotation method: physical vs. joystick-based) on the object search performance when users navigated a multistory virtual building. The study found no significant performance differences in the pointing, within-floor navigation, and between-floor navigation tasks between the desktop computer and iVR conditions. These studies, however, addressed only target-to-target navigation tasks, which combined spatial and visual skills necessary for an efficient search with spatial knowledge acquisition from the VEs. It is possible that, during navigation, users successfully traveled the route from one position to the target, but that fact does not necessarily mean that they had coded this in memory. Furthermore, the VEs used in the previously discussed studies were based on buildings, in which the targets were not landmarks, and the paths between them were not explicitly specified as routes. In such cases, some users might just navigate randomly through the VEs, and their performance might be associated with this travel but not spatial learning per se.

In summary, what deserves a more detailed examination is the effect of immersion levels on spatial learning outcomes after users travel in a large-scale outdoor VE with pre-defined landmarks and routes. Given the spatial learning errors that may accumulate during large-scale navigation (Hochmair & Frank, 2000; Ruddle, Volkova, Mohler & Bülthoff, 2011), research is needed that compares the knowledge of desktop users with that of iVR users gained from this type of VE, in order to understand the conditions under which different levels of immersion could have an effect on spatial knowledge acquisition. Therefore, one of our goals was to investigate whether added immersion offered by iVR systems enhances spatial learning and memory, and ultimately leads to more accurate mental spatial representations of large-scale outdoor VEs.

2.2. Viewpoint transitions

Traveling in real-world settings refers to moving from one location to another either by foot or by other means of transportation. To transfer this concept from the physical world to VEs, we need to redefine travel as changing location from one place to another via a navigation interface in the VE. In the case of a 1:1 ratio of physical and virtual space and by leveraging external or internal position tracking sensors, rotation and translation in the physical space can be directly mapped into the VE via a natural or, one could say, an implicit navigation interface (e.g., participants in Legault et al.'s study (2019) were able to walk around to pick up and move kitchen items in an iVR kitchen as if in a real kitchen).

In other cases, where the physical space is smaller than the virtual one, users can still physically walk (e.g., redirected walking: Razzaque, Kohn & Whitton, 2001) or move their body (e.g., walk-in-place: Templeman, Denbrook & Sibert, 1999) to travel virtually, though the visual change does not exactly match physical activities and has to be modulated to fit into the limited physical space. In other words, locomotion through VEs provides only partial body-based cues (Grechkin & Riecke, 2014). Body-based cues can be either rotational or translational and can be manipulated individually in VEs. For example, past research has concentrated on the situation in which users physically rotate to look around while their body movements are partially concordant (e.g., arm swinging: McCullough et al., 2015; leaning-based: Nguyen-Vo, Riecke & Stuerzlinger, 2018) with virtual translation movements through VEs.

However, the majority of applications merely support abstract or explicit navigation interfaces through traditional input devices (e.g., joystick, joypad, mouse and/or keyboard) or more advanced techniques dedicated to iVR (Nguyen-Vo et al., 2018; e.g., gaze-directed steering: Cardoso, 2016; *Pointing & Teleport*: Bozgeyikli et al., 2016). In these applications, change of location in VEs is purely visual and is discordant with movement of the user's body (Cherep et al., 2020). In other words, the user manipulates a joystick or other control device to experience a simulation of self-motion depending on the travel approach offered by the navigation interface. For example, continuous travel, also referred to as joystick-based navigation (Langbehn, Lubos & Steinicke, 2018), is similar to physical walking in everyday life in the sense that both generate continuous viewpoint transitions, providing a natural link from one static view to the next. Holmes, Marchette and Newcombe (2017) suggest that continuous viewpoint transitions could enhance spatial updating for small-scale spaces such as a tabletop array.[7] Similarly, Christou and Bülthoff (1999) found that continuous movement may be key to learning multi-level indoor VEs. In contrast, discrete viewpoint transitions are a characteristic of discontinuous travel realized, for example, by teleportation (Bowman et al., 1997; Bozgeyikli et al., 2016; Frommel, Sonntag & Weber, 2017). The latter has the advantage that it largely eliminates simulator sickness (Langbehn et al., 2018; Weißker, Kunert, Frohlich & Kulik, 2018). What remains an open question is whether continuous viewpoint transitions are more effective than discrete viewpoint transitions in spatial knowledge acquisition of large-scale outdoor VEs. Table 1 summarizes this brief discussion.

To further clarify the effect of viewpoint transitions on spatial learning, we make three comparisons and briefly discuss the results obtained from previous studies.

2.2.1. Walking vs. teleportation

Cherep et al. (2020) compared walking against teleportation; participants wore an HMD and performed triangle completion tasks in different VEs.[8] In the teleportation condition, participants teleported to translate (change position) but turned the body to rotate. The authors found that walking resulted in smaller angular errors than teleportation across all VEs. However, it is not clear whether the advantage of walking over teleportation can be attributed to continuous viewpoint transitions or translational body-based cues.

Table 1. Summary of virtual travel via navigation interfaces.

The ratio of physical space to virtual space	Physical activity	Navigation interface	Virtual activity	Characteristics of virtual travel
1	Walking	Natural/implicit	Walking	Continuous viewpoint transitions
< 1:1	Locomotion		Walking/Continuous travel	
≪ 1:1	No locomotion	Abstract/explicit	Continuous travel/Joystick-based	Continuous viewpoint transitions
			Discontinuous travel/Teleportation	Discrete viewpoint transitions

[7]Spatial updating is the strategy that people adopt to process sensory cues received during spatial learning (Hart & Moore, 1973).

[8]In a triangle completion task, the participant traverses two outbound path legs before pointing to or directly returning to the unmarked path origin.

2.2.2. Locomotion vs. teleportation

Coomer, Bullard, Clinton and Williams-Sanders (2018) examined the effect of viewpoint transitions, comparing two novel locomotion techniques (point-tugging: grabbing a point and pulling the VE forward; arm-cycling: users move arms to translate in the direction they are facing) in a large-scale immersive VE against teleportation. Results from their study indicated that (1) arm-cycling outperformed teleportation, with both yielding similar levels of simulator sickness; and (2) point-tugging and teleportation had similar navigation performance, whereas an increased simulator sickness was induced by the former. In a more recent study, Paris et al. (2019) assessed the effect of two locomotion methods (*ski*: moving arms in a cross-country ski-like motion; *hover*: tilting the hand controller to control the movement direction and speed) versus two types of teleportation on participants' performance of triangle completion. They found that the two locomotion methods had navigational advantages over both types of teleportation, all of which yielded similar levels of simulator sickness. These findings imply a trade-off between the benefits of continuous viewpoint transitions and possible adverse effects of simulator sickness during locomotion. Besides, effects of translational body-based cues cannot be ruled out, because the set of locomotion methods introduced in these studies enabled partial translation; users could still perceive self-motion from sensory information, yet without a one-to-one correspondence; such translational sensory information is missing in teleportation.

2.2.3. Joystick-based vs. teleportation

The comparison involves two traditional travel approaches that provide minimal translational body-based cues and have typically served as baseline conditions against more advanced locomotion techniques in several studies of VR locomotion (e.g., Coomer et al., 2018; Jacob Habgood, Moore, Wilson & Alapont, 2018; Langbehn et al., 2018). Most of these studies found that joystick-based navigation and teleportation led to similar spatial learning performance, but the former was associated with significantly greater simulator sickness relative to the latter. Given the possible detrimental role of simulator sickness in spatial learning, no firm conclusions about viewpoint transitions can be drawn from this comparison.

To summarize, the studies discussed consider the effects of navigation interfaces and associated characteristics of virtual travel on spatial knowledge acquisition of large-scale outdoor VEs. Regarding viewpoint transitions, they do not, however, address confounding factors, such as translational body-based cues and simulator sickness, in their experimental designs. New studies are needed to address this gap.

With all this in mind, we designed Experiment 1 to investigate the effects of viewpoint transitions and immersion on spatial knowledge acquisition when participants traveled to learn a large-scale outdoor VE. We conducted this investigation by comparing two travel approaches to changing participants' position (i.e., teleportation and continuous travel) within a desktop system, and comparing desktop-based and iVR-based navigation that both applied teleportation. In parallel, some of the coauthors conducted a complementary experiment that used a similar setup but focused only on immersion with a large number of participants; we report it as Experiment 2.

3. Experiment 1

In this experiment, participants either used a desktop computer with teleportation (desktop teleportation) or with continuous travel (desktop continuous travel), or they used teleportation in the HTC Vive HMD (Vive teleportation) to learn a multi-target large-scale outdoor VE. The comparison of desktop teleportation and desktop continuous travel examined the effect of viewpoint transitions on spatial learning. Given the potential benefit of continuous viewpoint transitions (Christou & Bülthoff, 1999; Holmes et al., 2017), we hypothesized that desktop teleportation participants would perform worse than desktop continuous travel participants in the current VE. The effect of immersion on spatial task performance has not been well established, but the effect was tested in the experiment by comparing teleportation using the desktop computer and Vive HMD.

3.1. Method

3.1.1. Material

The VE used in this experiment was adapted from the *standard Virtual Silcton paradigm*.[9] Virtual Silcton is a large-scale outdoor VE built in Unity3D[10] and has been modeled after Temple University's Ambler campus (Schinazi, Nardi, Newcombe, Shipley & Epstein, 2013; Weisberg & Newcombe, 2016; Weisberg, Schinazi, Newcombe, Shipley & Epstein, 2014). In Virtual Silcton, participants virtually traveled to learn two main routes in separate areas of the campus with four reference buildings along each route (Figure 2, top). They then traveled along two additional routes connecting the main routes. Each route was traveled twice, from start to end and back, with a direction indicated by red arrows on the ground. Reference buildings were indicated by blue gems, which hovered over the route, and were named with signs in front of the building. The buildings were named as follows: Turkey House, Fish Station, Goose Hall, Ant House, Bear Hall, Dog Church, Sheep Center, Horse Museum.[11]

[9]The standard Virtual Silcton paradigm is an open-access online product that was first launched in 2013 and administered via desktop computer, mouse, and keyboard (https://osf.io/6dhfz/). It integrates virtual navigation, learning assessments, and analytic tools for the study of human navigation behavior.

[10]https://unity3d.com/

[11]These were randomly assigned and easy-to-spell animal names, which were different from the standard Virtual Silcton paradigm in which buildings were named after famous geographers.

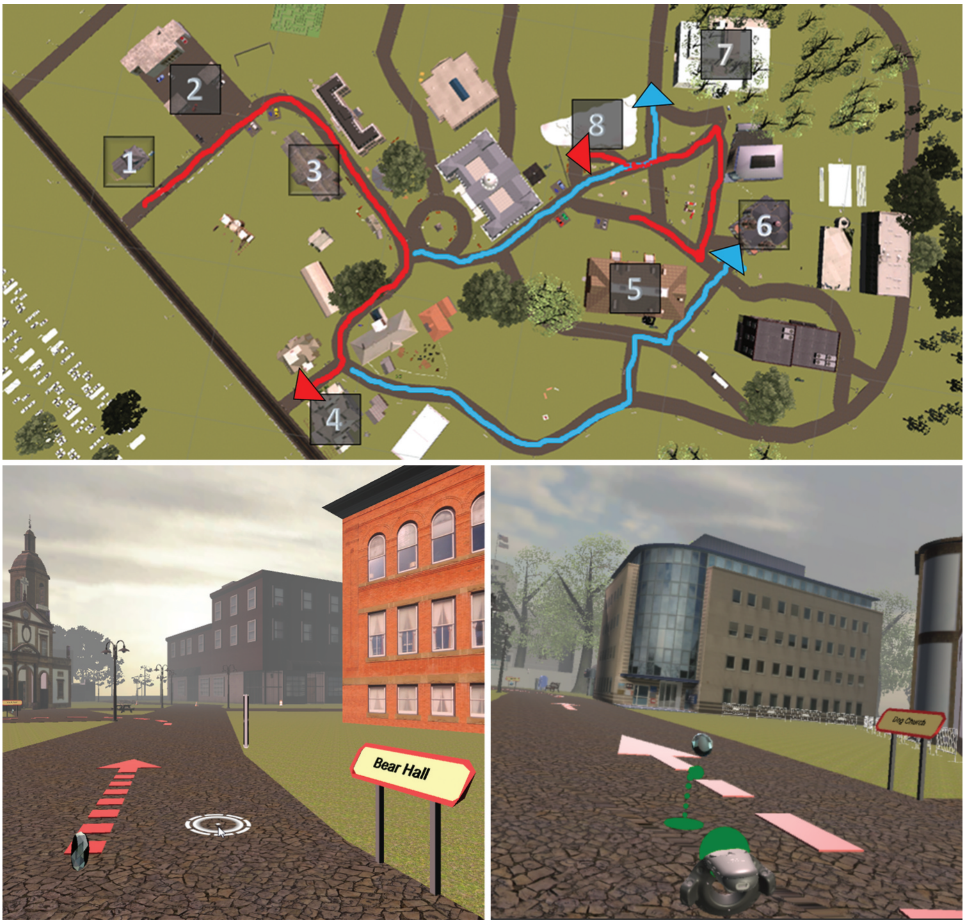

Figure 2. Aerial perspective of Virtual Silcton (top). Two main routes marked by red lines and two connecting routes marked by blue lines. Participants always learned the main routes then the connecting routes. Squares indicate locations of eight reference buildings that participants passed by and learned in sequence along the main routes. The two connecting routes were counter-balanced between participants. The bottom-left figure is a screenshot of the ground-level perspective using teleportation on a desktop screen, and the bottom-right figure is a screenshot of teleportation using the hand controller in an HTC Vive HMD.

The desktop VE was displayed using a 60 cm monitor (1920 x 1200 resolution) with a 90° geometric field of view.[12] It was positioned on a desktop in front of the participant and viewed from a normal distance of approximately 60 cm (53° physical field of view). Participants in the iVR condition stood in the center of the tracking area (3.4 m x 3.2 m), wore an HTC Vive HMD with a display resolution of 2160 × 1200 pixels and 110° geometric and projected fields of view. Both types of VE were rendered by an iBuyPower computer equipped with a Nvidia GTX 960 graphics card.

[12]Geometric field of view refers to the visual angle encompassing the virtual scene, which is equivalent to the field of view of the virtual camera and is adjustable by software.

For the experiment reported here, two travel approaches were developed for the low-immersion desktop computer. One was desktop teleportation. Participants pressed the left- and right-arrow keys to look around horizontally and the left mouse button to teleport. When holding the mouse button down, the participant would see a circle cursor that followed mouse movements but was always constrained to the ground (Figure 2, bottom left). Once releasing it, s/he would be teleported instantaneously to the cursor's position. The teleportation range was limited to a radius of 10 meters and had to occur within the route boundaries. The second travel approach was desktop continuous travel, which consisted of pressing arrow keys to look around horizontally and the left mouse button to move forward continuously. The moving velocity was constant at 5 meters/second, and the angular velocity for looking around was set to 100°/second.

Additionally, teleportation was implemented as the only travel approach for the iVR system.[13] The VE was adapted from being accessible on a desktop screen to being accessible using an HTC Vive HMD, in which participants were able to look around by moving their head and freely walk around the tracking area. However, participants had to use the Vive controller to perform teleportation for traveling beyond the tracking area (Figure 2, bottom right). The maximum teleportation distance was set to 10 meters within the route area.

3.1.2. Participants

Fifty-seven undergraduate students were recruited from the StudyFinder website[14] and two Penn State Geography courses to participate in a one-time study in exchange for 10 USD cash or extra course credit. Due to technical errors, we ended up with 55 participants (32 females) with ages ranging from 18 to 26 years (M = 20.2 years, SD = 1.58). Participants were randomly assigned to one of three VR conditions–desktop continuous travel (18 participants, average age 21 years, 11 females), desktop teleportation (18 participants, average age 19.9 years, 10 females), and Vive teleportation (19 participants, average age 19.7 years, 11 females).

3.1.3. Procedure

After consenting and providing basic demographic information, participants familiarized themselves with the travel approach and interactions required using the desktop computer or HTC Vive. Thereafter, participants were instructed to learn the names and locations – and thereby the spatial relations – of reference buildings in Virtual Silcton and then completed two spatial tasks. The whole experiment lasted approximately one hour.

[13]We initially introduced both continuous travel and teleportation in the Vive. However, a pilot study showed that continuous travel in the Vive caused users to experience moderate to serious simulator sickness.

[14]https://studyfinder.psu.edu/

3.1.3.1. Onsite pointing task. In the following task, participants were tested on how well they had learned the spatial relations between reference buildings located within or between the main routes. Participants were randomly teleported to the front of one reference building and were instructed to point to the remaining target buildings one by one, during which the name of the target building was displayed on the display for each pointing trial (e.g., "Point from Turkey House to Sheep Center"). Once finished, participants were placed in front of a new reference building and repeated the pointing trials for the remaining seven target buildings. In total, 56 directions along with pointing errors were recorded.[15] The direction records were divided into three groups: (1) within-route–visible pointings where the reference and target buildings belonged to the same main route and the target building could be seen by participants; (2) within-route–non-visible pointings where the target building was not visible from the reference building, but they were on the same main route; and (3) between-route pointings where the reference and target buildings were located on different main routes and were not visible to each other. These resulted in 15 within-route–visible, 9 within-route–non-visible, and 32 between-route pointing trials. In the desktop conditions, participants moved the mouse to position a crosshair toward one of the target buildings, then clicked to record the direction (Figure 3, left). In the Vive teleportation condition, participants held the Vive controller and pointed a green laser that was emitted from the controller tip toward one of the target buildings to complete a pointing trial (Figure 3, right).

3.1.3.2. Model-building task. This task was designed to measure how accurate participants' mental spatial representations were. Participants viewed a white

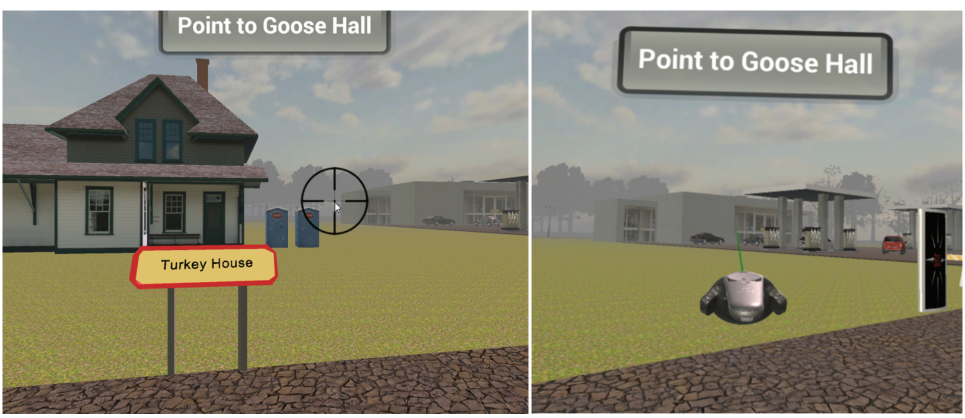

Figure 3. Onsite pointing task on the desktop screen (left) and HTC Vive HMD (right).

[15]Pointing error was measured as the absolute angular difference between the judged pointing direction and the actual direction of the target, resulting in a maximum possible error of 180°.

board and bird-eye-view images of the eight buildings. The route layout of Virtual Silcton was displayed on the white board. Participants were instructed to imagine the white board as a map and then place buildings to the position on the map that they believed the building would be located, during which a picture of the front view of the selected building and its name were displayed beside the map. Participants in the desktop conditions used the mouse to drag and drop buildings on the map while Vive teleportation participants used the laser pointer (the same as that used for the onsite pointing task) to pick up and put down buildings (Figure 4).

3.1.4. Data analysis

Two commonly used metrics in VE wayfinding literature, onsite pointing and model-building tasks (Ruddle & Lessels, 2006a; Weisberg et al., 2014), were used to assess learning outcomes.

Three types of errors were captured as measures of participants' pointing performance: within-route–visible error, within-route–non-visible error, and between-route error. A generalized linear mixed model (GLMM) was used to examine the effects of VR condition (desktop teleportation, desktop continuous travel, and Vive teleportation) and type of pointing trials (within-route–visible, within-route-non-visible, and between-route) on pointing errors using R (Field, Miles & Field, 2012). Specifically, VR condition and pointing trials were modeled as fixed effects of the pointing errors, and participants were modeled as a random effect.

For the model-building task, we analyzed participant performance using the *Gardony Map Drawing Analyzer* (GMDA; Gardony, Taylor & Brunyé, 2016). This software package for sketch map analysis provides multiple quantified indices that assess both the overall landmark configuration and inter-landmark spatial relationships. We used three indices provided by the GMDA: *configurational accuracy* (or bidimensional r^2), *distance accuracy*, and *angle accuracy*. Configurational accuracy provides a measure of the overall

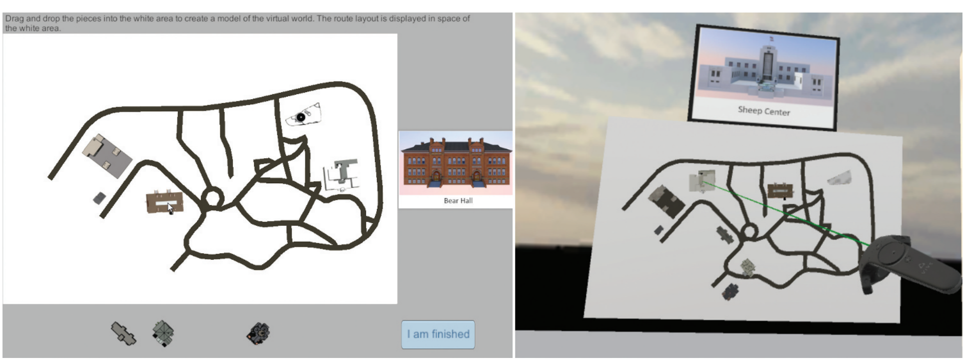

Figure 4. Model-building task using the desktop computer (left) and HTC Vive (right) in Experiment 1.

configural similarity between the coordinates of reference buildings in a mental spatial representation and the coordinates of reference buildings in the actual environment. This index is calculated based on a bidimensional regression approach and, therefore, is insensitive to scaling, translation, and rotation of the participant-generated map relative to the target environment (see Friedman & Kohler, 2003 for details). Distance accuracy and angle accuracy assess the inter-landmark configuration. Specifically, distance accuracy measures the accuracy of scaling of distances between reference buildings, and angle accuracy measures the accuracy of angles between reference buildings. All indices range from 0 to 1 with larger values indicating higher accuracies. Each of them was entered in a one-way analysis of variance (ANOVA) to examine the main effect of VR condition.

Additionally, we used the pointing and modeling data collected by Weisberg and Newcombe (2016) to obtain reference measurements on how accurate participants could become in these two tasks. More specifically, their pointing and modeling data served as a reference measure for the performance of our desktop continuous travel participants given that the desktop continuous travel condition in our study was adapted from Weisberg and Newcomb's study (Weisberg & Newcombe, 2016) and followed a similar experimental setup. The general comparability across studies was examined by comparing the desktop continuous travel sample means to ±1 standard deviation of means obtained from the reference study.

3.2. Results

Table 2 presents an overview of the means and standard deviations (SDs) across conditions (desktop teleportation, desktop continuous travel, Vive

Table 2. Means and standard deviations for pointing errors and model-building accuracies for the desktop continuous travel (DCT) condition, desktop teleportation (DTP) condition, Vive teleportation (VTP) condition, and reference condition in Experiment 1 (note: within-route–total is the averaged error for all within-route pointing trials. Reference measurements were obtained from the results reported by Weisberg & Newcombe, 2016).

		Condition			
Spatial task	Measure	DCT Mean (SD)	DTP Mean (SD)	VTP Mean (SD)	Reference Mean (SD)
Onsite pointing	Within-route–visible (°)	19.97 (12.25)	22.89 (14.85)	21.3 (13.0)	
	Within-route–non-visible (°)	25.39 (20.49)	34.32 (26.68)	40.68 (25.68)	
	Within-route–total (°)	22.0 (13.78)	27.18 (15.44)	28.57 (16.11)	23.12 (10.68)
	Between-route (°)	35.58 (22.19)	43.43 (27.85)	46.63 (18.68)	44.36 (13.85)
Model building	Configurational accuracy (r^2)	.83 (.25)	.78 (.21)	.59 (.29)	.47 (.27)
	Distance accuracy	.90 (.07)	.88 (.06)	.85 (.07)	
	Angle accuracy	.87 (.12)	.82 (.12)	.74 (.15)	

teleportation, and reference measurements). There was a significant main effect of type of pointing trial on pointing errors, $\chi^2(2) = 43.41$, $p < .001$. However, the pointing errors made by participants were not significantly different across the three VR conditions, $\chi^2(2) = 2.96$, $p = .23$. Also, the interaction effect of VR condition and type of pointing trials on pointing errors was not significant, $\chi^2(2) = 4.41$, $p = .35$. Contrasts were used to break down this main effect. The first contrast looked at differences between within-route–visible pointing trials and the average of within-route–non-visible and between-route pointing trials on pointing errors. This contrast was significant, $b = -5.43$, $t(104) = -6.57$, $p < .001$, $r = .54$, and tells us that participants made smaller pointing errors at the within-route–visible trials than those at the within-route–non-visible and between-route trials across all VR conditions. The second contrast examined if there was a difference between within-route–non-visible and between-route pointing trials on pointing errors. This contrast was significant, $b = -4.21$, $t(104) = -2.94$, $p = .004$, $r = .28$, and tells us that participants made smaller pointing errors at the within-route–non-visible trials than those at the between-route trials across all VR conditions.

For participant performance on the model-building task, the assumption of homogeneity of variance for one-way ANOVAs was met. There was a significant effect of VR condition on configurational accuracy, $F(2, 52) = 4.76$, $p = .01$, $\omega = .35$. Despite a large effect size, Tukey post-hoc tests revealed a non-significant difference between desktop teleportation and Vive teleportation conditions, $p = .07$, $d = .75$. There was also no significant difference between desktop teleportation and desktop continuous travel conditions, $p = .80$, $d = -.22$. Participants in the desktop continuous travel condition, however, had significantly higher configurational accuracy than in the Vive teleportation condition, $p = .01$, $d = .88$. For the scaling and rotation aspects of participant-generated maps, there was no significant difference on distance accuracy, $F(2, 52) = 2.32$, $p = .11$, $\omega = .21$; however, we found that the effect of VR condition was significant for angle accuracy, $F(2, 52) = 4.13$, $p = .02$, $\omega = .35$. Tukey post-hoc tests on the main effect showed that participants in the desktop continuous travel condition had significantly higher angle accuracy than in the Vive teleportation condition, $p = .02$, $d = .95$. No other post-hoc comparisons were significant (ps > .17).

Next, we examined whether the task performances of desktop continuous travel participants were comparable to the results of reference measurements. For desktop continuous travel participants, within-route–total errors were similar to the reference results (22.0 ± 13.78 vs. 23.12 ± 10.68, respectively), and between-route errors were also similar to the reference results (35.58 ± 22.19 vs. 44.36 ± 13.85, respectively); however, their configurational accuracy in the model-building task was much higher than the reference results, .83 ± .25 vs. .47 ± .27, respectively. To test whether participants' college majors moderated the effect of VR condition on configurational accuracy, we coded Geography, Environmental Resource Management, Energy, and Geosciences as Geo-related majors, and the rest as non-Geo majors (e.g., Public Relations). As can be seen by the frequencies cross tabulated in Table 3, there was a higher percentage of participants in the two desktop conditions than in the Vive teleportation condition majoring in Geo-related disciplines. A chi-square test of independence showed a significant relationship between VR condition and college major, X^2 (2, N = 55) = 6.46, p = .04. We then ran a 3 × 2 factorial ANOVA to test whether there was an interaction between VR condition and participant's college major on configurational accuracy. The assumption of homogeneity of variance was met. While the main effect of college major was significant (Geo-related major: M = .83, SD = .21; non-Geo major: M = .6, SD = .3; $F(1, 49) = 7.31$, p = .01, ω = .33), there was no significant interaction, $F(2, 49) = 2.40$, p = .10, ω = .26.

3.3. Discussion

Contrary to our expectations, our results did not provide any evidence to suggest that increasing immersion (e.g., HMD) and using continuous travel lead to better spatial learning performance. No significant differences in pointing errors were found for any types of pointing trials. The results are different from the previous spatial learning literature (Christou & Bülthoff, 1999; Holmes et al., 2017). Likewise, the comparable performance of participants in the Vive teleportation and desktop teleportation conditions implies a limited role of immersion that comes into play at least with the onsite pointing task. This finding is consistent with evidence from other studies of the immersion level and its effect on spatial learning toward large-scale indoor VEs (Li & Giudice, 2013; Santos et al., 2009), which indicates that the benefit gained from increasing immersion (e.g., HMD) may not be as pervasive as has been suggested in the literature (e.g., Krokos et al., 2019).

However, the results of the model-building task tell a different story, which potentially actually favors desktop methods. There was a significant condition effect on configurational accuracy in favor of both low-immersion desktop computers and continuous viewpoint transitions. Given that desktop continuous travel led to higher configurational accuracy than the reference condition (over one SD of the reference mean), we have to acknowledge that we are not confident to draw conclusions from the model-building results. Instead, we need to reflect

Table 3. Frequencies of Geo and non-Geo participants for each VR condition for Experiment 1.

	DCT		DTP		VTP	
College Major	Frequency	Percent	Frequency	Percent	Frequency	Percent
Geo	11	64.1	14	77.8	7	36.8
Non-Geo	7	35.9	4	22.2	12	63.2

on the experimental design and procedure in order to try to figure out the factors that may contribute to the deviation of our results from reference measurements.

The crux lays in the unbalanced sampling strategy and potential *ceiling effect*, which might have impaired the experimental validity with reduced statistical power and measurement accuracy. First, most of the participants in our study were recruited from one of two Geography courses, of whom more than half (58.2%) were majoring in Earth Science disciplines including, for example, Geography, Geosciences, and Environmental science. In the model-building task, Geo-related participants performed significantly better than others, possibly because these disciplines are particularly dependent on environmental spatial abilities (Hegarty, Crookes, Dara-Abrams & Shipley, 2010). Thus, the sampling bias may inflate any correlation of the data, especially considering that participants were recruited from a less general target population.

Second, configurational accuracy of the two desktop conditions was abnormally high, implying a ceiling effect. In other words, the variance of model-building performance was no longer measurable, as desktop participants could have always achieved high configurational accuracy regardless of how well they had learned the VE. One possible reason for this is the prevalence of Geo-related majors in the two desktop conditions (desktop continuous travel: 61.1%; desktop teleportation: 77.8%). Another possible reason of the potential ceiling effect is that in our study, unlike the reference condition in which one could only arrange building models on a white board, the route layout of Virtual Silcton was indeed displayed to participants, which could have boosted their model-building scores.

Notwithstanding the above, our pointing results fall within the range of errors in the reference condition, indicating that the present onsite pointing task is representative of spatial learning in other research efforts, despite changes in the experimental design. On the other hand, failure to prevent the ceiling effect from the model-building measurement may lead to a biased interpretation and misleading conclusions (Taylor, 2010). Fortunately, some of the coauthors conducted a larger experiment in parallel that provides an opportunity to reexamine these challenges, which will be reported below as Experiment 2.

4. Experiment 2

The following experiment is similar to Experiment 1, albeit with only two conditions and a larger sample of 198 participants recruited from a psychology participation pool for higher statistical power. This experiment investigated the effects of immersion on spatial learning by contrasting the desktop continuous travel and Vive teleportation conditions. The desktop continuous travel data had been collected over several years using the standard Virtual

Silcton paradigm (see footnote 9) with the original purpose of examining individual differences in navigation. The Vive teleportation data were collected from the same population using our newly developed Vive application to determine if transitioning to this methodology would change spatial cognition. While in the current experimental setup viewpoint transitions (continuous travel vs. teleportation) may confound immersion levels (low-immersion desktop computer vs. iVR), the results of Experiment 1 suggest that viewpoint transitions likely have little (if any) effect on spatial learning. Additionally, continuous travel and teleportation have been widely used in desktop and iVR games, respectively, which adds practical implications to the current comparison.

4.1. Method

4.1.1. Material

The VE was not changed from Experiment 1 except that the buildings were named differently for the desktop continuous travel condition (see footnote 11). For the Vive teleportation condition, the VE and the travel approach were the same as in Experiment 1, while participants were seated in a swivel chair that fixed their physical location to the center of the tracking area. Specifically, Vive teleportation participants were allowed to turn their heads and bodies to look around, but their physical walking was constrained by the chair. The HTC Vive used in the Vive teleportation condition was identical to Experiment 1. The travel approach for the desktop continuous travel condition was that of the standard Virtual Silcton paradigm. Specifically, desktop continuous travel participants pressed the arrow keys to perform translation movements in four degrees of freedom (i.e., forward, backward, left, and right) to mimic continuous travel with optic flow and moved the mouse to look around in both horizontal and vertical directions. The translating velocity was constant at 5 meters/second. The desktop VE was displayed on a 60 cm monitor (1920 x 1080 resolution) with a 90° geometric field of view. The physical field of view was approximately 53°. In both conditions the VE was rendered by a Dell computer equipped with an Intel HD 530 graphics card.

4.1.2. Participants

A total of 198 participants was recruited from the University of Wyoming Psychology Participation Pool and received course credit. The Vive teleportation condition (average age 19.9 years) consisted of 50 females and 38 males. With our newly developed Vive application, Vive teleportation participants always learned the two main routes of Virtual Silcton in the same order; however, the main routes were counterbalanced between participants in the standard paradigm (which was used for the desktop continuous travel condition). Because data analyses (described below) suggested that the learning order influenced

Vive teleportation participants' pointing performances, those desktop continuous travel participants who learned the main routes in a different order than Vive teleportation participants were excluded from our analysis. Consequently, we ended up with 56 participants in the desktop continuous travel condition, with an average age of 21 years, and with 33 females.[16]

4.1.3. Procedure

The experimental procedure was similar to that of Experiment 1 except that (1) Vive teleportation participants were seated in a swivel chair when traversing the VE, during which only vestibular feedback was obtained; (2) participants in both conditions were instructed to point to the front door of each target building in the onsite pointing task[17]; and (3) the model-building task was modified. Specifically, in the Vive teleportation condition, participants saw eight small-size building models that were lined up in a row on the left side. A table with the routes depicted on the tabletop was positioned in front of them. Participants were instructed to imagine the tabletop as a map and to place the eight buildings on the map. Participants used the Vive controller to pick up the building models and place them in the desired locations on the tabletop map (Figure 5, right).

4.1.4. Data analysis

Similar to Experiment 1, we examined how desktop continuous travel participants performed in the spatial tasks as compared to the reference results.

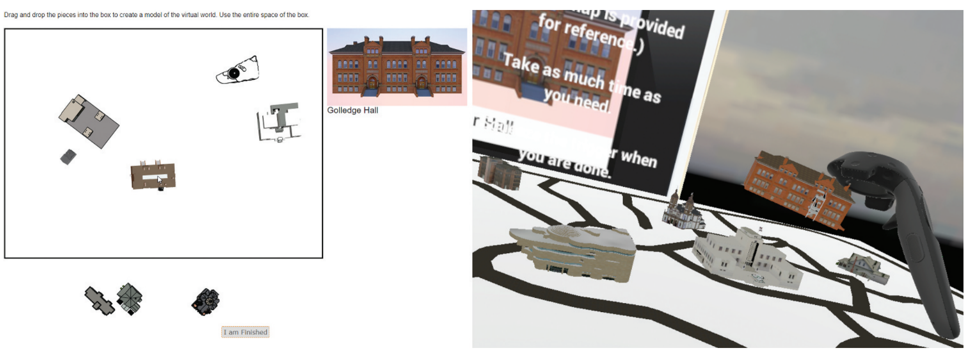

Figure 5. Model-building task using the desktop computer (left) and HTC Vive (right) in Experiment 2. The route layout of Virtual Silcton was only displayed to Vive teleportation participants.

[16]We used a navigation log file that was created by the standard paradigm to find out those desktop continuous travel participants who followed the same sequence as Vive teleportation participants when traveling along the main routes.

[17]The standard Silcton paradigm used the front door of the target building as reference location toward which the pointing direction was judged absolutely correct. In contrast, the newly developed Vive application used the geometric center of the building as reference location. To make the pointing data comparable between VR conditions, pointing errors for Vive teleportation participants were recalculated based on the front door of buildings.

A GLMM was used to examine the effects of VR condition and type of pointing trials on pointing errors. We then ran a repeated measures multivariate analysis of variance (MANOVA) to test whether there were condition differences for individual pointing trials using the *MANOVA.RM* package in R (Friedrich, Konietschke & Pauly, 2018); the Wald-type statistic (WTS) and modification ANOVA-type statistic (MATS) calculated by the *MANOVA()* function can be used for semi-parametric designs with unequal covariance matrices among conditions. In the post-hoc MANOVA, we used the Bonferroni correction to correct for multiple comparisons. The main effects of VR condition on model-building accuracies (configurational, distance, and angle) were tested using the Welch two-sample t-tests. Given the potentially confounding factor in the model-building task (i.e., with/without the routes pictured on the table map; Figure 5), we mainly used the pointing errors to draw conclusions about participants' learning performances.

4.2. Results

Table 4 presents an overview of the means and SDs across VR conditions (desktop continuous travel, Vive teleportation). For desktop continuous travel participants, their within-route–total errors were similar to the reference results (see the final line of Table 2; 19.47 ± 9.72 vs. 23.12 ± 10.68, respectively), between-route errors were similar to the reference results (40.94 ± 14.52 vs. 44.36 ± 13.85, respectively), and configurational accuracy was similar to the reference results (.62 ± .26 vs. .47 ± .27, respectively).

4.2.1. Desktop continuous travel vs. Vive teleportation comparison

There was a significant main effect of type of pointing trials on pointing errors, $\chi^2(2) = 213.22$, $p < .001$. However, the pointing errors made by desktop continuous travel and Vive teleportation participants were not significantly different, $\chi^2(2) = 1.88$, $p = .17$. There was a significant interaction effect of the

Table 4. Means and standard deviations for pointing errors and model-building accuracies for the desktop continuous travel (DCT) condition and Vive teleportation (VTP) condition in Experiment 2.

		Condition	
Spatial task	Measure	DCT Mean (SD)	VTP Mean (SD)
Onsite pointing	Within-route–visible (°)	13.79 (9.49)	21.48 (18.67)
	Within-route–non-visible (°)	28.93 (14.38)	30.01 (22.61)
	Within-route–total (°)	19.47 (9.72)	24.68 (18.42)
	Between-route (°)	40.94 (14.52)	42.79 (18.8)
Model building	Configurational accuracy (r^2)	.62 (.26)	.59 (.32)
	Distance accuracy	.84 (.05)	.83 (.07)
	Angle accuracy	.56 (.23)	.66 (.24)

VR condition and type of pointing trials on pointing errors, $\chi^2(2) = 7.14$, $p = .028$. This indicates that the main effect of type of pointing trials on pointing errors described previously was different for the two VR conditions. Contrasts were used to break down the interaction (i.e., VR condition x type of pointing trials). The first contrast looked for differences between desktop continuous travel and Vive teleportation participants on within-route–visible pointing trials. This contrast was significant, $b = -3.11$, $t(284) = -2.66$, $p = .008$, $r = .16$, and tells us that Vive teleportation participants made significantly larger within-route–visible pointing errors than desktop continuous travel participants. The second contrast revealed a non-significant difference in pointing errors between VR conditions when comparing within-route–non-visible to between-route trials, $b = 0.19$, $t(284) = 0.28$, $p = .78$, $r = .017$. Next, we examined whether there were condition effects on model-building performance using the Welch two-sample t-tests. The assumption of normality of configurational accuracy was met. There were no significant differences between desktop continuous travel and Vive teleportation conditions in configurational accuracy, $t(133.59) = .58$, $p = .56$, $d = .10$, or in distance accuracy, $t(141.38) = .62$, $p = .54$, $d = .10$. However, participants in the Vive teleportation condition had significantly higher angle accuracy than those in the desktop continuous travel condition, $t(122.52) = 2.48$, $p = .01$, $d = .42$.

4.2.2. Source of condition differences

The orthogonal comparisons after the GLMM revealed a significant condition effect on pointing errors for the within-route–visible pointing trials. Figure 6 shows the pointing errors that participants made at each within-route–visible pointing trial for both VR conditions. A MANOVA was conducted to test whether there were significant differences between desktop continuous travel and Vive teleportation conditions on pointing errors across all within-route–visible pointing trials using the *MANOVA()* function in R (Friedrich et al., 2018). There was a significant main effect of the VR condition on pointing errors, *WTS statistic*(15) = 47.53, *MATS statistic* = 69.99, $p < .001$. The MANOVA was followed up with univariate comparisons with Bonferroni correction, which revealed significant differences on pointing trials 5 → 7, 6 → 7, 5 → 8, 6 → 8, and 7 → 8 (numbers represent reference buildings shown in Figure 2, top). Specifically, Vive teleportation participants made significantly larger pointing errors than desktop continuous travel participants at these pointing trials, p's < .05.

One possible explanation of this finding is that when the target building was perceived as being relatively large,[18] finding its front door (toward which the pointing direction was judged absolutely correct) might have presented more

[18]The perceived size of target buildings depends on two factors: 1) the actual size of the building and 2) the distance the building is from the eye.

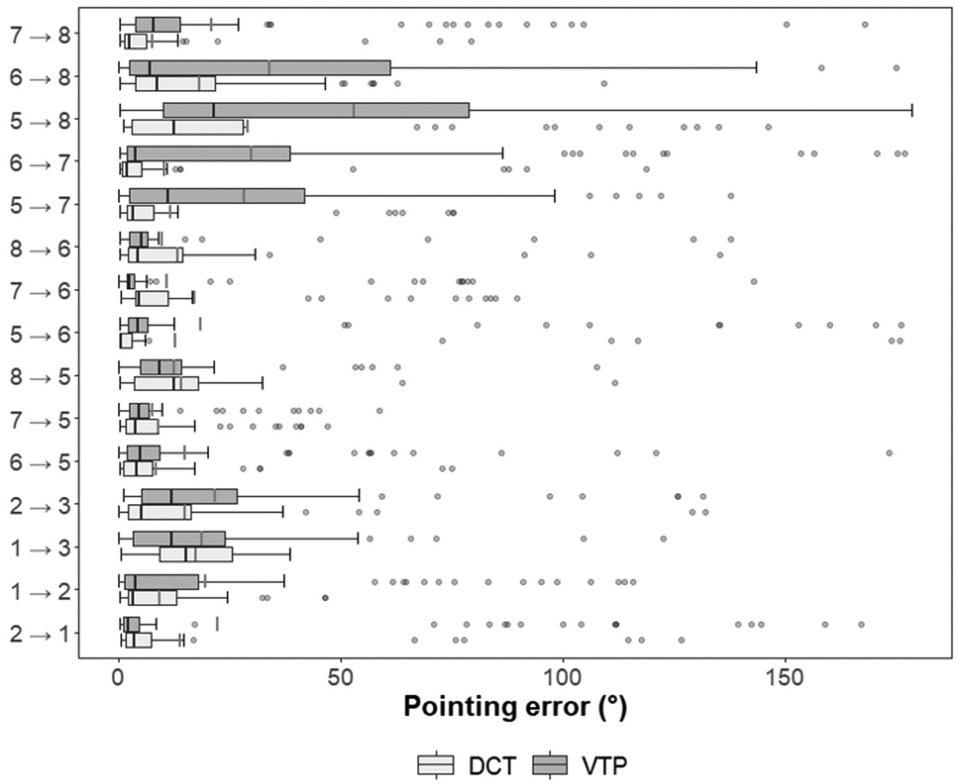

Figure 6. Box plots of pointing errors across within-route–visible pointing trials for the desktop continuous travel (DCT) condition and Vive teleportation (VTP) condition for Experiment 2. Numbers on the vertical axis represent buildings shown in Figure 2 (top). Each pointing trial was named by the identification number of the reference building that participants stood in front of followed by the identification number of the target building. From bottom to top, the pointing trials are sorted in order of the target buildings that participants would pass by when traveling along the main routes in Virtual Silcton. In the box plots, the boundary of the box closest to zero indicates the 25th percentile, a black line within the box denotes the median, a gray line denotes the mean, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers indicates the 10th and 90th percentiles. Points represent outliers outside the 10th and 90th percentiles.

of a challenge to Vive teleportation participants than to desktop continuous travel participants. To examine whether the worse performance of Vive teleportation participants came from the relatively large perceived size of the target buildings, we calculated the perceived visual angle subtended by the target buildings for the five pointing trials (5 → 7: 18.78°, 6 → 7: 18.84°, 5 → 8: 23.86°, 6 → 8: 17.97°, 7 → 8: 16.57°), all of which were within ± 1 standard deviation of means of perceived angles of the target buildings among all 15 visible pointing trials (19.26 ± 5.40°). For those pointing trials in which Vive teleportation participants had significantly worse performances than desktop continuous travel participants, the target buildings did not yield relatively large perceived angles compared to those at other within-route–visible pointing trials.

As can been seen in Figure 6, “7” and “8” – i.e., target buildings for pointing trials 5 → 7, 6 → 7, 5 → 8, 6 → 8, and 7 → 8 – were the last two reference buildings that participants would learn when traveling along the main routes in Virtual Silcton (see also Figure 2, top). To investigate whether Vive teleportation participants had difficulties remembering the location of these two reference buildings, we averaged the pointing errors that were made by each participant at non-visible pointing trials, including within-route–non-visible and between-route, that also used “7” or “8” indicated in Figure 2 (top) as the target building. We then ran a Welch two sample t-test to examine whether there was a significant difference between VR conditions on the pointing errors of non-visible pointing trials toward these two target buildings. Similar to the results of within-route–visible trials, Vive teleportation participants (M = 32.51, SD = 15.92) performed significantly worse than desktop continuous travel participants (M = 26.93, SD = 9.39), $t(141.32) = -2.65$, $p = .01$, $d = .41$.

4.3. Discussion

Overall, we observed similar performance scores between the desktop continuous travel and the reference condition (all relevant desktop continuous travel means were similar to reference means). This indicates that the ceiling effect on the model-building task that exists in the first experiment could have been circumvented through a more homogeneous, non-Geo majors participant pool.[19]

A possible concern about the model-building task is that the main effect of immersion might be confounded by the presence of roads linking the reference buildings (see Figure 5). Given that such roads were depicted only in the Vive teleportation condition, participants in this condition could have benefited simply because the route layout might have structured their mental representations of the environment. In response to this concern, we looked at participants’ model-building performance and found that participants in the Vive teleportation condition had significantly higher angle accuracy than in the desktop continuous travel condition. This result suggests that roads drawn on the table map may have played the role of anchoring the orientation of participants’ mental representations. However, participants in both conditions had almost the same configurational accuracy indicating that the retrieval of spatial relationships among target locations at the configurational level are not affected by the display of the route layout.

[19]Participants in Experiment 2 were recruited from a psychology participation pool. It is conceivable that most of them did not have any background in geo-related areas.

Regarding pointing performance, our results show that Vive teleportation participants, compared to desktop continuous travel participants, faced more challenges when learning the last two reference buildings in Virtual Silcton, reflected by their significantly higher pointing errors toward these two buildings at both within-route–visible and non-visible pointing trials. This finding is in line with the study of Makransky et al. (2017), which found that participants were more taxed mentally during learning later in the session when using iVR simulations as compared to desktop version of a simulation. Building on this, our results hint at potential support for the cognitive load theory view that the "seductive details" (i.e., interesting but irrelevant material) in the immersive learning environment increase the extraneous cognitive load (i.e., the cognitive processing that does not support the learning goal; see Sweller et al., 1998 for review) and therefore lower the user's cognitive interest (Lan, Fang, Legault & Li, 2015). Specifically, perhaps the iVR systems that offer a high level of presence (Buttussi & Chittaro, 2018; Chirico et al., 2016; Makransky et al., 2017; Shin, 2017) can interfere with reflection during learning, especially in the situation in which added immersion is not relevant to the instructional objective (i.e., learn the location of target buildings); thus the added perceptual realism could be categorized as a seductive detail which could distract participants by overstimulating or priming the wrong learning schema.

Additionally, it is interesting to note that Vive teleportation participants made significantly larger pointing errors toward buildings 7 and 8 than other target buildings (1–6). This result suggests that with the iVR system, experiencing Virtual Silcton above or below six reference buildings seems to have a drastically different learning outcome. Our finding hints at potential support for the error accumulation hypothesis (Hochmair & Frank, 2000; Ruddle et al., 2011) that human estimation errors for wayfinding in a large-scale unknown environment may accumulate over time. In contrast, desktop continuous travel participants made similar pointing errors across all reference buildings, implying that at least with our tasks, learning the same VE on a desktop screen requires cognitive capability that still falls within the available memory resources, during which error accumulation may be too subtle to be detected by our measurements. We have to acknowledge though that the different names used for the same reference building (famous geographer versus animal species for the desktop continuous travel and Vive teleportation condition, respectively; see footnote 11) may influence the building recall process as well as working memory; but, considering that participants in this experiment were all recruited from a psychology participation pool, we assume that individual differences in prior geographic knowledge would have little effect on learning outcomes.

5. General discussion

The primary motivation of this study was to investigate whether the added immersion of iVR systems and continuous viewpoint transitions, as compared to the traditional desktop computers and teleportation, could lead to improved learning performance in large-scale outdoor VEs. Specifically, the effect of viewpoint transitions was examined by comparing desktop continuous travel to desktop teleportation performance in Experiment 1. Although there were problems with the model-building data, we note that participants across all experimental conditions in Experiment 1 made similar within- and between-route–total errors compared to those in Experiment 2 (see Tables 2 and 4); both are comparable to the reference condition. Thus, data obtained from the onsite pointing task of Experiment 1 are presumed to be valid for testing our hypotheses. In contrast to the comparisons of viewpoint transitions in small-scale or multi-level indoor spaces (Christou & Bülthoff, 1999; Holmes et al., 2017), our results indicate that the differences between continuous travel and teleportation seem to affect spatial learning much less if users travel in large-scale outdoor VEs. This finding is partly in line with studies of urban VEs by Gaunet, Vidal, Kemeny and Berthoz (2001) and Weißker et al. (2018), which show that accuracy in estimation of the direction of the origin of the path (i.e., test on path integration)[20] is not influenced by forms of virtual travel. Our results provide further supportive evidence with regard to a more complex VE where multiple targets are present and adopting more advanced forms of spatial updating may be necessary. While directly teleporting from origin to destination is known to impair spatial learning (i.e., teleportation beyond *vista space*; see Weißker et al., 2018), the maximum radius of 10 m in the current form of teleportation is much smaller than the visible area accessible from a single viewpoint in Virtual Silcton; therefore, this range-restricted teleportation may support automatic spatial updating in a manner of continuous travel, both of which allows users to seamlessly integrate the knowledge of where they come from and where they are going. It is perhaps not surprising that spatial learning performance in the desktop teleportation condition was no worse than in the desktop continuous travel condition.

Gallistel (1990) and Gallistel and Matzel (2013) provide an alternative perspective on why continuous travel might not result in better spatial learning outcomes than teleportation. The authors indicate that individuals can determine their positions relative to non-visible places using two types of navigation systems: path integration and piloting (see also Mou & Wang, 2015; Zhang & Mou, 2017). As mentioned in footnote 20, path integration is

[20]Path integration, as the basic form of spatial updating, refers to the process by which people use sensory cues to continuously track their position and orientation relative to the origin or destination within the environment in the absence of suitable positional cues of targets (i.e., position-informative information; see He & McNamara, 2017 for review).

the process of using self-motion cues (e.g., vestibular cues, proprioceptive cues, and optic flow) to estimate one's traveled distance and moving direction, and then calculating the location of a non-visible target on the traversed path. Piloting is the other way of estimating one's position, during which navigators estimate the location of a non-visible target by relying on some visible items (e.g., landmarks) and the spatial relations between the visible items and the non-visible target (Mou & Wang, 2015). Although people usually use both navigation systems in everyday navigation (Zhang & Mou, 2017), it is possible that the piloting system became dominant during spatial learning in Virtual Silcton, leading to a similar performance between desktop continuous travel and desktop teleportation participants. First, because body-based senses (pertaining to self-motion cues) were not available in the two desktop conditions, the path integration system can be assumed to be less reliable than the piloting system. Second, Virtual Silcton contains a plethora of visual landmarks, which could foster the development of piloting by resetting and removing errors accumulated in the path integration system after disorientation (Nardini, Jones, Bedford & Braddick, 2008; Zhang & Mou, 2017). Considering the advantage of piloting over path integration, continuous viewpoint transitions along with other self-motion cues would have little effect on spatial learning, particularly when participants needed to travel over a long distance to learn the locations of multiple targets and their spatial relations in such a large-scale outdoor VE.

Nonetheless, results of the current research seem to be discordant with other previous studies, according to which better spatial learning performances were obtained when participants continuously traveled through large-scale outdoor VEs (Cherep et al., 2020; Coomer et al., 2018; Paris et al., 2019). One possible explanation could be the different type of VR system used. In the studies that observed better performance using continuous travel compared to teleportation, continuous viewpoint transitions were realized in iVR systems through walking or locomotion, which provided participants with full or partial translational body-based information as well as translational motion cues in their visual periphery; such sensory information is missing in teleportation. In contrast, a desktop computer was used in the current study for participants to perform virtual travel, during which body-based sensory information and peripheral self-motion cues were eliminated in both the desktop continuous travel and desktop teleportation condition. Thus, it could be hypothesized that either translational body-based information, peripheral motion cues, or both are of critical importance for people to efficiently navigate through large-scale outdoor VEs. A future experiment in which continuous travel is implemented with and without these features could help test this hypothesis.

In addition to viewpoint transitions, the results of an onsite pointing as well as a model-building task indicate that low-immersion desktop environments are similarly effective for supporting spatial learning of large-scale outdoor

VEs. Indeed, in the second experiment, the performance in the desktop condition (desktop continuous travel) was significantly better than in the iVR condition (Vive teleportation) when participants were instructed to point to the last two reference buildings along the second main route.

Overall, our findings are in line with some empirical studies of immersion and its motivational value and cognitive outcomes toward learning (Karaseitanidis et al., 2006; Li & Giudice, 2013; Lugrin et al., 2013; Makransky et al., 2017; Santos et al., 2009), namely, that for actual learning purposes it may be more appropriate to use low-immersion desktop computers than using iVR systems. Immersive technologies, such as VR, have been proposed as a new technique to induce novelty or the feeling of awe within laboratory conditions (Chirico et al., 2017). Van Elk, Karinen, Specker, Stamkou and Baas (2016) indicated a strong correlation between cognitive absorption (i.e., the tendency to get fully immersed in one's experiences) and the feeling of awe. From this perspective, Vive teleportation participants who "enjoyed" their virtual experiences might have not focused on the spatial relations of target buildings. Instead, their attention could be directed to novel action cues (e.g., red arrows on the ground, Bézier laser for teleportation, and invisible route boundaries) or other seductive details of digital simulations rather than spatial information.

As stated in the literature, one critical affordance of iVR systems is to support embodied experiences in a way that different visual and perceptual cues can be manipulated to induce the user's feeling of being and acting in VEs (Chirico et al., 2016). Notwithstanding, our results imply that iVR simulations may be overstimulating due to users' prolonged exposure to VEs. When Vive teleportation participants were fully absorbed in the VE, their multiple sensory cues, which were supposed to be processed for spatial knowledge acquisition, would be soon overwhelmed by seductive details of the iVR simulation. Such added immersion could interfere with the spatial learning process. Therefore, during learning later in the VE, Vive teleportation participants might not have ample cognitive resources for assimilating new information to existing mental spatial representations. An intriguing question for future research would be to test experimentally whether there is a negative association between the sense of presence experienced by individuals and their spatial learning performance.

6. Conclusions, limitations, and future research

Our study contributes to assessing the effectiveness of using iVR systems and continuous travel for spatial learning in large-scale outdoor VEs when body-based cues to self-motion are limited. Findings from our study suggest that neither increased immersion nor continuous viewpoint transitions leads to better performance. Some learning situations may benefit from continuous viewpoint transitions or higher immersion (e.g., Dede, 2009; Holmes et al., 2017; Shin, 2017), but at least for the range of tasks in the current large-scale outdoor VE, the low-immersion desktop computer with either form of virtual travel (continuous travel or teleportation) seems to be sufficient to fulfil the needs of spatial learning, especially given that iVR systems are more expensive, less comfortable, and more complex to implement. Despite some challenges we discuss below regarding the research design, the findings point to critical gaps in the literature and raise caution about simplified assumptions that increasing immersion and presence automatically lead to better learning performance.

There are a number of limitations in this study that should be borne in mind and be addressed in future research. First, given the unbalanced sampling strategy of Experiment 1 and the mixed design of Experiment 2 that viewpoint transitions and immersion varied across two VR conditions, data collected from the present research are subject to biases and confounding that may have influenced the validity and reliability of our results. Studies that examine the use of an iVR system jointly with continuous travel will help us with more rigorous control over variables, as well as further our understanding of how the continuous viewpoint transitions impact spatial learning in highly immersive large-scale VEs. Additionally, other potentially confounding factors to consider include the different names used for the same reference building in Virtual Silcton (Experiment 2), table map with or without the route layout depicted in the model-building task (Experiment 2), and mode of testing for both experiments (performing spatial learning tasks on the desktop screen or in iVR). A follow-up study involving benchmark tests (e.g., controlling for viewpoint transitions and level of immersion in Virtual Silcton while using two modes of testing) is necessary to help clarify the contribution of each confounding variable to performance.

Second, we only used two measures of spatial knowledge acquisition (i.e., onsite pointing task and model-building task), and hence explaining any differences that occurred in performance primarily relied on hypotheses and anecdotal observation. Future study with a wider adoption of metrics of spatial learning, such as the estimates of straight-line/route distance and the time that participants spend to perform navigation trials, is necessary to provide a comprehensive understanding of various facets of wayfinding behavior and spatial memory as well as will allow easier comparison between the results of the studies conducted by different research groups.

Third, the interference of the feeling of awe cannot be ruled out. More than 60% of the participants had never used iVR before. Thus, this new technology may be overstimulating and could distract users from actual learning. Performing spatial learning tasks in highly immersive VEs over a number of sessions might diminish this awe effect.

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Declaration of interest

The authors declare that they have no competing interests.

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Data availability

The virtual environment used in the current study and the datasets along with the analysis code are available on request from the corresponding author, Jiayan Zhao.

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