

## Virtual Reality Test Design for Spatial Navigation Ability

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### Abstract

Spatial navigation is a crucial cognitive ability that ensures effective functioning in people's daily work and life. With the continuous development of Virtual Reality (VR) technology, its suitability for spatial navigation research has become increasingly evident. Under current technical conditions, there remain certain differences in spatial perception and behavioral performance between individuals in VR and in reality; researchers should continuously verify and update their research findings within this new technological environment. When designing spatial navigation tests based on VR, researchers must first comprehensively consider equipment fidelity along with participants' familiarity and user experience to select appropriate display devices and locomotion techniques. Secondly, they should thoroughly understand the design logic of spatial navigation paradigms, which typically comprise two stages—"learning" and "testing"—and ensure the scientific rigor of task design at each stage. When designing scenarios and tasks, test difficulty should be modulated by manipulating environmental factors that influence spatial navigation. Given the complexity of VR assessment tools, researchers should control and evaluate the quality of these tools from multiple dimensions.

### Full Text

#### Preamble

#### The Design of Virtual Reality Tests for Spatial Navigation Ability

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**Abstract:** Spatial navigation is a critical cognitive ability that ensures effective functioning in daily work and life. With the continuous advancement of Virtual Reality (VR) technology, its compatibility with spatial navigation research has become increasingly prominent. Under current technological conditions, notable

differences remain between spatial perception and behavioral performance in VR versus the real world, and researchers should continuously verify and update their findings in this evolving technological landscape. When designing spatial navigation tests based on VR, it is essential to first comprehensively consider equipment fidelity as well as participants' familiarity with and experience using the devices to select appropriate display equipment and locomotion techniques. Second, designers must thoroughly understand the design logic of spatial navigation paradigms, which typically include “learning” and “testing” phases, while ensuring scientific rigor in task design at each stage. Third, when designing scenarios and tasks, environmental factors affecting spatial navigation should be systematically manipulated to appropriately adjust test difficulty. Given the complexity of VR assessment tools, researchers should evaluate and control the quality of these instruments across multiple dimensions.

**Keywords:** spatial navigation ability, virtual reality, simulation-based assessment

In recent years, the scope of psychological measurement has gradually shifted from laboratory research paradigms assessing basic cognitive abilities toward evaluating the comprehensive capabilities required for individuals to perform specific activities in real-world contexts. Among spatial abilities, previous research has primarily focused on small-scale spatial ability—the capacity to perceive, imagine, and mentally manipulate objects external to oneself, such as mentally rotating figures or visualizing paper folding and unfolding. However, this “basic” ability construct is insufficient to fully describe the cognitive processes involved in real-world environmental orientation, spatial layout learning and memory, and path planning. These processes involve large-scale spatial abilities, collectively termed spatial navigation ability (Wolbers & Hegarty, 2010). This ability shows significant individual differences in the population (Spiers et al., 2023; van der Ham et al., 2020; Zhang et al., 2023) and is susceptible to aging effects (Lester et al., 2017). Symptoms such as declining sense of direction and spatial memory represent key cognitive markers in the early stages of disorders like Alzheimer's disease (AD) (Coughlan et al., 2018). Therefore, whether for personnel selection in specific positions or for monitoring and intervention in preclinical AD, accurately quantifying individual differences in spatial navigation ability is a crucial prerequisite.

Early spatial navigation tests primarily consisted of self-report questionnaires (e.g., Hegarty et al., 2002; Lawton, 1994), where participants self-assessed their spatial navigation experiences in daily life. While questionnaires are easy to administer and demonstrate acceptable reliability and validity—remaining a common auxiliary measurement method—they inevitably suffer from lack of objectivity. To more directly observe performance differences among individuals with varying abilities, researchers have conducted spatial navigation tests in real-world environments such as residential areas (Ishikawa & Montello, 2006), botanical gardens (Muffato et al., 2016), nuclear facilities (Stites et al., 2020), and university campuses (Pullano et al., 2024). Such studies require large-scale

physical spaces, allowing participants to walk through scenes in person, which ensures high ecological validity but also presents limitations: they are time-consuming and labor-intensive, difficult to replicate, hard to control for factors like noise, weather, and traffic, and cannot be generalized to other contexts (van der Ham et al., 2015).

To address these issues, an increasing number of researchers have adopted simulation-based assessment methods, using VR technology to construct two- or three-dimensional scenes that simulate specific real-world environments such as towns (Weisberg & Newcombe, 2016), museums (Burles et al., 2020), and wilderness settings (Gagnon et al., 2018), or task scenarios required by specific paradigms such as virtual water mazes (Thornberry et al., 2021), Y-mazes (Rodgers et al., 2012), dual-path paradigms (Weisberg et al., 2014), and triangle completion paradigms (Adamo et al., 2012; Xie et al., 2017). Compared to real-world testing, VR tests are not constrained by venue or time, offering greater efficiency, safety, and controllability. They enable environmental design and manipulation, provide natural interaction and immediate feedback, and ensure both standardization and ecological validity. Furthermore, VR devices exhibit excellent compatibility with neuroimaging technologies, allowing for the collection of multimodal data through non-invasive techniques such as EEG, eye-tracking, and fMRI (Cogné et al., 2017; Migo et al., 2016). In recent years, an increasing number of VR assessment tools for spatial navigation have been widely applied in areas including mild cognitive impairment (MCI) screening, neurorehabilitation training, military personnel selection and professional training, and architectural space safety optimization design (Castegnaro et al., 2022; Coughlan et al., 2019; Da Costa et al., 2022; Diersch & Wolbers, 2019; Feng et al., 2022; Moussavi et al., 2022; Shi et al., 2021; Tarnanas et al., 2015; Wiener et al., 2020; Yang & Kalantari, 2024; Zen et al., 2013).

This study adopts an assessment perspective, first clarifying the feasibility of using VR as a test medium by comparing spatial perception and behavioral differences between VR and the real world across multiple dimensions. Second, it addresses a series of issues to consider during test design, including: how to select appropriate display devices and locomotion techniques, how to design scientifically valid and effective assessment paradigms, and which environmental factors affecting spatial navigation task difficulty should be manipulated. Finally, it explores issues related to quality evaluation of VR assessment tools.

## 2. Differences in Spatial Perception and Behavior Between VR and the Real World

VR technology has developed rapidly over the past two decades, profoundly reshaping research methods for human behavior (Brookes et al., 2020; Tarr & Warren, 2002). By presenting visual images and non-visual multi-channel stimuli, it provides real-time interactive scenarios that create immersive experiences for users (Garcia-Betances et al., 2015). When using VR to design tests, the first question to address is whether research conclusions based on VR can be gener-

alized to the real world. Currently, this remains a complex and open question, particularly controversial in the field of spatial navigation.

Some supportive evidence suggests that people's spatial navigation performance in VR is fundamentally similar to that in the real world (Coutrot et al., 2019; Cushman et al., 2008; Lloyd et al., 2009; Marín-Morales et al., 2019; Richardson et al., 1999). However, other studies have revealed differences in perception and behavior in VR compared to the real world, manifested primarily in the following aspects.

At the perceptual level, differences exist in the sensory information available between VR and real environments. In desktop VR, participants remain physically stationary, relying solely on visual cues for spatial navigation while lacking vestibular and kinesthetic information (Ladouce et al., 2017; Park et al., 2018), which weakens performance in spatial orientation and other aspects. Additionally, conflicts between visual and vestibular inputs can easily lead to motion sickness (Diersch & Wolbers, 2019; Krohn et al., 2020). Furthermore, individuals exhibit certain biases in perceiving distance, size, and speed cues in VR. For example, Bhagavathula et al. (2018) compared pedestrian street-crossing behavior in VR and real-world environments, finding similarities in crossing intentions and perceived traffic risks but significant differences in perceived vehicle speed. Kuliga et al. (2015) found that participants in virtual environments showed size and distance perception biases, tending to overestimate corridor length and narrowness. Other studies analyzing eye-tracking data have revealed differences in visual attention, with individuals processing visual information more efficiently in real environments while conducting visual information searches more efficiently in virtual environments (Dong et al., 2022). Kimura et al. (2017) conducted spatial reorientation tests in both real and VR versions of rectangular rooms, finding that individuals differed in their utilization of different types of visual cues in space between the two environments. Compared to the real world, people in VR relied more on discrete, salient cues and less on geometric feature cues of spatial layouts.

Differences in perceptual cues and processing patterns affect individuals' spatial navigation behavior and task performance. van der Ham et al. (2015) found that participants showed better spatial memory performance in real-world environments and demonstrated through experiments that poorer performance in VR was due to lack of direct physical participation. Savino et al. (2019) found that participants experienced greater task load and showed poorer performance in virtual environments. Kalantari et al. (2024) showed that compared to real environments, participants in virtual environments spent more time and distance exploring, exhibited more information-seeking behavior, but demonstrated poorer spatial navigation performance—making more wrong turns at decision points and showing greater directional judgment errors. Researchers inferred from participants' self-reported metrics that the greater uncertainty, cognitive load, and task difficulty experienced in VR triggered more information-seeking behavior, broader exploration, and more time spent searching for signs and other environ-

mental cues, consequently leading to poorer wayfinding performance and spatial memory.

These inconsistent results can be partly attributed to changes in VR technology. Sanchez-Vives and Slater (2005) compared visual complexity between real and virtual worlds, showing that even high-end computers could not replicate the complexity of the physical world. However, this study was conducted nearly 20 years ago, when resolution and image processing capabilities were far inferior to today's standards. Moreover, VR realism depends not only on visual fidelity but also on factors such as quality of body tracking, frame rate, latency, and content design (Cummings & Bailenson, 2016).

Currently, some differences between VR and reality are unavoidable. When walking in the real world, individuals receive full-body kinesthetic feedback, which requires more physical effort than movement in VR. VR also falls short in replicating the inherent multisensory cues of the real world, such as smell, sound, and fine-grained tactile sensations. The absence or conflict of these cues in VR can interfere with spatial navigation activities. Additionally, differences in perceived distance and speed, along with the lack of feedback from one's own actions, may cause individuals to behave differently in VR than in the real world, such as reduced head movement and "tunnel vision" (Ewart & Johnson, 2021). Nevertheless, VR-related technology is developing rapidly, and people's familiarity with VR devices is gradually increasing. Many problems identified in previous studies may be improved under new technological conditions. As Ewart and Johnson (2021) noted, our research often lags behind technological development, and past conclusions about differences between VR and the real world may no longer apply to current VR systems. Therefore, researchers should specify the hardware and software versions used in their papers and continuously monitor new technological developments to verify and update their findings in a timely manner.

### 3. Design of Spatial Navigation VR Tests

Simulation-based assessment aims to provide more accurate and comprehensive evaluation results by simulating real-world situations or tasks that fully engage participants' target abilities. For spatial navigation ability, the realism of assessment tools is reflected in visual presentation (primarily determined by display devices) and interaction methods (i.e., how to simulate human movement in real space, which depends on locomotion techniques). Test designers need to understand how different display devices and locomotion techniques affect participant performance and whether such effects vary across tasks.

VR technology greatly expands assessment contexts and interaction types, allowing test designers considerable freedom while ensuring scientific validity and effectiveness of assessment content, procedures, and formats. By reviewing the design logic of previous spatial navigation tasks, Section 3.2 summarizes and proposes a design framework for common assessment paradigms.

In terms of scenario and task design, VR technology's advantage lies in the comprehensiveness and convenience of variable manipulation. Test designers can add or simplify environmental elements and task rules according to assessment needs, thereby flexibly controlling test difficulty. Section 3.3 systematically organizes environmental factors affecting spatial navigation performance.

### 3.1 Selection of Display Devices and Locomotion Techniques

In recent years, the field of view (FOV) provided by VR headsets has continuously increased, and six degrees of freedom (6-DOF) tracking technology has become widely applied, greatly enhancing the simulation effects of VR products (Jensen & Konradsen, 2018; Penelope & Emmanuel, 2022). Ragan et al. (2015) proposed three dimensions for evaluating VR fidelity: display fidelity, interaction fidelity, and scenario fidelity. Previous spatial navigation studies using VR have shown considerable variation in device configurations. Generally, higher fidelity enhances participants' immersion, engagement, and performance, but designers must also consider participants' familiarity with and experience using the equipment.

For spatial navigation tests, researchers are most concerned with display fidelity and interaction fidelity, which primarily depend on the selection of display devices and locomotion techniques. The two most commonly used display devices are Desktop VR and Head-Mounted Displays (HMDs). Desktop VR, also known as non-immersive VR, is a small desktop-based virtual reality system built on a standard PC platform that uses mid-to-low-end graphics workstations and stereoscopic displays to generate virtual scenes. Users interact with the scene through hand-controlled input devices such as keyboards, mice, or joysticks. HMDs use head-mounted display devices to block external visual and auditory input, immersing users in the virtual environment. Their 3D visual principle involves presenting different images to the left and right eye screens, with the brain generating a three-dimensional perception from these differential inputs. HMDs create stronger immersive experiences for users and support a richer variety of interaction devices.

Many studies have compared the effects of these two display device types on participants' spatial navigation performance and user experience. Early studies found that participants performed better in Desktop VR, and that video game experience only affected performance in Desktop VR (Elmqvist et al., 2008; Sousa et al., 2009). Sousa et al. (2009) conducted interviews about user experience, with most participants reporting dizziness when wearing VR headsets and that tangled device cables interfered with their turning behavior. However, as display device fidelity and portability have improved, an increasing number of recent studies indicate that HMDs provide stronger immersion than Desktop VR (Buttussi & Chittaro, 2018; Buttussi & Chittaro, 2023; Kim et al., 2014), and that participants using VR headsets explore virtual environments more thoroughly (Feng et al., 2022; Ruddle et al., 2014).

Notably, the effectiveness of display devices is closely related to the locomotion techniques they employ. Through specific virtual locomotion techniques, virtual avatars can move arbitrarily within VR environments while keeping participants physically stationary or moving only within a limited real-world space (Templeman et al., 1999), also known as in-place locomotion techniques (Buttussi & Chittaro, 2023).

Relatively simple and common devices include keyboards, mice (or their combination), and joysticks, which only require users to stand or sit in place to control movement in the virtual environment. Earlier studies mostly supported using keyboards or mice (Lapointe et al., 2011; Thrash et al., 2015), possibly because people were more familiar with keyboard-mouse operations at the time, avoiding the learning cost of joystick operation. With the popularization of VR products and improvements in device interaction fidelity, joysticks have gradually become mainstream VR accessories, accompanied by new questions: Which method works better, teleportation or continuous locomotion/steering? Teleportation refers to users pointing a laser from the joystick to a distant location and instantly moving to that position by clicking a button. Continuous locomotion involves holding down a button on the joystick to walk at a constant speed. Most studies have found that compared to continuous locomotion, teleportation causes weaker motion sickness, provides stronger immersion, and yields better performance in spatial navigation tasks (Buttussi & Chittaro, 2021; Buttussi & Chittaro, 2023; Langbehn et al., 2018). However, some researchers argue that teleportation creates a discontinuous sense of space, and that continuous locomotion is less likely to cause dizziness (Feng et al., 2022). Buttussi and Chittaro (2023) found that the impact of these two locomotion techniques on spatial navigation performance depends on display device type (HMD vs. Desktop VR), virtual environment type (indoor vs. outdoor), and the type of spatial knowledge being measured. Additionally, Cherep et al. (2022) found that adaptation to teleportation varies among individuals. Therefore, researchers should consider equipment configuration, scenario and task types, and target populations when choosing between these locomotion techniques.

When humans walk in real space, internal feedback from body movement is crucial for the spatial updating process, conveying information about changes in direction (vestibular) and position (proprioception). Individuals integrate these different sources of information in the brain to form organized spatial representations (Montello, 2005). When sensory input from the real world conflicts with input from VR, participants may experience cybersickness—feeling nausea, headaches, and eye strain (Chang et al., 2020; Cheng & Liu, 2014). Using in-place locomotion techniques, especially when the body remains stationary, participants do not receive information from body movement while the scene in their field of view continuously shifts. This conflict between sensory inputs can easily cause cybersickness and weaken performance in spatial navigation tasks (He et al., 2019c; Ruddle et al., 2011). Templeman et al. (1999) argued that ecological locomotion techniques should resemble real-world human movement mechanisms and characteristics, such as continuous body participation in move-

ment control with perceived physical exertion, visual flow information updating speed consistent with walking speed, ability to free hands for other operations during walking, and minimal concern about falling.

van der Ham et al. (2015) investigated the effects of body movement and directional information on spatial navigation performance. The experiment set up four conditions: (1) Desktop VR, where participants remained seated and interacted with the virtual environment on a computer screen; (2) the same condition with additional directional information (a compass presented on screen); (3) walking in a real-world environment; and (4) a “hybrid” approach to test the effect of “body movement”—participants walked in an open space while holding a tablet to view their current position and road conditions in the virtual environment, with real-time position updates through GPS tracking. Results showed significantly better performance in the latter two conditions on pointing and map-drawing tasks, indicating that direct physical participation is important for spatial memory performance, particularly for survey knowledge formation.

Although walking in person most closely matches actual human movement patterns, it imposes high requirements on equipment costs, venue size, tracking technology, and safety assurance. Therefore, Riecke et al. (2010) attempted to decompose control of virtual movement into two aspects: steering control and traveling control, and investigated whether both types of control required direct physical participation in VR. They compared three locomotion technique schemes using VR headsets: (1) using a joystick to control both steering and traveling, (2) walking in person, and (3) using a joystick to control traveling while physically rotating in place to control steering. Results showed that spatial navigation performance under the third scheme was significantly better than the first and almost equivalent to walking in person. This finding is significant, demonstrating that allowing only body rotation in place can significantly enhance participants’ immersion and reduce dizziness, achieving a balance between economic efficiency and ecological validity. Subsequent studies have supported this conclusion (Cherep et al., 2020; Cherep et al., 2022; Kelly et al., 2020; Lim et al., 2020). Today, an increasing number of locomotion techniques support participants’ activity within small spaces, such as linear treadmills, omnidirectional treadmills (Ruddle et al., 2013), or VR bicycles.

Beyond locomotion techniques, body ownership is also one of the core elements for enhancing VR immersion and presence. Through synchronized stimulation of multisensory feedback (visual, auditory, tactile, proprioceptive, etc.), users gain the perception that the virtual body belongs to them (Kilteni et al., 2012; Spanlang et al., 2014), as exemplified by the “rubber hand illusion” (Botvinick & Cohen, 1998). The key to such techniques lies in the synchrony of information across different sensory channels. For example, “visual-proprioceptive” synchrony requires aligning the virtual body with users’ perception of their limb positions, presenting the virtual body and its limbs where they should appear. “Visual-kinesthetic” synchrony requires the virtual body to move in the same way as the real body, with actions highly consistent with users’ real movements,

achievable through motion capture or joystick tracking. The key to “visual-tactile” synchrony is providing tactile feedback, such as joystick vibration when the virtual hand in view touches an object. Thus, even if participants cannot see their own bodies in the headset, they can still experience a strong sense of embodiment. Body ownership not only reduces dizziness but also helps improve participants’ spatial navigation task performance in virtual environments (Pan & Antonia, 2018; Moon et al., 2022).

After selecting display devices and locomotion techniques, researchers should consider whether to include a practice session. Grübel et al. (2017) found that the sensorimotor process of interacting with VR equipment significantly affects individual task performance. Therefore, researchers recommend adding extra practice before testing to familiarize participants with device operation until they reach a preset performance standard before entering formal testing, avoiding confounding with the target ability being measured. During practice, the virtual environment, interaction devices, and test tasks should be introduced gradually to prevent participants from experiencing stress due to processing too much information simultaneously (Diersch & Wolbers, 2019). Additionally, an important advantage of VR is its greater inclusivity for participant populations, covering the needs of some special groups (Kalantari & Neo, 2020). Particularly for spatial navigation ability assessment in older adults or patients with neurological diseases, ecological validity and clinical feasibility must be balanced, with appropriate optimization of interaction elements and testing protocols (Colombo et al., 2024). For example, when using treadmills, age-related declines in sensorimotor control must be considered. To avoid fall risks, older adults often prioritize sensorimotor processing, which occupies cognitive processing resources needed for task completion (Schäfer et al., 2006). To address this issue, Lövdén et al. (2005) showed through experiments that providing walkers (i.e., adding handrails to treadmills) improved older adults’ task performance. Schellenbach et al. (2010) demonstrated that prior practice on treadmills...

### 3.2 Design Framework for Common Assessment Paradigms

Spatial navigation is a composite cognitive ability encompassing perceptual, learning, representational, memory, planning, and orientation components (Wolbers & Hegarty, 2010), making it difficult to comprehensively assess through a single task (Thornberry et al., 2021). Moreover, spatial navigation tests have long lacked a unified theoretical organizational framework, leading to terminological confusion, including unclear ability structures, inconsistent construct names for the same task types, and ambiguous relationships between different tests (Sánchez-Escudero et al., 2024; Uttal et al., 2024). Generally, researchers design specialized navigation tasks based on specific application needs (e.g., military personnel selection; Hegarty & Waller, 2005) or target specific ability facets, or adapt classic tests. Although researchers have designed numerous test tasks, except for tasks measuring “perspective taking” ability that adopt some special forms (Beatini et al., 2024; Brucato et al., 2023; Sophia & Carsten,

2024), most other paradigms can essentially be reduced to a two-stage “learning → testing” format (Figure 1 [Figure 1: see original paper]).

### Figure 1. Common Design Framework for Spatial Navigation Tests

In the learning phase, tasks can first be divided into two categories based on whether a map is provided: (1) providing an overall layout map before departure (Morganti et al., 2013; Spiers et al., 2023); (2) never providing a map, with participants learning space from a first-person perspective through movement in the scene. In the latter case, learning methods can be further divided into two types: (a) learning along a pre-designed route (Bullens et al., 2010; Hegarty et al., 2023; Weisberg et al., 2014; Weisberg & Newcombe, 2016), and (b) allowing free movement in the scene (Brunec et al., 2023; Gagnon et al., 2018; Thornberry et al., 2021). The latter form more closely matches how people explore unfamiliar environments in daily life and helps reveal individual differences in spatial learning patterns, but it can introduce confounding variables in process control that affect data quality. Test designers should determine the learning phase format after comprehensively considering measurement purposes, variable control, and data analysis approaches.

The purpose of the testing phase is to evaluate the level of spatial knowledge formed after spatial learning, or the form of spatial representation. The most common evaluation framework for this is the “Landmark-Route-Survey Model” proposed by Siegel and White (1975). They suggested that people form spatial knowledge representations in new environments through three stages: (1) Landmark knowledge—memory of prominent, identifiable objects or scene features in the environment; (2) Route knowledge—composed of sequences of landmarks and related decisions, such as “turn left at the gas station, go straight past two intersections to reach the post office.” Spatial knowledge at this stage lacks metric information such as angles and distances; (3) Survey knowledge—a fine and stable representation similar to a “map” that integrates spatial information using an allocentric reference system, which does not change with individual movement. Subsequent empirical research has shown that the development of these three types of spatial knowledge does not necessarily follow a strict sequential order. For example, some studies have found that people can complete tasks requiring metric information, such as finding shortcuts or estimating directions or distances, within a short time after encountering a new environment (Loomis et al., 1993). Moreover, different representations can function separately or co-exist simultaneously (Peer et al., 2021), and the speed and sequence of forming various spatial representations show large individual differences (Ishikawa, 2023; Maxim & Brown, 2023).

Table 1 organizes common assessment tasks for the three types of spatial knowledge. Among them, survey knowledge assessment has two approaches: (1) direct measurement by requiring participants to draw or complete maps, and (2) indirect measurement based on specific tasks, where researchers assume that individuals can only successfully complete these tasks after forming metric survey knowledge, such as pointing tasks, distance estimation tasks, and shortcut

tasks (Epstein et al., 2017; Newcombe, 2018).

**Table 1. Assessment Tasks Corresponding to Three Types of Spatial Knowledge**

*Landmark Recognition Task:* Present a series of photos sequentially, requiring participants to judge whether buildings or objects in the photos appeared during the learning phase (Stites et al., 2020; van der Ham et al., 2020). Present two photos simultaneously, one showing a building or location in the target area and the other a similar distractor, requiring participants to select which photo is from the target area (Pullano et al., 2024).

*Route Repetition Task:* Retrace the route learned in the learning phase from a first-person perspective (Muffato et al., 2016).

*Route Knowledge Task:* Present segments of the path from start to destination in photo form, requiring participants to order these paths according to their spatial sequence (Pullano et al., 2024).

*Path-Route Task:* At a certain location, have participants choose from 2 or 3 directions which direction leads to the target location (van et al., 2020).

*Shortcut Task:* Require participants to reach the target location using the shortest path, where the most direct route was not previously traveled during the learning phase (He et al., 2023; Stites et al., 2020).

*Pointing Task/Direction Estimation Task:* Require participants to stand (or imagine standing) at a certain location and point out the direction of a landmark that cannot be directly seen relative to their current position (He et al., 2023; Ishikawa & Montello, 2006; Muffato et al., 2016).

*Distance Estimation Task:* On a blank sheet of paper, use a standard line to represent a certain actual distance (e.g., using a 2cm line to represent 0.6km), requiring participants to draw a line representing their estimated distance between two designated locations based on the standard line (Ishikawa & Montello, 2006). Present three landmarks and require participants to imagine and judge from a bird's-eye view which two landmarks are closest (van der Ham et al., 2020).

*Map Drawing Task:* Require participants to draw the overall layout of a previously learned space on a blank sheet of paper, reconstructing the positions of some buildings and roads (Ishikawa & Montello, 2006; Muffato et al., 2016).

*Map Completion Task:* Provide a simplified map and require participants to complete the start point, end point, designated buildings, or routes (Stites et al., 2020).

*Survey Knowledge Task:* Label several areas on a simplified map and present several photos below, requiring participants to match the location of each building in the photos to the corresponding area on the map (Pullano et al., 2024).

*Model-Building Task:* Present a blank plane and several top-down views of buildings, requiring participants to drag each building onto the blank plane to reconstruct the spatial layout of the scene (Pagkratidou et al., 2020).

### 3.3 Scenario and Task Design: Manipulation of Environmental Factors

When designing test scenarios and tasks, environmental factors affecting participant performance must be comprehensively considered. Environmental factors influencing spatial navigation activities can be broadly divided into three categories: task-related factors, visual cue-related factors, and spatial layout complexity-related factors.

The first category is task-related factors—considerations when establishing task rules and designing items (levels), such as whether tasks are time-limited, the number of target locations in wayfinding tasks, the number of decision points along the shortest path, whether the shortest route involves extensive backtracking (Coutrot et al., 2022; Yesiltepe et al., 2023), and whether the direction of target locations aligns with the reference frame direction in direction judgment tasks (He & McNamara, 2018). Researchers can manipulate such variables to differentiate item difficulty and modify or delete items based on pilot test results.

The second category is visual cue-related factors. A common phenomenon in daily life is that a person can smoothly walk from point A to point B, yet cannot clearly describe the route from A to B when not in that scene. To explain this phenomenon, Dalton (2001) divided spatial knowledge required for wayfinding into two types: “knowledge in the head”—information about the scene stored in memory or related decision-making experience, and “knowledge in the world”—visual cues in the scene such as salient landmarks, signs, and spatial contour features. When designing scenarios, researchers must carefully consider which visual cues can assist and which increase task difficulty. For example, obstacles formed by buildings, high walls, and tree clusters reduce spatial visibility, causing spatial representations to be segmented into several relatively independent “sub-maps,” reducing accuracy in distance and direction estimation, making spatial updating and path integration more difficult, and weakening spatial navigation efficiency (He & Brown, 2019a; Horner et al., 2016; Maxim & Brown, 2023; Meilinger et al., 2016). Manipulating the “obstacle” variable is difficult in real space but can be well addressed in VR. For instance, some researchers created an “X-ray vision” condition where some buildings became transparent, finding that participants’ wayfinding and direction judgment performance significantly improved under this condition (He et al., 2019b; He et al., 2020). Weather conditions can also be manipulated to change visibility, such as creating visual effects of rain, snow, or fog (Coutrot et al., 2022; Yesiltepe et al., 2023). The principle of “obstacle” effects is to manipulate difficulty by changing visibility. Additionally, direct auxiliary cues can be provided, such as road signs (Farr et al., 2012; Johanson et al., 2023), distal global cues (Peer et al., 2021;

Wolbers & Hegarty, 2010), and maps. The presentation format of maps (Stites et al., 2020) and whether partial occlusion exists (Coutrot et al., 2022) also affect spatial navigation task difficulty. However, too many visual cues may increase participants' cognitive load and have negative effects. For example, Nori et al. (2023) added moving crowds to the same virtual scene and found that participants' spatial anxiety levels significantly increased and spatial navigation performance deteriorated. In Farran et al.'s (2015) study, participants showed no significant difference in spatial navigation performance between cue-rich and cue-sparse environments, suggesting that overly complex scenes are unnecessary to avoid introducing additional interference.

The third category is factors related to spatial layout complexity, such as the number of intersections/decision points (Richter, 2009), number of "dead ends" (Yesiltepe et al., 2023), number of circular roads (Marquardt & Schmiege, 2009; Natapov et al., 2020), average number of options at decision points (also called interconnection density) (Slone et al., 2016), geometric structural features of space (Kimura et al., 2017; Wolbers & Hegarty, 2010), regularity of building arrangement (Barton et al., 2014), and street network entropy (SNE) (Batty et al., 2014; Boeing, 2019; Coutrot et al., 2022). Notably, the impact of spatial layout complexity on spatial navigation performance relates to task type (He et al., 2019c). For route knowledge, which essentially consists of sequences of "stimulus-response" associations, task difficulty is mainly affected by the number of decision points, number of landmarks, and similarity between landmarks. Survey knowledge formation depends on accurate spatial updating and path integration, primarily affected by visibility, variability in road orientation, and regularity of building arrangement. For example, grid-like spatial layouts often facilitate faster survey knowledge formation (Peer et al., 2021).

The above spatial layout factors can be quantified and manipulated using metrics from space syntax (He et al., 2019c; Li & Klippel, 2016; Pagkratidou et al., 2020; Yesiltepe et al., 2023). Space syntax is a set of methods that apply mathematical modeling to social analysis of architectural and urban spaces, now widely used in urban planning, human geography, psychology, tourism, anthropology, and other fields to understand relationships between spatial features and human behavior (Bafna, 2003). Pagkratidou et al. (2020) referenced axial analysis and visibility graph analysis techniques from space syntax, using several metrics to quantify geographic location characteristics of different areas and examine their relationship with spatial memory task performance. Direction judgment results showed that participants made more accurate judgments when asked to point to areas with higher integration, connectivity, and choice values—areas that also had higher visual integration and visual connectivity. This finding has implications for task design, as researchers can use space syntax to calculate characteristic parameters of different areas and adjust task difficulty accordingly. Other studies combining free exploration paradigm process data with space syntax found that in unfamiliar environments, participants preferentially explore areas with higher integration, from which they can more effectively acquire spatial information and form survey representations (Brunec

et al., 2023; Emo et al., 2012).

Beyond manipulating the above three categories of environmental factors, researchers can use VR to create scenarios impossible in the real world, such as impossible loops (Galbraith et al., 2009), compressed buildings (Chan et al., 2023), or activities unachievable in reality, such as instantaneous teleportation between two non-adjacent locations (Murry & Glennerster, 2018; Vass et al., 2016; Warren et al., 2017). These special virtual environment designs are important for understanding the cognitive mechanisms and individual differences in human spatial navigation.

#### 4. Quality Evaluation of VR Assessment Tools

As the compatibility between VR technology and spatial navigation research becomes increasingly prominent, more researchers are using VR as a test medium to adapt classic assessment tasks (Adamo et al., 2012; Commins et al., 2020; Rodgers et al., 2012; Thornberry et al., 2021; Weisberg et al., 2014; Xie et al., 2017) or develop new, simulated spatial navigation assessment scenarios (Colombo et al., 2024; Feng et al., 2022; Ranjbar Pouya et al., 2017; Shi et al., 2021; Ventura et al., 2013). Although this new assessment approach overcomes some limitations of traditional tests, it has also raised concerns in the academic community about the psychometric quality of such assessment tools, directly affecting the interpretation of corresponding research results. Sánchez-Escudero et al. (2024) systematically reviewed the quality of VR- or serious game-based spatial navigation assessment tools published between 2012 and 2023 according to COSMIN guidelines (Mokkink et al., 2018), finding that none of the 37 empirical studies identified reported complete psychometric quality test results. Among them, only 2 studies (5.4%) reported construct validity, using exploratory factor analysis (Bellassen et al., 2012) and confirmatory factor analysis (Allison et al., 2019) to demonstrate the ability structure measured by the tools. Three studies (8.1%) reported internal consistency reliability: Caffò et al. (2018) treated scores from five subtests of the Virtual Reorientation Test (VReoT) as five items, calculating a Cronbach's  $\alpha$  coefficient of 0.79; Allison et al. reported reliability for two versions of a cognitive mapping task in two studies, with  $\alpha = 0.86$  for the first version (Allison et al., 2016), and for the revised version, internal consistency for continuous scores measured by Cronbach's  $\alpha$  ( $\alpha = 0.83$  for the learning phase,  $\alpha = 0.35$  for the recall phase), while internal consistency for dichotomously scored items was calculated using Kuder-Richardson-20 (KR-20) (landmark recognition task KR-20 = 0.87, scene recognition task KR-20 = 0.87, free recall task KR-20 = 0.62). Four studies (10.8%) reported test-retest reliability for five assessment tools, all measured using Intraclass Correlation Coefficient (ICC) (Tarnanas et al., 2015; Allison et al., 2019; Coughlan et al., 2020; Park, 2022). Ten studies (27%) reported criterion-related validity and diagnostic accuracy for 11 assessment tools (Allison et al., 2016, 2019; Bellassen et al., 2012; Caffò et al., 2012; Castegnaro et al., 2022; Coughlan et al., 2019; Da Costa et al., 2022; Laczó et al., 2022; Levine et al., 2020; Park, 2022), with most

reporting area under the ROC curve for continuous scores, and seven studies evaluating test sensitivity and specificity using Youden's index. Nine studies (24.3%) reported convergent validity—correlations between tool assessment results and neuropsychological or neurological measures (Castegnaro et al., 2022; Da Costa et al., 2022; Kunz et al., 2015; Laczó et al., 2022; Lee et al., 2014; Lesk et al., 2014; Morganti et al., 2013; Parizkova et al., 2018; Ritchie et al., 2018). Thirty-two studies (86.5%) reported known-group validity for 29 assessment tools—testing whether tools can effectively distinguish groups known to differ in spatial navigation ability, such as young people, older adults in early symptomatic stages of AD, and late-stage AD patients (Allison et al., 2016; Bayahya et al., 2021; Bellassen et al., 2012; Bierbrauer et al., 2020; Caffò et al., 2012, 2018; Castegnaro et al., 2022; Colmant et al., 2023; Coughlan et al., 2019; Da Costa et al., 2022; Davis & Sikorskii, 2020; Gellersen et al., 2021; Konishi et al., 2018; Kunz et al., 2015; Laczó et al., 2021, 2022; Lesk et al., 2014; Migo et al., 2016; Mohammadi et al., 2018; Morganti et al., 2013; Moussavi et al., 2022; Park, 2022; Parizkova et al., 2018; Pink et al., 2023; Plaza-Rosales et al., 2023; Puthusseryppady et al., 2022; Ritchie et al., 2018; Serino et al., 2015, 2018; Tarnanas et al., 2012, 2015; Zen et al., 2013).

As a new test medium, VR differs substantially from traditional paper-and-pencil tests in terms of interaction methods, data types, variable control, testing scale, user experience, and application scenarios. Given the complexity of VR assessment tools, test developers and users should comprehensively evaluate and control the quality of VR assessment tools across multiple dimensions.

Krohn et al. (2020) proposed the VR quality assessment checklist framework (VR-Check), providing systematic guidelines for paradigm optimization in neuropsychological cognitive assessment research. The framework includes the following ten evaluation dimensions:

1. **Domain Specificity:** The degree to which the VR paradigm actually measures the intended theoretical construct.
2. **Ecological Relevance:** The extent to which the VR assessment task reflects the application of target abilities in daily life, specifically evaluated from three aspects: environment, stimuli, and activities.
3. **Technical Feasibility:** Whether the designed task can be reasonably implemented in VR, whether devices are compatible, whether testing venues have restrictions, and other practical issues.
4. **User Feasibility:** Whether the VR test's interaction methods, task difficulty, testing duration, attentional demands, and dizziness levels are acceptable for the target population.
5. **User Motivation:** Evaluation based on factors that may promote user engagement, such as fun, reward-punishment mechanisms, and test face validity.
6. **Task Adaptability:** Whether it is easy to develop parallel versions of the test and whether task difficulty is easy to adjust.
7. **Performance Quantification:** VR can track and record user behavior

with high resolution in time and space, so whether user performance can be automatically measured is an important evaluation dimension.

8. **Immersive Capacities:** Assessed from two perspectives: (a) objective technical attributes of the VR system, and (b) users' subjective experience of "presence" brought by the virtual environment.
9. **Training Feasibility:** Whether VR tests can be repeatedly applied as training tools beyond their diagnostic function.
10. **Predictable Pitfalls:** Whether potential pitfalls in VR test design and development have been anticipated and avoided, and whether resource consumption and potential knowledge gains have been reasonably balanced.

Compared to psychometric test quality evaluation standards, the first two items of the VR-Check framework similarly emphasize the importance of construct validity and ecological validity, but do not address test reliability. In Sánchez-Escudero et al.'s (2024) review, only 8.1% of empirical studies reported reliability analysis results for VR assessment tools, and almost none reached the reliability levels of paper-and-pencil tests. In spatial navigation VR tests involving scene interaction, certain learning time is typically required. With limited testing duration, large numbers of items often cannot be administered, which may be one of the main reasons for insufficient reliability estimation precision of such tools.

The outstanding contribution of the VR-Check framework lies in defining the optimal model for VR assessment tools from multiple dimensions. However, current and even future VR tests may struggle to simultaneously meet all evaluation criteria. In practical applications, VR-Check is more suitable as a guiding framework for different stages of test development. Researchers are advised to check each item during the initial design phase to determine which items are more important for current assessment goals and whether trade-offs between different items are needed. For example, pursuing immersive, high-fidelity virtual environments can easily introduce variables unrelated to measurement goals, potentially affecting variable control and reliability/validity of assessment tasks.

Most existing spatial ability tests have been developed for specific application needs such as personnel selection or disease screening, lacking sufficient description of theoretical frameworks and ability definitions, complete psychometric quality testing (Newcombe et al., 2023; Sánchez-Escudero et al., 2024), specific scoring methods and norm explanations, or even public availability. These issues limit effective academic exchange and application. Uttal et al. (2024) noted that systematic organization and review of existing spatial thinking-related tests is currently necessary. This study focuses on large-scale cognitive abilities within spatial thinking—spatial navigation ability—and discusses a series of key issues in designing VR tests for spatial navigation ability.

Using VR as a test medium represents an important manifestation of the trend toward intelligent assessment. Through VR technology, spatial navigation activities under arbitrary scenarios and environmental conditions can be simulated within limited physical space, greatly enhancing scenario expandability

while ensuring test control and standardization. Future research needs to further overcome a series of challenges in this field. First are issues under current technological conditions: low frame rates and long interaction delays can easily cause cybersickness or motion sickness, limiting participants' ability performance, with the magnitude of this effect varying among individuals (Chang et al., 2020); individual differences in video game experience lead to different familiarity with tasks and interaction operations, interfering with test results (Murias et al., 2016); using new interaction devices often requires learning costs and involves many uncertainties. Researchers should actively take measures to address these issues, such as providing sufficient practice opportunities before formal testing; collecting relevant individual difference information for statistical control, such as motion sickness susceptibility; and simplifying task interaction rules as much as possible to reduce additional cognitive load. Second, future VR tests may usher in technology-driven transformations, such as integrating multimodal data like eye-tracking, EEG, and biofeedback for precise assessment of spatial navigation ability with mutually corroborating multimodal indicators. Finally, researchers should pay attention to the open-source nature of tools and data, allowing assessment tools to be reused, adapted, expanded, and quality-reviewed by different researchers, and continuously monitor new technological developments to verify and update research findings in a timely manner.

The characteristics and mechanisms of human-VR interaction are interdisciplinary topics spanning psychology and artificial intelligence. Related technical devices are constantly evolving at a rapid pace, and people's familiarity with VR is gradually increasing, presenting both opportunities and challenges. Future collaboration among more researchers in related fields is needed to integrate continuously developing VR technology into the development of spatial navigation ability tests, help reveal the cognitive mechanisms of spatial navigation, achieve more precise and efficient ability assessment, and continuously expand the application scenarios of VR technology in psychological research.

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