Virtual reality as a tool to understand spatial navigation

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Key points

- Spatial navigation is a complex task involving perception, attention, memory, and decision making. Virtual reality provides control over the environment and the observer in ways that are impossible in the real world, allowing for careful exploration and analysis of complex spatial behavior.
- Immersive virtual reality experienced through a head-mounted display allows for free walking within the boundaries of the physical space, but locomotion (movement) interfaces are necessary when exploring larger environments or using other display types (e.g., desktop VR). Locomotion interfaces are characterized by trade-offs, including availability of self-motion cues, cybersickness, and fatigue.
- Virtual reality is an ideal tool for studying the contributions of spatial cues to navigation, including cues from the environment and cues from the body generated during self-motion.
- Individuals vary considerably in their ability to navigate and perform other spatial tasks. Commonly studied correlates of navigation include gender, age, and anxiety. Virtual reality enables research on individual differences by providing novel environments, by making it easier to test large numbers of individuals, and facilitating spatial tasks that reveal individual differences in spatial thinking.

Abstract

Spatial navigation, the ability to explore, learn, and remember one's environment, is a skill that is fundamental to everyday goals. Navigation is challenging to study because it requires understanding and integrating multiple sources of information from the environment and the body as well as many cognitive processes including perception, attention, memory, and decision making. Virtual Reality (VR), the presentation and experience of a synthetic sensory environment, provides a method to study spatial navigation in controlled, ecologically valid, and innovative ways. In this review, we describe VR as a tool to study spatial navigation with the perspective that basic science questions and applications mutually inform one another. We focus on how VR has advanced an understanding of the spatial cues, spatial knowledge, and individual differences involved in spatial navigation and discuss the role and implications of different VR technologies that allow for these investigations.

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Introduction

Spatial navigation is a complex process that involves the ability to keep track of spatial locations with self movement, find one's way home, remember previously learned routes, and plan new routes to familiar locations. Navigating through both new and familiar environments is essential to accomplish many everyday goals such as finding your car in a parking lot, arriving at a doctor's office, or exploring a new city. These examples describe navigational spaces on different scales. Searching in a parking lot requires assessing *vista space*, which can be visually experienced from a single location; whereas navigating through an office building or a city involves *environmental space*, or a space that requires movement of the observer to completely experience (Montello, 1993). The complexity of navigation comes from the fact that there are several cues, frames of reference, and forms of spatial knowledge that contribute to the process of navigation over multiple scales (Wolbers and Wiener, 2014). And although most everyone navigates, there are large individual differences in navigation strategies and performance (Hegarty et al., 2002), most notably variations with gender and older age (Merhav and Wolbers, 2019; Nazareth et al., 2019). Our goal is to examine how virtual reality (VR) can be used to increase our understanding of spatial navigation processes.

Virtual reality is the presentation of a synthetic sensory environment to a user through some form of display technology. Most commonly, this display technology is visual and presents a three-dimensional (3D) environment, often involving a stereoscopic display (Jerald, 2015). As the complexity and richness of the sensory stimulus increases, other senses, particularly hearing, may be engaged. The goal of VR is to present to the user a simulation of an environment that is not the physical world of the user, a so-called *virtual environment.* Measuring the success of a virtual reality simulation at achieving a synthetic environment different from the one the user is located in has been the subject of significant research (Bowman and McMahan, 2007; Cummings and Bailenson, 2016; Gagnon et al., 2021; Skarbez et al., 2017; Stoffregen et al., 2003), and a discussion of it is beyond the scope of this article. However, virtual environments have achieved sufficient ecological validity to conduct in-depth research with spatial navigation. As is common in spatial navigation research, the focus of this article is on virtual environments that are primarily visual, although there are virtual environments that do not engage vision at all, which are typically known as virtual auditory displays (Xu et al., 2007).

Navigation relies on several possible types of spatial knowledge that tell the actor about spatial locations in their environment. Classically, this knowledge has been described as three types: landmark, route, and survey knowledge (Siegel and White, 1975). Landmarks are salient objects in stable spatial positions that can be associated with actions in the environment or used as beacons to guide actions. Route knowledge often relies on these landmarks and is considered a series of place-action associations such as knowledge about paths and turning directions. Survey knowledge involves configural and interconnected representations of space, often described as map-like, with globally consistent metric distances and directions between locations. There is a common understanding of a "cognitive map" defined in rodents and extended to humans, as a survey representation of space that is built through experience to resemble a metric Euclidean coordinate structure (O'keefe and Nadel, 1979; Tolman, 1948). The advantage of a cognitive map is that it allows for flexible use of spatial knowledge, in order to plan novel routes, accommodate detours, and take shortcuts. More recent theories propose an additional type of knowledge that falls between route and survey, defined as a labeled or "cognitive graph" (Chrastil and Warren, 2014; Ericson and Warren, 2020; Peer et al., 2021). Graph knowledge represents multiple connected routes, but when purely topological, contains no metric or angle information. A cognitive graph, however, adds local metric information to interconnected routes, supporting the flexibility of taking novel routes or shortcuts in a learned space without reference to a global coordinate system.

Different types of cues contribute to the acquisition of spatial knowledge during navigation. The basic goal of *spatial updating*—keeping track of one's own position and orientation while navigating—is accomplished by *path integration,* the use of translational and rotational self-motion cues, and the use of *environmental cues.* A walk through a familiar downtown shopping district presents many recognizable environmental cues, such as store fronts, parks, bus stops, and street intersections. Environmental cues include landmarks as well as geometric cues, such as intersecting streets, which allow the navigator to pinpoint self-location by connecting visual input with a spatial memory of the area. In addition to these environmental cues, path integration relies on external sources of information for self-motion from vision or audition (e.g., optic flow) as well as multiple sources of internal ideothetic information for sensing linear and rotational self-motion including efferent motor commands, proprioceptive information from limb movement, and vestibular information from head-movement (Chrastil and Warren, 2013; Waller and Hodgson, 2013). In the case of shopping, the navigator has access to self-motion cues indicating that they exited the shoe store, turned left at the sidewalk, and walked straight for 30 feet. This self-motion information specifies self-location relative both to the shoe store (i.e., the path origin) and the larger environment when combined with the navigator's memory of the area. Spatial cues for navigation must be used with respect to a spatial reference system. In an egocentric reference frame, spatial locations are referenced relative to the navigator's perspective, although multiple egocentric frames exist with respect to different body parts (eye, head, trunk). An allocentric reference frame is independent of the navigator's position and orientation, anchored instead, in the environment. As described above, survey knowledge representations are often described as allocentric.

Why use VR to study spatial navigation?

Human navigation is ideally studied in the real world, where people can move naturally through full-cue environments and make navigation decisions in tasks representative of their daily goals. In fact, many experimental paradigms have studied navigation in real world contexts, using college campuses, city streets, and open terrain (Ishikawa and Montello, 2006; Malinowski and Gillespie, 2001; Montello, 1991; Munion et al., 2019; Schinazi et al., 2013). But, there are some challenges and limitations to these methods. Using real world environments reduces experimental control over the characteristics (e.g., landmarks, paths, clutter), familiarity, distractions, weather, and other changes that occur within an environment (e.g., construction, landscaping). Further, real world navigation tasks often require physical effort and may not be accessible for children, older adults, or those who are disabled. More generally, because of constraints of testing in a specific spatial location, use of real environments limits *any* diversity of the population tested. There are also limitations in the size of spaces that can be studied in the real world—for example, navigating through a campus might be feasible, but a large city may not be.

VR provides a tool for spatial navigation research that addresses these limitations in the real world while also expanding opportunities for design and measurement (Diersch and Wolbers, 2019; Loomis et al., 1999). With current 3D development platforms (such as Unity), virtual environments can be created at different scales and with different levels of realism, which also allows for more comprehensive testing of potential individual differences in navigation. For example, a large scale campus or city may be presented in VR to test individual differences in the formation of cognitive maps (Brunyé et al., 2018; Weisberg and Newcombe, 2016) or a large vs. small virtual maze may test the use of landmarks and types of spatial knowledge (Chrastil and Warren, 2013, 2014; Ericson and Warren, 2020; Padilla et al., 2017) or strategies (Boone et al., 2018; Marchette et al., 2011; Yu et al., 2021). VR navigation games such as *Sea Hero Quest* are also now being used to test large populations across different demographics and memory capabilities in extensive virtual environments (Spiers et al., 2021). For smaller scale spaces, a main strength of VR is that cues for navigation can be tightly controlled and manipulated in order to precisely define their contribution. For example, in the real world, it is very difficult to decouple visual and body-based information for self-motion, but in VR decoupling can easily be accomplished by implementing locomotion methods that do not involve actual walking (e.g., teleporting or steering methods with a controller) (Barhorst-Cates et al., 2020, 2021b; Cherep et al., 2020; Kelly et al., 2020; Paris et al., 2017, 2019). Similarly, environmental cues such as landmarks and room geometry can be systematically controlled (Bodily et al., 2011; Doeller and Burgess, 2008; Kelly et al., 2022, 2013b). In addition to experimental control, VR expands opportunities for data collection across numerous spatial dimensions. Immersive head-mounted displays (HMDs) track both head and eye movements and even when nonimmersive displays such as desktop monitors and controllers for self-movement are used, continuous navigation paths that are recorded can provide a rich dataset to relate to other behavioral measures of spatial knowledge (Brunec et al., 2022, 2020; Gagnon et al., 2016, 2018). Finally, VR displays can be combined with neuroscience methods, most often functional MRI, to test for neural mechanisms that may underlie navigational abilities and performance (Bonner and Epstein, 2017; Furman et al., 2014; Harris and Wolbers, 2014; Marchette et al., 2015).

The opportunities are great, but there are also limitations for VR as a basic research tool. These limitations are often specific to the different VR technologies. Desktop or screen-based displays used while the observer is seated or standing allow for locomotion through large-scale spaces with controllers but limit the availability or realism of body-based cues. Immersive HMDs with tracking systems address this problem by allowing for physical locomotion, but then are usually limited by the physical space of the real room. Treadmill locomotion (or other physical locomotion methods such as walking in place) can allow for locomotion over a larger range than a physical room might allow, but the biomechanics of walking on a treadmill are not the same as walking in the real world (Nilsson et al., 2018a; Paris et al., 2022; Wilson et al., 2016) and this difference may influence navigation performance and spatial memory. VR is also limited by the mechanics and characteristics of the display, such as a reduced field of view (FOV) compared to the real world, possible inaccuracies relating to optics (inter-pupillary distance, accommodation and convergence), and the weight and tethering of the HMD. Further, known distortions in perception of scale (size and distance) of space exist (Creem-Regehr et al., 2023; Kelly, 2022; Renner et al., 2013), which could influence the encoding of spaces and the acquisition of spatial knowledge. Cybersickness is an additional limitation, and dropout rate in experiments due to cybersickness is a factor in VR studies of spatial navigation, especially when physical locomotion is not possible (Rebenitsch and Owen, 2016).

Approaches to spatial navigation with VR are inherently interdisciplinary, combining expertise in computer science, human-computer interaction, and spatial cognition. An understanding of the use of VR as a tool to study navigation benefits from considering both applied and theoretical motivations and implications. For example, development of locomotion interfaces addresses the applied problem of interacting with VR spaces that are larger than physical spaces, but also can be studied for the ways in which decoupling information for self-motion influences spatial navigation. Our goal is to describe VR as a tool both as an application of available technologies and as a method to address critical basic science questions about the processes and representations underlying spatial navigation. These basic research questions focus on (i) the cues and spatial knowledge used in navigational tasks and (ii) how an understanding of individual differences can elucidate spatial cognition mechanisms. We also review evaluations of direct comparisons between spatial navigation performance in real and virtual environments, an important question for the generalizability of findings in VR. We conclude with a discussion of opportunities for future directions of spatial navigation research with VR.

Virtual reality technologies and methodologies

Nonimmersive VR, also called desktop VR, is the most basic form of virtual reality. In this form of VR, a virtual environment is presented through a computer monitor, much like in a video game (see Fig. 1). Users typically interact with and move through the virtual environment using a keyboard, joystick, or other device like a gamepad, etc. Occasionally, devices like treadmills have been used in combination with monitors to provide more realism in movement. A substantial body of research in spatial navigation has occurred using desktop VR. The advantages of desktop VR are that it is easy to set up and configure a scene for use by a person with just a computer and monitor, there is little danger of cybersickness (Ramaseri Chandra et al., 2022), and the user is not encumbered by wearing a device on their head. The disadvantages of this type of VR are several. First, it has limited field of view (FOV) compared to the other types of VR and the real world. Parameters such as FOV and resolution depend upon individual monitors and thus have some variability, but a general case can serve as an example. A 34″ computer monitor at a viewing distance of 25″ will have an FOV of approximately 60° horizontally.[1] Given that most computer monitors have a 16:9 aspect ratio (or approximate), the vertical FOV will be less than the horizontal FOV. The apparent resolution of such a monitor using technology commonly available at the time of this writing would likely be close to 60 pixels per degree, approximately one-half of foveal visual acuity (Curcio et al., 1990). More directly relevant to navigation are the limitations of this technology on the ability to acquire cues useful for developing spatial knowledge. The limited FOV restricts the user's ability to apprehend the environment, especially because the user cannot simply turn their head to acquire new access to the scene. Instead, rotation must be instigated using one of the control mechanisms such as a keyboard or mouse to turn the viewpoint. Likewise, these same mechanisms must be used to move the user through the environment, depriving the user of proprioceptive and vestibular cues associated with bipedal locomotion (Chrastil et al., 2019; Nardini et al., 2008).

The two most common types of immersive VR are those presented through displays that are worn on the head (head-mounted displays, HMDs) or room-size displays that surround the user (CAVEs) as shown in **Fig. 1**. Less common are large screen immersive displays or display domes that can accommodate groups of people (Lantz, 2007; Takatori et al., 2019). CAVEs (Manjrekar et al., 2014) surround the user with high resolution screens; four to six is typical depending on the design of the CAVE. Thus the FOV of the user can be fully engaged, and the distance of the user to the screen is such that the resolution of the screens can exceed visual acuity. Users in CAVEs often wear stereoscopic glasses so that a three-dimensional view is presented to them. Tracking can be worn to make the perspective correct, but most CAVE installations only display the correct perspective for one person (Lebiedź and Mazikowski, 2021). Thus, multiple users will experience distorted views of the environment (Banks et al., 2009; Kelly et al., 2013a; Pollock et al., 2012). Users can freely walk within the bounds of the room of the CAVE; locomotion to a greater extent can be accomplished by integrating a treadmill within the CAVE, or by using a locomotion method used for nonimmersive VR. The main drawbacks of CAVEs as virtual reality devices for exploring spatial navigation is that they are expensive and require significant tuning and maintenance. While some specialized work on navigation and wayfinding has been done in CAVEs (e.g., Christou et al., 2016; Marsh et al., 2006; Rodríguez et al., 2021), this article will not focus on them as an immersive technology medium.

Head-mounted displays provide immersive VR at the commodity level. There are a number of modern immersive HMDs that all offer some variation in cost, weight, resolution, and FOV. Additionally, some HMDs may require more computational power to drive, e.g., if they have higher resolution and wider FOV, and thus may need tethering to a computer. As a general rule, the higher the FOV and resolution of the device, the more it will weigh. This factor can be significant for spatial navigation studies that take time, as heavier HMDs become increasingly uncomfortable to wear. At the time of this writing, the general range of HMD weights is from 500 g to 1 kg. Horizontal FOVs of the devices can vary significantly as well, from approximately 100° to 200°, whereas vertical FOVs vary somewhat more narrowly around 100°. The resolution of modern HMDs varies widely as well, with low-end devices having resolution on the order of 20 pixels per degree, but high-end devices achieving 70 pixels per degree in foveal regions.

These factors can all be important. HMDs have the highest incidence of causing cybersickness in virtual reality when compared to other technologies (Rebenitsch and Owen, 2016), but the reasons why this sickness occurs are still an open area of research.

Fig. 1 Examples of virtual reality display technologies: left, desktop virtual reality; center, a CAVE; right, HMD-based virtual reality.

[1]An approximate calculation for a 34 in monitor with a 16:9 aspect ratio. Many monitors of that size will be slightly curved, reducing FOV, and some will have a narrower aspect ratio, e.g., 21:9.

However, wider FOVs have long been implicated in increased cybersickness (Chang et al., 2020; Ramaseri Chandra et al., 2022), along with postural stability (Arcioni et al., 2019), among other factors. It is possible that increased HMD weight may contribute to decreased postural stability. Additionally, because HMDs are stereoscopic displays, the interpupillary distance (IPD) of the HMD must be adjusted correctly for correct or optimal stereo viewing. The adjustments on commodity level displays are limited and do not cover the range reasonably exhibited by the general population. Recent research by Stanney et al. (2020) indicates that limited IPD ranges on HMDs may exclude up to 30% of the female population and that IPD non-fit is a significant factor in cybersickness. Additionally, both weight and FOV of HMDs are implicated in the well-known problem of distance mis-perception in VR (Creem-Regehr et al., 2023; Kelly, 2022). Finally, proprioceptive and vestibular cues are sometimes available when moving in a virtual environment displayed through an HMD. In particular, head motion and the vestibular and other cues that come with that motion is almost always available in an HMD. Larger body movements such as bipedal locomotion, containing proprioceptive cues, may be accommodated as well, as will be discussed in the following.

Locomotion interfaces

Virtual reality provides constructed scenarios under control of an experimenter. This fact gives the designer flexibility in exploring navigational questions of interest. Some of these questions may involve a participant moving around in a large virtual environment; by large we mean larger than the space in which the participant or user is able to easily or freely move in the physical world. A person in virtual reality is usually limited in movement in the physical world since most virtual reality systems operate indoors, and thus the room size or roaming distance within a room provides the range of movement. This range may be significantly smaller than the space that the virtual environment encompasses, if, for example, the virtual environment is one of a city or a large outdoor space that may take up many kilometers.

Locomoting through a large virtual environment when the physical space is constrained is an issue that has received considerable attention, and there are many techniques for doing it (Al Zayer et al., 2020; Boletsis, 2017; Nilsson et al., 2018b). **Fig. 2** depicts examples of some of these techniques. From the perspective of spatial navigation, it is important that the method used not distort a user's spatial awareness. A significant literature exists on the effects of various locomotion methods on users' spatial awareness (Bruder et al., 2015; Cherep et al., 2020; Paris et al., 2019; Rahimi et al., 2020; Riecke et al., 2010; Ruddle and Lessels, 2009). An obvious method for moving unlimited distances in a virtual environment with limited physical space is with the aid of a physically assistive device, such as a treadmill (Darken et al., 1997; Warren and Bowman, 2017). A linear treadmill presents obvious difficulties since a user often wants to turn. A more general solution is to use an omnidirectional treadmill, in which a user can walk in any direction. Difficulties with omnidirectional treadmills are that users can have balance problems when turning and, at the time of this writing, omnidirectional treadmills are significantly more expensive than head-mounted virtual reality systems (Hooks et al., 2020). Except for the expense, modern treadmills provide reasonable proxies for real walking in virtual environments (Li et al., 2021; Liang et al., 2018; Ruddle et al., 2011, 2013).

The easiest and most straightforward locomotion method to implement in a virtual environment is teleportation (Bozgeyikli et al., 2016). In teleportation, the user indicates their desired destination in some manner—a common method is by casting a ray to the destination point—and is instantly moved to that destination. Their orientation could be preserved from the origin, or they could be instantaneously reoriented. In this method of locomotion there is no optic flow, the change of position is abrupt and discontinuous, and only correlated with whatever body movement caused the change of position to occur, e.g., a button press. Teleportation is a popular method of locomotion in a virtual environment because when compared to other locomotion methods it

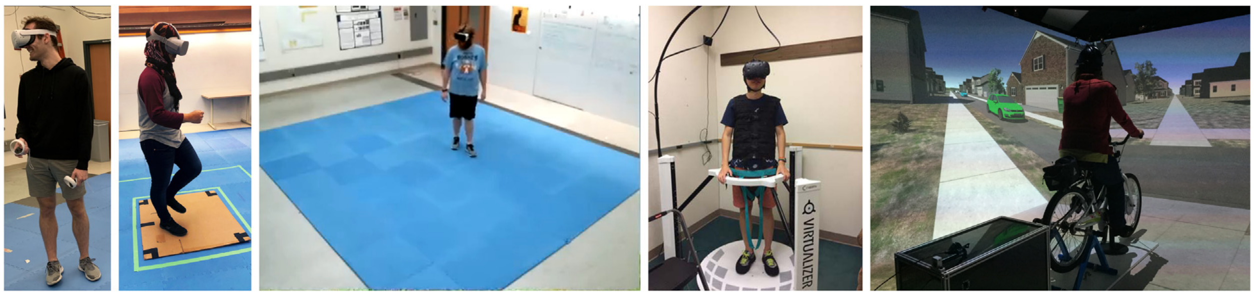

Fig. 2 Examples of locomotion techniques in virtual reality, from left to right: steering using a motion controller, walking in place, resetting/redirected walking, walking on an omnidirectional treadmill, and virtual bicycling in a large screen immersive display. Treadmill image Adapted from Liang, M. et al. (2018). Dissociation of frontal-midline delta-theta and posterior alpha oscillations: A mobile EEG study. Psychophysiology, 55(9), e13090, with permission from John Wiley and Sons. Bicycling image courtesy Joe Kearney.

has a lower incidence of cybersickness. Several studies have compared cybersickness using teleportatation as a locomotion method to other common locomotion techniques, and found cybersickness lower on average when using teleportation (Bozgeyikli et al., 2016; Christou and Aristidou, 2017; Clifton and Palmisano, 2020; Frommel et al., 2017; Griffin et al., 2018; Weißker et al., 2018). To our knowledge, no study has reported teleportation as worse than another locomotion technique in terms of cybersickness in the mean, although some have found no statistical difference (Griffin et al., 2018; Langbehn et al., 2018; Paris et al., 2019). However, Clifton and Palmisano (2020) noted significant individual differences in their study, where several participants were significantly more cybersick using teleportation than steering (see following). The disadvantage of teleportation is that a body of research has shown that it has significant and negative impacts on spatial awareness, and degrades ability to navigate through virtual environments (Cherep et al., 2020; Langbehn et al., 2018).

Another popular class of locomotion methods for moving through a virtual environment is a class called steering methods (Al Zayer et al., 2020; Martinez et al., 2022). In steering methods, a user is continuously moved through the environment. Their direction of motion may be controlled by the orientation of the head (head or "gaze"-based steering), body (body-based steering), pointing, body lean, or a motion controller such as a joystick. If not implemented properly, steering methods can lead to increased cybersickness (Caserman et al., 2021; Christou and Aristidou, 2017). Steering methods suppress proprioceptive and vestibular cues that would be present in natural walking. Some studies have shown that users do not perform comparably to natural walking in tasks involving spatial cognition when using pure steering methods (Ruddle and Lessels, 2009; Suma et al., 2010). One simple modification that can be made to steering methods to improve them is to use body-based rotations as part of the turning mechanism (Riecke et al., 2010). Some implementations of steering methods lead to increased cybersickness in users, so implementing a steering method must be done with care. Despite these drawbacks, it is likely that steering methods are the most often used method of locomotion in virtual reality studies of spatial navigation.

Walking-in-Place is a class of methods that simulate locomotion using proxy leg motions while remaining stationary (Nilsson et al., 2016; Usoh et al., 1999). It has the advantage of mimicking bipedal locomotion. If rotation is achieved by turning the body, as is normally done in most modern implementations, then some vestibular and proprioceptive cues from natural walking are available to the user. A distinguishing feature of walking-in-place implementations is whether they require additional sensors outside of, for example, an HMD. These are needed if the gaze direction and direction of locomotion are to be kept independent, as in natural locomotion. Some methods use additional sensors, allowing this decoupling (Feasel et al., 2008), and others do not (Hanson et al., 2019; Tregillus and Folmer, 2016; Williams et al., 2011), opting for a more minimal implementation with the disadvantage that gaze and direction of locomotion are the same. However, Williams et al. (2013) showed that this gaze-based method was better than a decoupled method on spatial orientation tasks. Walking-in-place locomotion methods typically do not cause simulator sickness (Usoh et al., 1999; Wilson et al., 2016); they do not require additional space beyond standing space to implement, but there has been little study of them perceptually or in navigation.

A popular class of methods for locomotion among virtual reality researchers are called redirected walking methods (Nilsson et al., 2018a). These methods employ natural walking as the dominant mode of movement in a virtual environment. These methods work by exploiting the fact that vision usually dominates perception of self-motion over proprioceptive and vestibular cues (Berthoz et al., 1975; Warren et al., 2001). Thus, the visual cues of a virtual environment will provide primary cues of motion direction and heading if senses momentarily disagree. Hence, a curved path can be plotted in a limited physical space room, and made to seem as if it is straight in a virtual environment. This technique, named redirected walking, allows users to walk paths that considerably exceed the physical boundaries of the enclosing physical space they are in. Two typical difficulties with redirected walking techniques arise. The first is that if users are guided on paths that have curvatures exceeding a certain radius of curvature, then they can notice the discrepancy. People's sensitivity to this curvature has been measured and a good boundary for most people is 22 m, indicating that a large physical space may be required to implement redirected walking methods (Steinicke et al., 2008, 2010). Additionally, if the radius of curvature is sufficiently sharp and discrepant from the visual path, redirected walking techniques can induce cybersickness. Secondly, redirected walking techniques have difficulty permitting users to freely explore an unbounded virtual environment, because a user's path may eventually lead them into contact with a boundary of the space they are in. If free exploration is desired, redirected walking methods typically add an additional method to reorient the user when they approach a boundary (Williams et al., 2007a; Xie et al., 2010).

All of these methods have been used in complex navigational and wayfinding tasks in virtual reality (Langbehn et al., 2018; Nabiyouni et al., 2015; Nilsson et al., 2016; Suma et al., 2010). Each has disadvantages and advantages, and current research does not indicate that there is a clearly preferred method for locomotion in virtual reality. Moreover, some of these methods can be combined in interesting ways. For example, teleporting can be used to traverse very large distances and one of the other more naturalistic methods could then be used to explore a more local space. Thus, the choice of the best locomotion method or methods depends on factors such as the available physical space, cost, and desire to minimize cybersickness, among other factors (see **Table 1**). However, most comparative studies show that steering methods perform poorly in comparison to the other methods (Chance et al., 1998; Langbehn et al., 2018; Riecke et al., 2010; Ruddle and Lessels, 2009), and so if a general recommendation is to be made, it would be to avoid them if possible, or implement them with body-based turning if necessary (Riecke et al., 2010).

Table 1 Summary of locomotion mode properties for movement in virtual reality.

Locomotion interface	*Self-motion cues*	*Cyber-sickness*	*Travel distance*	*Advantages*	*Limitations*
Real walking	Visual flow, proprioceptive, vestibular, efferent motor commands	◔	Time, fatigue	Natural walking	Movement tied to size of physical space
Treadmill	As above	◔	Time, fatigue		Linear prohibits easy turning; omnidirectional requires learning; balance problems
Teleportation	Vestibular with head rotation; no visual flow, proprioceptive, or efference with translation	◔	None	No extra space needed	Little active self-movement
Steering	Visual flow; vestibular if gaze or body-based rotation	●	Time	No extra space needed	Little active self-movement
Walking-in-place	Visual flow; some vestibular and proprioceptive	◔	Time, fatigue	No extra space needed	Fatiguing; requires additional sensors to decouple gaze and travel direction
Redirected walking	Decoupled visual and body-based cues	◑	Time, fatigue	Close to natural walking	Sometimes requires intervention in free exploration

What spatial navigation questions can VR answer?

VR provides control over the environment and the observer in ways that are not possible in the real world. Use of these controlled virtual environments also allows for access to populations that are increased in diversity (in age, gender, spatial abilities, geographic locations, neurological conditions) as compared to studies conducted in a single real world location. Environmental and self-motion cues are both critical for navigation and have been studied extensively using VR paradigms where cues can be varied or decoupled. We begin with a review and analysis of the outcomes of manipulating these cues in virtual environments on spatial learning and memory (mostly in immersive VR and vista-scale spaces). We then present an example of how VR methods uniquely test theories of spatial representations used in navigation using immersive VR. In the final section, we discuss the role of virtual environments in advancing our understanding of individual differences in navigation strategies and performance. The individual differences research tends to focus on larger environmental-scale spaces such as mazes and campuses and primarily uses nonimmersive desktop VR, although some exceptions are noted.

Cues for navigation

Movement through the real world provides numerous spatial cues that the navigator can use to identify self-location, which is crucial to learning and navigating an environment. As introduced earlier, those cues can be categorized as self-motion cues and environmental cues. Some self-motion cues originate from the environment (e.g., optical flow is visual information originating in the environment), but they are distinct from environmental cues which emphasize recognition of familiar places and objects. Environmental cues and self-motion cues are typically tightly coupled during navigation through the real world, and therefore provide similar information about self-location. However, these cues are often decoupled in navigation through virtual environments, especially due to constraints imposed by the locomotion interface, reviewed above. How does the navigator resolve self-location in the face of conflicting or deficient environmental and self-motion cues? VR provides the ideal test bed to explore this question, serving researchers who develop and study new locomotion interfaces as well as researchers focused on basic navigation theory.

Environmental cues

Typical real and virtual environments contain several environmental cues that can support piloting (i.e., navigation by recognition of familiar objects and scenes). Research has focused in particular on the contributions of environmental cues defined by boundaries and landmarks. Spatial boundaries provide multiple cues that may contribute to navigation. For example, an important location in the corner of a rectangular room is defined by a short wall to the left and long wall to the right (a local boundary cue), and it is also the first corner moving clockwise relative to the principal axis of the space (a global boundary cue). Virtual environments are ideally suited to evaluate the contributions of local and global boundary information due to the ease with which environmental shape can be manipulated in VR. In one study (Bodily et al., 2011), participants learned the location of a hidden goal positioned in one corner of an otherwise empty trapezoidal room. The goal corner was defined by an obtuse intersection between a short wall on the left and long wall on the right (local cue) as well as by its position as the first corner moving clockwise from the direction of the principal axis. Later, participants were asked to find the goal location when placed into several differently-shaped test rooms, including a rectangle with right angle corners inconsistent with the local cues in the learning room, a parallelogram with corners that contained local and global cues consistent relative to the learning room but a different global shape, and a parallelogram with local and global cues that were inconsistent with the learning room. Their findings indicate that participants used both local and global boundary cues when available, and placing the cues in direct conflict led to chance performance. Similar studies using virtual environments have placed local and global boundary cues into conflict by manipulating the VE shape as well as whether learning and testing occur within the enclosed space or on the outside of the space, which changes local cues but preserves global cues (Buckley et al., 2016). These and other related studies using VR (Kelly et al., 2013b; Sturz and Bodily, 2011) also conclude that both local and global boundary cues influence spatial learning and reorientation.

Virtual environments have also been used to evaluate the relative contributions of spatial boundaries and landmarks in navigation. In one study (Doeller and Burgess, 2008), participants used desktop VR to learn a goal location defined by a landmark (a traffic cone) and/or a boundary (a circular border of cliffs surrounding the navigable space). During testing, participants were asked to return to the goal location in the presence of just one cue. Participants who learned in the presence of a single cue were capable of accurate navigation at test, regardless of cue type. However, those who learned in the presence of both the landmark and the boundary were more accurate when tested with the boundary alone than with the landmark alone. These results indicate that the boundary overshadowed the landmark when learning occurred in the presence of both cues, highlighting a potentially elevated role of boundaries over landmarks (see Mou and Zhou, 2013 for similar experimental manipulations and conclusions, but also Buckley et al., 2021 who did not find support for the special status of boundaries).

Although spatial boundaries are important environmental cues for navigation, they may be less salient in virtual compared to real environments. One study (Kimura et al., 2017) created similar real and virtual environments consisting of a rectangular room with colored landmarks in the corners. Participants in the VR condition (experienced through an HMD) were less able to use the room geometry to return to a learned location and relied more heavily on the landmarks than the room shape when both were available, compared to participants in the real environment. One possibility is that the restricted FOV in VR reduced the salience of geometric cues, which typically surround the navigator. To summarize, spatial learning and navigation are influenced by environmental cues, which commonly include boundaries defined by the shape of the surrounding space as well as landmarks, which tend to be more focal.

Self-motion cues

The moving navigator also has access to self-motion cues that provide cumulative information about traveled distance and direction, which serve to support path integration. Self-motion cues alone provide fairly precise information over short distances (Klatzky et al., 1990; Mittelstaedt and Mittelstaedt, 2001), but cumulative errors make them less reliable in isolation over longer distances unless combined with environmental cues (Harootonian et al., 2020; Souman et al., 2009).

In an early VR study on navigation (Chance et al., 1998), participants learned locations in a virtual maze while wearing an HMD. Movement through the maze was controlled either by physically walking or by manipulating a joystick. Whereas walking provided body-based self-motion cues as well as visual self-motion cues, joystick locomotion provided visual cues only. Following learning, participants pointed between learned locations as a measure of the fidelity of their cognitive map. Pointing performance was superior when the VE was learned by walking compared to using a joystick. This and other similar studies using larger VEs (Lim et al., 2020; Ruddle and Lessels, 2009) demonstrate the importance of body-based self-motion cues for learning spatial layouts.

Other experiments have used simpler tasks in which the participant walks an outbound path before attempting to point or return to the origin of their path. This task is referred to as triangle completion when there are two outbound path segments (see **Fig. 3** for a detailed example of the triangle completion task). VR is an ideal tool to distinguish the relative importance of visual and body-based self-motion cues in this type of task. In one study (Klatzky et al., 1998), participants made large errors when they experienced only visual self-motion cues on the outbound path, but performed well when they used the body to rotate through the path turn. Interestingly, performance was no better when using the body to translate (i.e., to walk forward) along the path segments, although other similar studies report a benefit of body-based translation cues (Ruddle and Lessels, 2006). Research on the teleporting interface, whereby the user selects a position (and sometimes an orientation) in the VE before being instantly relocated, has also revealed the impact of body-based and visual self-motion cues on navigation. As a reminder, teleporting involves discrete jumps in location that exclude body-based and self-motion cues (Bowman et al., 1997; Bozgeyikli et al., 2016). Compared to walking, performance on a triangle completion task was worse when teleporting to translate and using the body to rotate (Barhorst-Cates et al., 2020, 2021b; Cherep et al., 2022, 2020), and worse still when teleporting to translate and rotate (Kelly et al., 2022, 2020). Yet, performance when using a joystick interface with continuous visual self-motion was no worse than walking (Barhorst-Cates et al., 2020, 2021b), suggesting that visual cues can be sufficient for task performance (also see Riecke et al., 2002, but contrast with the findings of Klatzky et al., 1998; Ruddle and Lessels, 2006).

Cue combination

Navigation, whether in a real or virtual environment, typically involves several environmental and self-motion cues. Each cue indicates the location of the navigator and their goal, but discrepancies can occur due to limitations in human sensory processing, attention, or memory. Adult navigators can combine these spatial cues to navigate with greater accuracy than would be possible if they relied on a single cue (McNamara and Chen, 2021). In a common paradigm, participants walk a short outbound path before attempting to point to the path origin. Environmental cues and self-motion cues are available during the outbound path, but experimental manipulations selectively remove cues (by disorienting the participant or obscuring the virtual environment) in some conditions. Responses are more precise when multiple cues are available compared to single-cue conditions, and further manipulation of cues indicates that they are often combined in a statistically optimal manner (Chen et al., 2017; Nardini et al., 2008; Sjolund et al., 2018). However, other tasks such as path reproduction have been found to produce sub-optimal cue combination (Chrastil et al., 2019; Petrini et al., 2016).

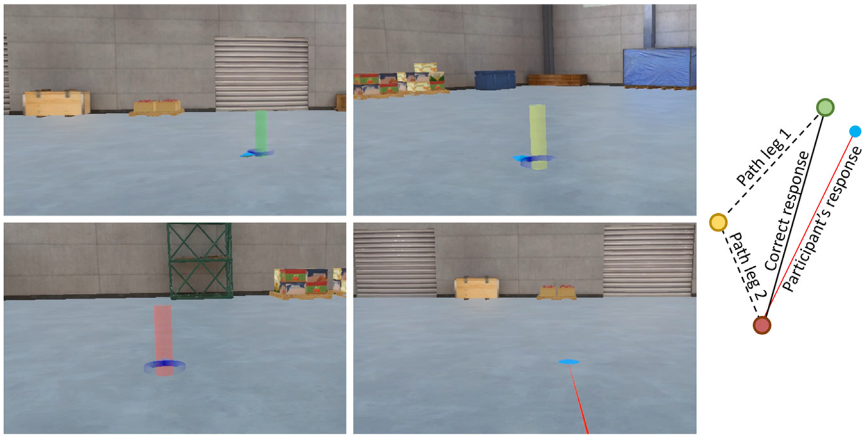

Fig. 3 Example of a triangle completion task in a virtual environment. The over-head diagram on the right shows outbound path legs 1 and 2 and the participant's response, which can be executed by pointing or walking to the remembered location of the path origin. The screenshots show the path origin, marked by a green post (top-left), the end of the first path leg, marked by a yellow post (top-right), the end of the second path leg, marked by the red post (bottom-left), and the participant's pointing response (bottom-right).

Research on redirected walking (separation of the physically traveled path and the visually traveled path, described above) is seemingly at odds with the finding that environmental cues and self-motion cues are combined to estimate the navigator's location within the environment. Some redirection techniques, such as freeze-turn (the user's perspective of the virtual world freezes while they rotate to face open walking space in the physical world), freeze-backup (the virtual world freezes while the user backs up to provide more open walking space), and large rotational gain (the virtual world rotates at a much faster or slower rate than the user, e.g., 2:1) involve manipulations that place body-based and visual cues in large conflict, and this conflict is apparent to the user. Yet, participants who walk on a path interrupted by these redirection techniques are able to point to previously learned locations in the virtual environment with relatively good accuracy (Williams et al., 2007a), indicating that they can mostly suppress the conflicting body-based cues and rely solely on visual cues. Research in which the visual world is offset from the body by varying degrees indicates that small deviations between body-based and visual cues lead to cue combination, whereas large deviations lead to reliance on a single cue type (Harootonian et al., 2022; Sjolund et al., 2018; Zhao and Warren, 2015), reflecting a qualitative change in cue processing when large conflicts are detected. In this way, redirection techniques that involve large conflict may cause greater reliance on visual input.

Other types of redirected walking involve less noticeable separation of body-based and visual cues, yet research on these techniques also suggests dominance of visual cues over body-based cues. One such redirected walking technique leverages change-blindness, or the lack of awareness of changes to objects that are not immediately visible or attended to at the time of change (Simons and Levin, 1997). In one example, the location of a door changed from one wall to another while the user was occupied with another task (Suma et al., 2011). In another example, the wall separating adjacent rooms covertly shifted while the user walked through a connecting corridor (Suma et al., 2012). These manipulations are far less likely to be noticed by the user compared to the redirection techniques described above (e.g., freeze-turn). Yet, change-blindness techniques also reveal almost complete reliance on environmental cues.

Perhaps the most popular redirected walking technique utilizes more subtle but continuous changes to the virtual world to gradually steer the user into open space in the real world. When asked to point to previously visited locations after traveling a simple path involving steering-based redirected walking, participant responses were primarily influenced by the visual environment and showed no connection to the physically walked path (Hodgson et al., 2008). It is unknown why these results diverge from basic research indicating that self-motion cues and environmental cues are combined, but some speculation is possible. First, redirected walking research typically includes too few trials to properly assess cue combination (Chen et al., 2017), so cue combination may be undetectable. Second, redirected walking studies commonly use environments with several environmental cues (e.g., room walls, proximal landmarks, distal landmarks), whereas cue combination research typically provides only one or two environmental cues, perhaps explaining the difference in reliance on visual information.

Spatial representations

Different types of spatial representations, such as cognitive graphs and cognitive maps (reviewed above), contain overlapping forms of spatial information, and this overlap creates challenges for testing spatial cognitive theories that require unique predictions about each type of spatial knowledge. For example, a navigator with graph knowledge of a campus environment could point with reasonable accuracy to another building across campus by combining knowledge about connectivity and local metric information. Likewise, a navigator with a cognitive map containing information about inter-object distances and directions could use that knowledge to follow a connected route. In this way, many spatial behaviors are not unique to either cognitive graphs or cognitive maps, making it difficult to determine which type of spatial knowledge has been acquired.

Virtual reality has proven useful in distinguishing cognitive graphs from cognitive maps. In one study (Warren et al., 2017), participants walked through a network of hallways within VR and were later asked to reconstruct the shortest path and also to point between learned locations. In one condition, the virtual environment contained "wormholes," which instantly transported the navigator to a different location in the environment. Wormholes were placed such that they were not visibly noticeable, but their presence created an environment that would be impossible in the real world and also impossible to represent in a globally-consistent cognitive map. Participants readily navigated and learned the impossible environment, pointed between learned locations, and took shortcuts, often incorporating the wormholes into their spatial representation. These findings are evidence in favor of cognitive graphs and highlight the creativity with which researchers can leverage VR to distinguish between competing theories of navigation (see Fig. 4).

Other VR studies provide further support for cognitive graph theory, showing that error and latency when pointing between learned locations increases as a function of the number of connections between those locations (Strickrodt et al., 2019; Warren, 2019), as would be expected when using a spatial representation based on connectivity. Peer et al. (2021) offer a balanced perspective of conditions that are conducive to developing cognitive graphs versus cognitive maps, including environmental complexity, visibility, spatial scale, and individual characteristics of the navigator.

Individual differences

It is somewhat evident that there are differences in navigation ability across individuals. Think of the friend who can easily and efficiently navigate to a location and contrast that with the friend who always seems to be lost. These individual differences in spatial navigation ability do not have to be innate; they can also develop due to neurological damage (Cogné et al., 2017; van der Ham et al., 2010) or can increase with expertise (Maguire et al., 2006). There are many substantive reviews that have covered a number of individual differences that can affect navigation (Weisberg and Newcombe, 2018; Wolbers and Hegarty, 2010) as well as whole volumes (Hegarty and Waller, 2005). Here, we review a subset of individual differences, including gender, age, anxiety, strategy preference and others that have been tested using virtual navigation paradigms—either desktop or HMD-based. Virtual tasks have allowed for many advances in our theoretical understanding of individual differences because they can constrain (or not) learning of spaces, present all participants with a *novel* space to ensure baseline knowledge is controlled, easily implement different types of tests for spatial memory (such as pointing from one location to another quickly), and can be used with neuroimaging to discern underlying mechanisms that may account for the differences observed. Further, identifying individual differences often requires testing a large number of subjects, so implementations in virtual environments allows for ease of testing across locations as well.

Route integration

When considering whether and how individuals form a cognitive map of their environments, there is evidence to suggest that not everyone may actually successfully form maps (Foo et al., 2005; Weisberg and Newcombe, 2016). Much of the initial work investigating individual differences in navigation in the real world used self-reported strategy measures to assess individual differences and then correlated performance on these measures with navigation behavior in the real world. Some of these investigations were quite extensive in their training of participants on large-scale, real world environments. For example, Ishikawa and Montello (2006) drove participants on two different novel routes for many sessions of training as well as on a connector between the two routes. Knowledge of the routes was regularly assessed across training sessions and the findings showed two distinct groups of participants:

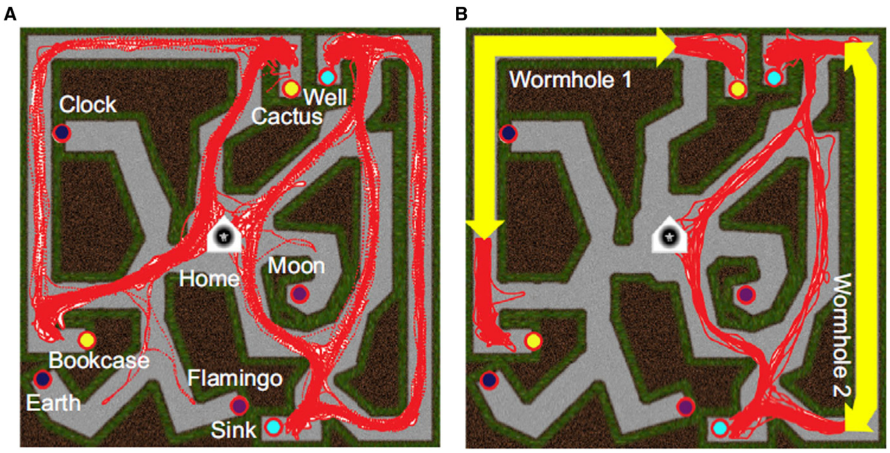

Fig. 4 Example of a Euclidean virtual maze environment (A) and impossible non-Euclidean environment with wormholes (B). Adapted from Warren et al. (2017). Wormholes in virtual space: From cognitive maps to cognitive graphs. Cognition, 166, 152–163, with permission from Elsevier.

one who learned the routes very early in training with surprising metric accuracy and another that never fully encoded the routes. Schinazi et al. (2013) also showed differences in participants' abilities to infer the location of buildings along learned routes along with connecting routes on a college campus. In addition to behavioral findings that supported Ishikawa and Montello (2006), Schinazi and colleagues also found that the size of participants' right posterior hippocampus related to their ability to integrate routes and infer the position of buildings (but see Weisberg et al., 2019, who did not replicate this finding).

The above reviewed work investigating *route integration* across different types of real environments and training led to the development of similar paradigms for virtual navigation. Virtual environments are a perfect tool for assessing differences in route integration given the ease of constructing novel environments that participants truly have to learn, as well as not having to physically drive or walk participants through the spaces. Spatial cues such as landmarks and buildings can also be tailored to the exact needs of the experimenter. But, because of the need to move over large distances, most of this work used desktop VR. For example, Weisberg et al. (2014) created a virtual environment modeled after the one used in Schinazi et al. (2013), called virtual Silcton (see **Fig. 5**). In the virtual experiment, participants passively experienced two routes for which they were told to learn the locations of buildings along the routes. After experiencing those routes, they were shown two new routes that connected the initially encoded routes. After learning of all routes was complete, participants were asked to point to buildings from different locations as well as build a map of the environment by placing the buildings where they were remembered to be located on a blank field. In addition to these spatial memory tasks, participants also completed various self-report measures for spatial ability, including the Santa Barbara Sense of Direction (SBSOD) scale (Hegarty et al., 2002). The findings of this virtual route integration task replicated that of the real world tasks; there were individuals who were superior in performance. However, this study also showed that SBSOD scores were correlated with performance, specifically for developing an understanding of connecting routes. Thus, individual differences in the perception of one's navigation ability seemed to relate to actual navigation performance in this virtual task. To follow up on this finding, Weisberg and Newcombe (2016) further defined the differences between individuals in navigation performance on the same virtual route integration task by defining groups that were considered to be integrators, non-integrators, and imprecise navigators. They found that imprecise navigators had worse spatial and verbal working memory, which could have contributed to an inability to integrate routes effectively. Integrators, in contrast, formed durable representations of routes that included specific information about associated buildings. They also performed better in an unrelated, but virtual, goal-oriented spatial learning task (akin to a rodent T-maze and discussed further below, see Marchette et al., 2011). Importantly, the differences in groups was not due to motivation. The observed difference for integrators and working memory was further refined in Blacker et al. (2017). Findings suggest that across all types of navigators, the ability to keep spatial relations in working memory was better at predicting performance than working memory for spatial location. The environment created by Weisberg et al. (2014) has also been used to

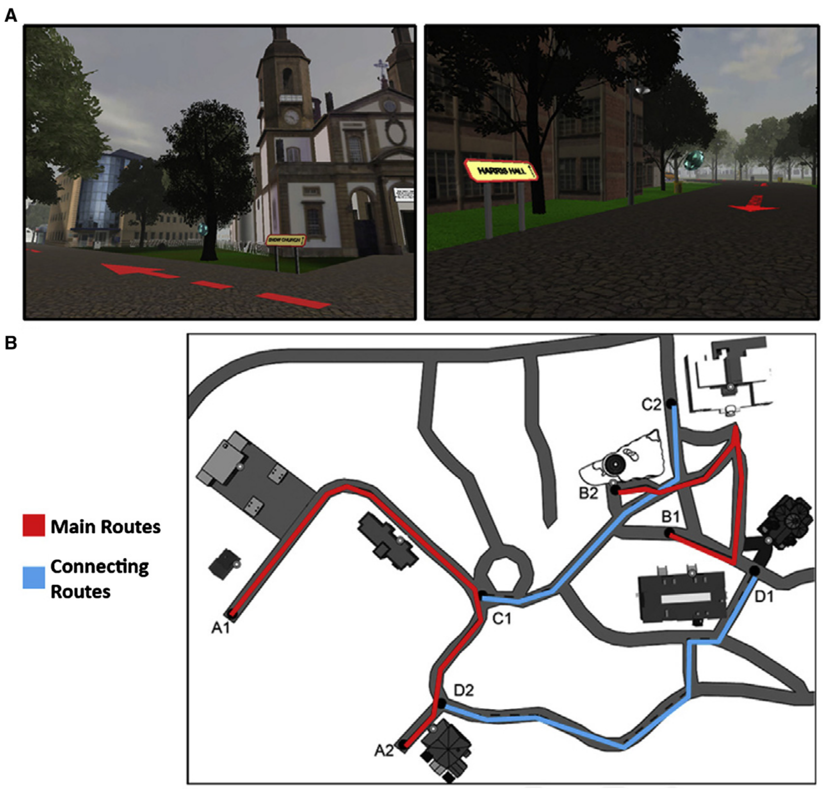

Fig. 5 Images from virtual Silcton (A) and a map of the routes (B). Adapted from Weisberg et al. (2019). Everyday taxi drivers: Do better navigators have larger hippocampi? Cortex, 115, 280–293, with permission from Elsevier.

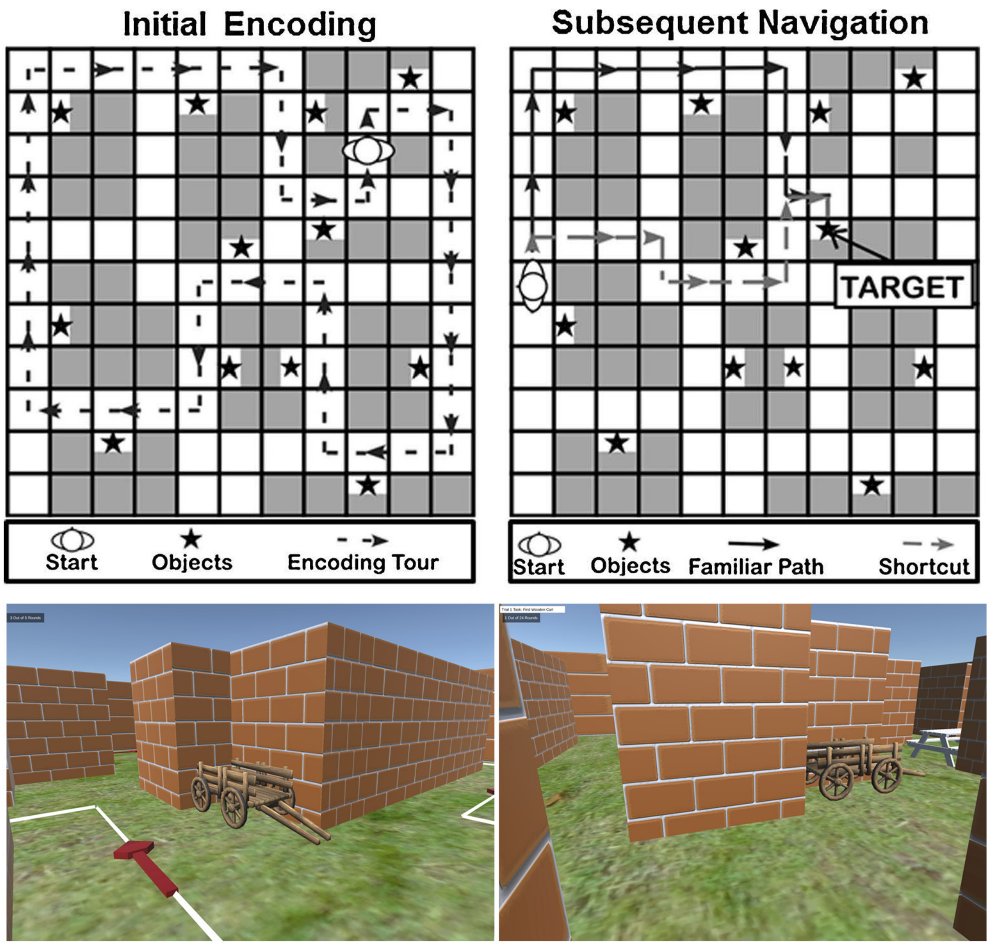

Fig. 6 (Top) Schematic maps of a DSP maze (CC-BY-NC-SA). (Bottom) Screen shots of a DSP maze virtual environment during encoding (left) and testing (right). (Top) Adapted from Marchette, S.A., Bakker, A., Shelton, A.L. (2011). Cognitive mappers to creatures of habit: Differential engagement of place and response learning mechanisms predicts human navigational behavior. J. Neurosci. 31(43), 15264–15268.

investigate other individual differences—such as GPS use—to understand their effects on spatial learning (Ruginski et al., 2019). Findings showed that those who used GPS more in everyday life showed decreased performance in the route integration task, but this decrease was mediated by the participants' perspective taking and mental rotation abilities.

Strategy preference

In addition to integrating routes, individual differences have also been observed in what is called the *dual-solution paradigm* or DSP (Marchette et al., 2011), see **Fig. 6**. In this paradigm, navigators are asked to navigate through a maze, using a desktop VR display and a controller, in order to encode the locations of target objects and then asked to navigate back to those objects once their locations have been learned. However, the return task allows for flexible navigation as participants can take routes learned previously to those targets, but they can also take shortcuts. This ability to apply different strategies—either place-based (potentially take a shortcut when possible) or response-based (take the previously learned route even if it takes longer)—to retrieval of target locations allowed for assessment of individual differences in navigation strategy in a behavioral task rather than relying on self report only. Indeed, those who used a place-based strategy more also showed increased activation in the hippocampus during retrieval providing neural evidence for the distinct strategies as well.

Further, Marchette et al. (2011) argue that successful navigation can occur by using either strategy and that these strategies could be on a continuum with people choosing to use one or another given current task demands. However, there seems to be a clear personal preference or bias for individuals to use a specific strategy that is evidence in brain activation and behavioral performance during both encoding and subsequent retrieval (Furman et al., 2014). This preference was observed in integrators as defined by Weisberg and Newcombe (2016), who were also more likely to engage in place-based strategies for the DSP. Strategy use in the DSP may also differ in individuals based on the architecture of their home environments (Barhorst-Cates et al., 2021a). Barhorst-Cates et al. (2021a) employed a battery of tests, including the DSP as well as a virtual Morris water maze task, with participants from two different home locations: Padua and Salt Lake City. These home environments are vastly different in terms of distal landmarks (e.g., large mountains in Utah but not Padua) and street layouts (winding in Padua, grid-like in Utah). They hypothesized that navigation pressures introduced in each environment could manifest in differences in performance on tasks such as the DSP. Surprisingly, Padua participants were more likely to use a place-based strategy than Salt Lake participants, which also correlated with better performance in the water maze task with distal cues. Overall, individual differences in experience with home environments did relate to strategy adoption and cue use in navigation tasks (see also similar conclusions from the large population sample tested on the game Sea Hero Quest (Coutrot et al., 2022)). Finally, there have also been observed differences in gender for the DSP. Specifically, males tend to utilize place-based strategies (i.e., take shortcuts) more than females and are more quick to respond in DSP trials (Boone et al., 2018). We will discuss differences in spatial navigation across genders further below.

Landmarks and cue use

Another important aspect of navigation is the use of cues—and many individual differences have been observed in tasks testing cue-use for navigation. One common task that has been used to test for reliance on distal as compared to proximal cues for navigation is the Morris water maze task. Originally used to assess navigational cue use in rats and other animals, the Morris water maze task has also been adapted for use with humans. Again, the implementation of this task in desktop virtual environments has made conducting experiments that investigate human cue use much easier. In most iterations of the task, participants are required to find a target in an arena-like space that has either proximal cues located within the arena to help guide location of the target across training, or distal cues located outside of the arena that can provide orientation information for locating the target across training. One of the most reliable individual differences observed with this task is that females tend to perform worse than males. Chai and Jacobs (2009) showed that men performed better than women in both the distal and proximal cue conditions, but that this difference was pronounced when only distal cues were available to locate the target. This difference was also supported by men reporting a preference for survey strategies for navigation whereas women reported relying more on landmarks. Padilla et al. (2017) partially replicated the findings of Chai and Jacobs, but in a natural virtual environment (shown in Fig. 7) that was either large in scale or small. In the small-scale environment, which was similar in size to the Chai and Jacobs environment, women performed worse with distal cues only, but there was no difference between men and women in the proximal cue condition. However, this difference did reappear when the size of the environment was scaled up by a factor of 4. In the large environment, women performed worse at locating the target in both the distal only and proximal only cue conditions. In addition to the cue condition findings, Padilla et al. (2017) also found another individual difference—mobility experience, or the number of unique places that one had traveled to—also affected performance. Specifically, in the smaller environment, females with more mobility experience showed less error in the proximal cue condition, and in the large environment, both males and females showed better performance in the proximal cue condition as they scored higher in mobility. This finding is interesting because it suggests that factors outside of gender could be trained or experienced in order to improve performance on navigation tasks like the Morris water maze in order to reduce the observed gender gap.

Given that men tend to report using survey spatial strategies more (Castelli et al., 2008; Lawton, 1994), an obvious question is whether women could also be trained or instructed to use such a strategy and whether such instructions would be effective in improving navigation. Pazzaglia and Taylor (2007) asked participants to learn a complex virtual environment either with an overhead map showing their location as it updated or with a virtual leader from an egocentric perspective. Their findings showed that those participants who reported using survey strategies to navigate performed well when learning the environment from either perspective, but that low-survey use participants performed worse in the overhead map condition. Such results suggest that strategy preference can interact with tasks to make navigation more or less successful, so if women have a preference for route strategies it could affect their performance for certain tasks. A final point to note for gender differences is that there is work suggesting that women may perform worse than males simply due to the virtual nature of these tasks (Waller, 2000; Waller et al., 1998), consistent with the notion of task-specific gender differences in spatial abilities (Voyer et al., 1995). This should be considered when developing and implementing virtual navigation tasks.

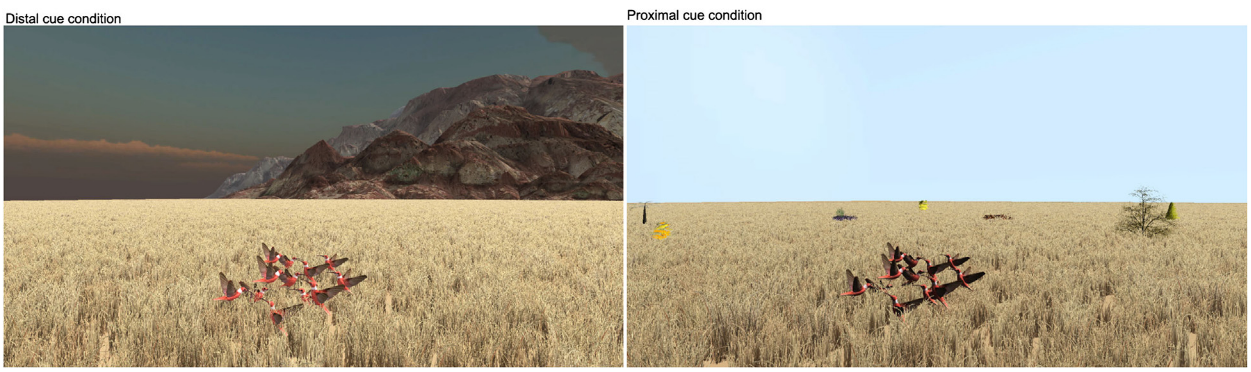

Fig. 7 A virtual Morris water maze adapted to a natural outdoor environment. Adapted from Padilla, L.M. et al. (2017). Sex differences in virtual navigation influenced by scale and navigation experience. Psychon. Bull. Rev. 24(2), 582–590, with permission from Springer Nature.

Anxiety

Although there are gender differences for certain spatial navigation tasks as assessed virtually, there is not a clear consensus as to what underlies these differences. One hypothesis that has been investigated more recently is that gender differences in spatial navigation may relate more broadly to anxiety. The widely used measure of self reported sense of direction (SBSOD, Hegarty et al., 2002) was found to be negatively correlated with spatial anxiety when the scale was validated and proposed. However, it should also be noted that the SBSOD is also positively correlated with emotional stability as assessed with the Big Five personality test, so it could also be that just expecting to perform poorly on a navigation task could lead to anxiety (Condon et al., 2015). Further work has directly tested relationships with anxiety and navigation in virtual tasks. For example, Gagnon et al. (2016) had participants explore a large, natural virtual environment to search for targets. After finding them, they had to point to all of them from each other and from the starting location. Exploration paths taken to find the targets were also analyzed to relate navigation strategy and efficiency to spatial memory. The results showed that females paused and revisited locations more during search, which led to worse navigation efficiency in locating targets. However, trait levels of harm avoidance were also positively correlated with revisiting behaviors across all participants, suggesting that caution in navigation more broadly may partially explain observed gender differences in navigation. These findings for differences in exploration behaviors across gender relating to differences in spatial memory were replicated and expanded in Gagnon et al. (2018). Ruginski et al. (2018) directly manipulated anxiety (between-participants) and then asked participants to traverse a route and remember where targets were located in a desktop virtual environment. Men performed better than women on both a pointing to targets task as well as a map landmark placement task. But manipulations of anxiety further affected women for both tasks. The results cannot rule out that pre-existing anxiety about navigation tasks could have affected women, especially when anxiety was increased with the manipulation. However, they do suggest that a link between anxiety and gender differences in navigation does exist even in virtual tasks and that further work could continue to investigate that link.

Age differences

The use of virtual environments has enabled extensive study of differences in navigational processes associated with older age (Diersch and Wolbers, 2019; Wiener et al., 2020). Generally, healthy aging is associated with a decline in spatial navigation abilities (but see Zhou et al., 2022 for a review of superior older navigators), and problems with navigation are often the first behavioral signs of Alzheimer’s dementia. A number of the VR tasks (or variations of them) described in this section have been used to help to identify changes in cue use, strategies, and spatial learning that occur with aging, both with behavioral and neural measures.

Early studies with a virtual Morris water maze showed that compared to young adults, older adults (over 65 years) traversed a longer distance to return to the platform during the learning trials and showed worse memory (search accuracy or proximity to the goal) for the platform location on probe trials. Older adults also showed poorer map constructions and greater use of proximal cues as compared to geometrical room cues (Moffat and Resnick, 2002). Using this task in an fMRI paradigm showed that brain activity and volume associated with task performance differed with age. Older adults showed less activation in the hippocampus, parahippocampal gyrus, and retrosplenial cortex, and increased activation in anterior cingulate gyrus and medial frontal lobe, compared to younger adults (Moffat et al., 2006, 2007). More recent studies with a revised virtual Morris water maze that more closely matched mazes used with rodents found that a subgroup of older adults were as accurate as young adults in their search accuracy, and better performance in older adults was associated with orbitofrontal cortex and the cerebellum (Reynolds et al., 2019; Zhong et al., 2017). Brain activation results such as these support the notion that spatial memory functions, while associated with the medial temporal regions in younger adults, may shift toward the prefrontal cortex in older adults.

Age differences in navigation strategies have also been tested with virtual environment mazes. A virtual “plus” maze can test for the use of an allocentric place strategy, an egocentric response strategy, or switching between strategies (Harris et al., 2012; Harris and Wolbers, 2014), similar to the goals of the DSP described above. Harris and Wolbers (2014) created a realistic town version of a plus maze and compared younger and older participants’ abilities to learn a route and return to goal locations. They found that older adults were less likely to take shortcuts, which was attributed to deficits in the ability to switch strategies from learned routes (egocentric strategy) to novel shortcuts (allocentric strategy). The study also identified large age differences in a cognitive mapping test, supporting established deficits in allocentric spatial processing, but found that the use of a route following strategy was more likely explained by inabilities to switch strategies. Using a different “Y-maze,” Rodgers et al. (2012) found strong preference for egocentric navigation strategies in older adults, as compared to younger adults who showed an equal distribution of egocentric and allocentric.

A number of studies show effects of older age on both short-term memory for location, such as in path integration, and longer-term spatial learning such as in spatial memory tasks after navigation experience. In a purely visual path integration task (i.e., a virtual environment presenting optic flow with joystick control), older adults tended to overshoot shorter distances/turns and undershoot longer distances/turns in distance or rotation reproduction tasks, respectively (Harris and Wolbers, 2012). In another visually presented triangle completion task, older adults made greater errors in rotation and distance than younger adults, and in comparison to a real world environment without vision (Adamo et al., 2012). More recently, Stangl et al. (2020) allowed for physical movement in an immersive HMD to test age effects on path integration along 10 different curved paths. Using a mathematical modeling approach, they determined that errors in path integration are mostly accounted for by unbiased noise that accumulates and is magnified in older adults. These path integration tasks show age differences, but focus on short term spatial updating of self-position in the environment. Other studies have examined age differences in spatial learning in virtual environments, focused more on long term acquisition of spatial knowledge (Hilton et al., 2020, 2021; Merhav et al., 2019; Merhav and Wolbers, 2019;

Yamamoto and DeGirolamo, 2012). In a route learning and landmark knowledge task, older adults showed worse memory for routes and landmarks, although when given additional time to learn the routes, some differences were attenuated. With flexible learning time, associative cue knowledge improved to the level of young adults, but deficits (relative to young participants) in landmark sequence knowledge remained. Yamamoto and DeGirolamo (2012) compared landmark memory after learning a virtual environment by moving (with joystick) in the environment from a ground-level first person perspective or from a bird's eye aerial perspective. Older participants were less accurate than younger adults at constructing a map of landmark layout after the first-person navigation, but there was no age difference after the aerial learning. This finding suggests that spatial learning from maps may be better preserved with normal aging and that other results showing deficits in allocentric representations may be due to the need to encode and transform spatial information from one frame of reference to the other. Again, studies such as these that use non-immersive virtual environments without physical movement may lead to different conclusions than those with whole-body tracking, such as in Merhav and Wolbers (2019). Here, the study used a 2-day spatial learning task in a fully immersive virtual environment, aimed at testing the abilities of young and older participants to update new navigational memories. Older and younger adults encoded environments on the first day with either egocentric, allocentric, or combined cues for object location. On the second day of encoding, some of the locations were relocated. Then, retrieval of the new locations was assessed. Age related impairments in updating new locations were found in both the allocentric and egocentric encoding tasks. Older adults also had stronger memory representations of the initial locations. In another studying using an immersive HMD Morris water maze task, older adults showed lower precision but comparable landmark use to young adults (McAvan et al., 2021).

On the other end of the age spectrum, virtual environments have been used to study developmental changes in spatial navigation and memory during childhood. Most often with desktop VR displays and virtual mazes, studies examined landmark, route, and survey knowledge acquisition at different ages (Broadbent et al., 2015; Jansen-Osmann and Fuchs, 2006; Jansen-Osmann et al., 2007; Lingwood et al., 2015; Nazareth et al., 2018; Nys et al., 2015). These studies found that landmarks aid route learning more for younger children versus older children and adults (Lingwood et al., 2015), that environmental structure affects young children's wayfinding more than older children (Jansen-Osmann et al., 2007), and that younger children explore environments differently when allowed to freely explore (Farran et al., 2022; Jansen-Osmann and Fuchs, 2006; Jansen-Osmann et al., 2007). Farran et al. (2022) showed that exploration patterns in 5–11 year olds for a fairly realistic virtual city become more "active" with increasing age (visiting more of the environment, revisiting similar areas and pausing less often) and this exploration pattern related to navigational success (time to find targets and return home). These results were similar to studies that assessed effects of exploration patterns on spatial memory in adults in a virtual environment (Gagnon et al., 2016, 2018) and in the real world (Munion et al., 2019). Children with Autistic Spectrum Disorder also show reduced exploration in virtual environments compared to typically developing children (Fornasari et al., 2013). Nazareth et al. (2018) extended the study of route integration and spatial knowledge acquisition to test differences in 8–16 year olds. They found that children were better at within-route versus between-route pointing (as with adults), that "integrators" develop later, and that perspective-taking ability explained a good amount of age-related improvement in pointing accuracy. Examinations of developmental differences in cue use for spatial memory have shown that children use single landmark cues earlier than environmental boundary cues (Glöckner et al., 2021) and that generally object-location memory improves with age (León et al., 2014; Rodríguez et al., 2021). Desktop virtual environments have even been used with children 2–3 years of age, showing an increased use of visual motion cues for spatial orientation at 35 versus 30 months (van den Brink and Janzen, 2013). In contrast to the abundance of screen-based VR studies including children, only a few studies have used immersive VR in the study of spatial navigation with children. This is likely due to prior limitations in the accessibility of HMDs for children (e.g., fit and availability). One HMD study Negen et al. (2019) tested 3–8 year olds on a perspective taking task where they had to point to a remembered location after being teleported to a new location in the environment (see **Fig. 8**). They found support for a developmental progression of children encoding first relative to themselves, then to a single landmark in the world, and finally encoding relative to multiple landmarks in the scene. In two other studies testing cue use and integration with HMDs, both Petrini et al. (2016) and Barhorst-Cates et al. (2021b) showed increased reliance on visual information in a spatial updating task compared to adults and Petrini et al. (2016) found optimal cue integration in children that was not seen in adults in their task.

Comparing spatial navigation in real and virtual environments

The work discussed above demonstrates a number of experimental manipulations and theoretical contributions for understanding spatial navigation in VR, mostly assuming that the results found using virtual environments generalize to real world behavior. In fact, although there have been numerous studies comparing space perception in real and virtual environments (Creem-Regehr et al., 2023; Kelly, 2022; Renner et al., 2013), direct comparisons with spatial navigation tasks are relatively scarce. This lack of comparisons is likely because of methodological constraints that led to the choice of VR as a method to begin with, such as the need for traversal over large, controlled environments or manipulations of specific room shapes or features. However, a handful of recent studies have attempted to match navigation tasks across real and virtual environments and have produced mixed results about their equivalence. For vista-space tasks, early work comparing perspective taking in real versus virtual environments showed functional similarity—that manipulations of locomotion type (physical or imagined) and disparity of rotation affected performance similarly across the two environments (Williams et al., 2007b). More recently, as described above, Kimura et al. (2017) showed that viewers relied more on landmarks than on room geometry in a task involving returning to a remembered location in VR compared to the same paradigm in the real world. In contrast, participants performed similarly on a spatial orientation task involving walking to

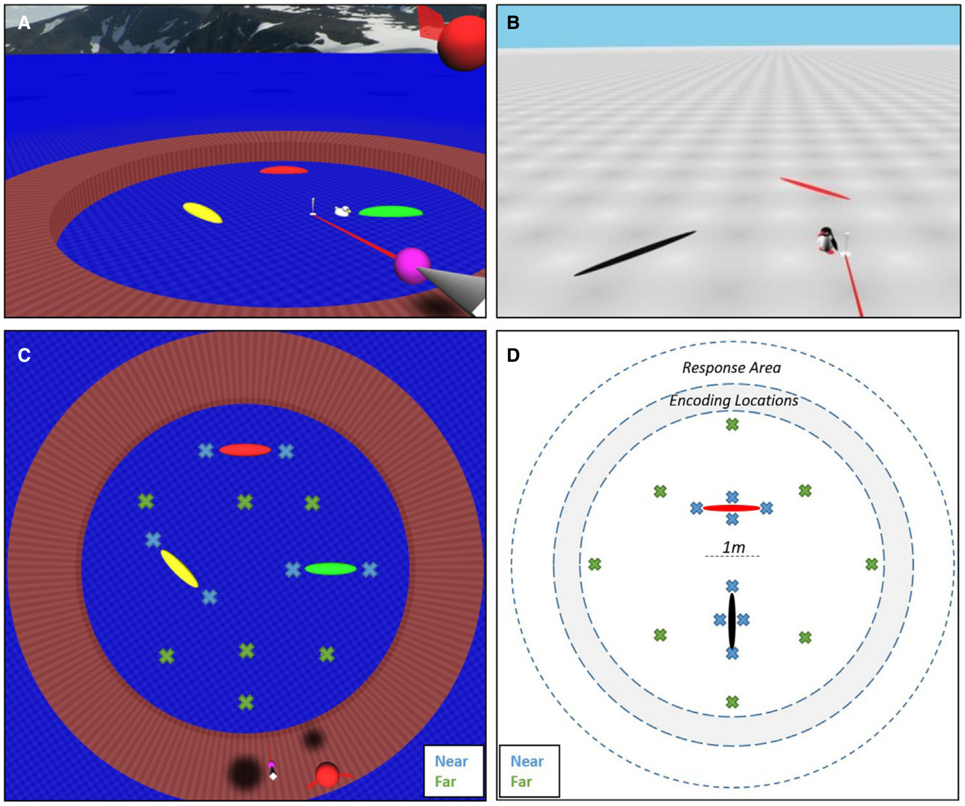

Fig. 8 Virtual environments used with children to test memory for location of a cartoon animal from a new perspective. Adapted from Negen, J. et al. (2019). Coding locations relative to one or many landmarks in childhood. PLoS Comput. Biol. 15(10), e1007380 (CC BY 4.0).

remembered objects in VR compared to the real world, but in this paradigm, room characteristics were not manipulated (Pastel et al., 2022). Zisch et al. (2022) compared the effects of moving wall boundaries on spatial memory for an object's location in the real world, Desktop-VR, and HMD-VR, following an established paradigm and predictive models of human spatial memory (Hartley et al., 2004). They concluded notable similarities in model fits based on performance distributions across all three environments, although some underestimation of distance in HMD-VR and greater disorientation in the real world, generally supporting equivalence across real and two types of virtual environments despite differences in the availability of body-based cues (see also Huffman and Ekstrom (2019) for similar claims based on brain activation patterns).

In the context of larger, environmental-scale navigation tasks, one study extended the investigation of gender differences previously found in the Silcton virtual route integration task (Weisberg et al., 2014) to test the generalization of effects to the real world (Cocquyt et al., 2022). Women and men gave direction estimates and drew sketch maps based on exploration of the large-scale virtual environment and their own familiar real world environment. A second experiment compared women only on estimates after exploring the virtual environment or a novel real world environment (a part of campus that was not familiar to participants). Together, the results replicated a male advantage in accuracy of cognitive maps in the virtual environment task, but there was no gender difference in the real world task. Further, women performed relatively better in the novel real world environment compared to the virtual environment, suggesting that gender differences found in virtual tasks could be partially explained by the use of the virtual environment itself. In a different context, Marín-Morales et al. (2018) compared exploration patterns in a real museum and a virtual replica of the museum experienced through an HMD and teleporting with controllers. There were some differences in the first room that may have been due to the novelty of the virtual environment, but patterns of trajectories and time spent in the rooms was quite similar. However, measures of spatial knowledge were not included in this task.

Despite only relatively few studies directly examining the equivalence of navigation in real and virtual environments, the similarity in patterns of performance is promising. Future work is needed to explore the reasons why gender differences found in virtual environments may not be seen in the real world.

Conclusions and future directions

Virtual Reality has advanced research on the basic science of spatial navigation and likewise, spatial navigation research has informed virtual reality as an application. As presented here, VR provides an opportunity to control variables in ways that are difficult to accomplish in the real world, contributing to an understanding of the cues and mechanisms that underlie spatial navigation as a complex task involving perception, attention, memory, and decision making. VR has evolved in methods over decades of development, and multidisciplinary approaches at the intersection of engineering and behavior will continue to advance the field. This review focused on spatial cues, spatial knowledge, and individual differences in spatial navigation behavior. In parts, we touched on how VR as a tool informs an understanding of neural mechanisms underlying spatial navigation, but a complete presentation of VR studies aimed at neuroscience questions or neuropsychological applications is outside of the scope of this review. There are other related VR spatial navigation applications that we also do not discuss here. For example, an important question is how training in VR transfers to real world spatial knowledge. Many applications use VR as a spatial training method for situations that may be dangerous or in need of highly skilled practice (e.g., firefighting, flight planning) and this has motivated both applied (Aoki et al., 2008; Bertram et al., 2015; Gamberini et al., 2003) and basic (Clemenson et al., 2020; Hejtmanek et al., 2020; Richardson et al., 1999; Waller, 2000; Witmer et al., 1996) research approaches to evaluate VR training. Another relevant, but omitted area in this review is the use of VR to study navigation in non-human animals (Stowers et al., 2017; Thurley and Ayaz, 2017). VR for animals is a promising way to combine both behavioral and neural approaches to studying navigational mechanisms.

The increasing accessibility of VR methodologies introduces further opportunities for future research. HMDs have drastically decreased in cost and increased in quality (lighter weight, larger FOV), opening up possibilities to extend what was desktop VR to immersive displays that allow for head and body rotation and stereo viewing. This expansion of immersive VR could allow for studies to test environmental-scale spaces such as cities and mazes that more closely resemble the real world. Although use of HMDs will still often constrain the scale of the space that the observer can move around in, combining HMDs with new locomotion devices such as an omnidirectional treadmill (Hejtmanek et al., 2020) can provide additional body-based cues. Although there is strong evidence reviewed in the current paper supporting the importance of body-based cues in navigation, the relative weighting and role of vision (with or without body-movement) is still debated (Huffman and Ekstrom, 2019, 2021; Steel et al., 2021). Future work could also directly compare matched HMD and Desktop VR paradigms where the defining difference is the presence of body-based self-motion cues. Another advancement that could facilitate spatial navigation research is a recent trend to provide VR platforms for creating or running spatial navigation paradigms and tasks such as in Starrett et al. (2021) and Wiener et al. (2020). Although there are challenges with sharing environments and programs (e.g., differences in equipment, updates in software versions, etc.), VR research in spatial navigation could benefit from efforts to establish collaborations that support increased open access to virtual environment software infrastructure as well as high quality VR models of different types of spaces. Related to this, labs have found ways to expand immersive VR studies remotely by recruiting participants who have consumer-level HMDs in their homes (Kelly et al., 2022). This work generally replicated navigation performance found in the lab, although there were some differences that may be attributed to the expertise of the remote participants.

One direction for future research is to combine multiple VR navigation tasks along with performance in the real world as a modern "battery" of spatial skills. This approach could better characterize individual differences across a range of different navigational task components (Newcombe, 2018), possibly informing ways that navigational assistance applications could be tailored to individual skills. For example, Yu et al. (2021) recently took this approach with a study on midlife adults (aged 43–61 years), who are less studied in the literature, by implementing an immersive VR path integration task and two desktop VR maze tasks to test spatial knowledge acquisition and strategy preference. As described above, Weisberg and Newcombe (2016) also related performance on a virtual route integration task to performance on a goal-oriented virtual maze task and Barhorst-Cates et al. (2021a) assessed the DSP, virtual Morris water maze, and real world pointing in the same individuals. Knowledge of individual differences could also advance the development of new locomotion interfaces that support natural locomotion and facilitate spatial learning in individualized ways, as well as make personalized recommendations for locomotion interfaces that are best-suited to an individual based on their abilities and experiences. Further, the study of individual differences in VR could be extended to people with sensory, motor, or cognitive deficits, with the goals of understanding basic mechanisms, improving accessibility, and providing treatment or rehabilitation (Bouchard and Rizzo, 2019).

One promising new feature of modern HMDs is the inclusion of eye tracking technology. Eye movement patterns measured during navigation could provide additional useful data on effects of attention and strategies on spatial learning as well as enhance locomotion experiences (Marwecki et al., 2019; Piumsomboon et al., 2017). Finally, the ability to create unique virtual worlds is one of the greatest advantages of using VR as a tool for navigation research. More studies that manipulate these virtual environments in physically impossible or creative ways will undoubtedly benefit our understanding of spatial navigation processes.

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