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Map-based navigation: Individual differences in perspective taking and path integration☆

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ABSTRACT

Spatial navigation is an everyday activity that necessitates multiple cognitive processes, including map reading, perspective taking, and path integration (tracking position and orientation during self-motion). These processes must work in concert to enable individuals to orient themselves and locomote to goal locations, but it remains unclear whether proficiency in one type of spatial processing necessarily implies proficiency in other forms of spatial processing during navigation. Here, we study the processes of transforming a map-indicated viewpoint to locate and move to surrounding invisible targets in a simple open arena. Participants (n = 210) performed a novel immersive Viewpoint Transformation Task (iVTT, He et al., 2022), a map-based navigation task in a virtual environment in which people first viewed a map of an environment from a top-down perspective, then physically walked to a goal location (specified on the map) in an immersive virtual environment, using a first-person perspective. We examined the effects of spatial perspective taking (using the Spatial Orientation and Money Roadmap Tasks) and path integration (using the Triangle Completion Task) on individual differences in task performance. In a regression analysis, a measure of perspective taking and a measure of path integration independently predicted iVTT performance. Notably a small number of participants (5%) exhibited difficulty with the initial perspective taking step. Our results suggest that both the ability to assume a different perspective to plan movement and the use of path integration to update one's position while executing the movement contribute to effectively utilizing map-based information during navigation.

1. Introduction

Spatial navigation requires multiple cognitive processes working in concert to enable individuals to orient themselves in different environments (McNaughton et al., 2006; Wolbers and Hegarty, 2010; Chrastil, 2013). For example, when individuals need to relate information from a map to their surroundings to walk to a target location, in consulting a you-are-here map (Levine, 1982; Levine et al., 1984) or a GPS navigation device (He et al., 2022), the information presented on the map may be displayed in a direction different from their current physical orientation. Then, individuals need to track their movements while they walk, to judge whether they have reached the targets indicated on the map. Here, we define map-based navigation as the ability to mentally transform a plan view acquired from a map into a first-person view, and use that to guide locomotion to a goal location.

Spatial perspective taking involves the mental transformation from one's physical viewpoint to another (e.g., imagine you are facing the wall behind you without physically turning around). Perspective taking plays a critical role in understanding others' navigational directions or planning routes from maps that are misaligned with one's current view of the environment (Kozhevnikov and Hegarty, 2001; Hegarty and Waller, 2004). *Path integration* is the ability to update one's position and orientation in an environment during movement, which can be used to encode distances and location but can also be used to execute a trajectory to a goal (Loomis et al., 2002; Chrastil and Warren, 2017, 2021). Thus, both perspective taking and path integration are important for

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successful map-based navigation, but little is known about how these two abilities interact in response to spatial task demands.

In this study, we measured map-based navigation ability using the immersive Viewpoint Transformation Task (iVTT), a task which measures this ability in an ambulatory virtual environment (He et al., 2022). While map-based navigation often occurs in complex environments, He et al. (2022) developed this task as the simplest case of map-based navigation to isolate the perspective taking and path integration aspects of this form of navigation (analogous to using a list of words to study episodic memory). Our research addresses unanswered questions from He et al.'s original paper, notably regarding the relative contributions of spatial perspective taking ability and path integration ability to map-based navigation ability. Furthermore, it proposes a new, efficient psychometric measure based on He et al.'s (2022) experimental iVTT that can be used to test for individual differences in map-based navigation.

1.1. Measures of spatial perspective taking and its relation to navigation

People often have to take different perspectives to understand or integrate spatial information from various sources, including reading a you-are-here map or GPS navigation device, understanding route directions from others, and recollecting previous navigation experiences. Research in spatial cognition has identified spatial perspective taking ability as a critical component of navigation ability by showing its associations with different aspects of navigation. For example, it is correlated with self-reported sense of direction in daily life (Hegarty et al., 2002; Hegarty and Waller, 2004) and has been found to mediate the relationship between small-scale spatial abilities (e.g., mental rotation) and navigation skills, (Allen et al., 1996; Ruginski et al., 2019). In the brain, shifting between top-down and first-person perspectives is thought to rely on the retrosplenial cortex (Byrne et al., 2007), although less is known about this process in humans than in animals (Alexander et al., 2023).

To assess this skill, two established tasks are frequently employed: the Spatial Orientation Task (SOT; Fig. 1(a); Kozhevnikov and Hegarty, 2001; Hegarty and Waller, 2004; Friedman et al., 2020) and the Roadmap Task (MRM; Fig. 1(b); Money et al., 1965, modified by Zacks et al., 2000). Brucato et al. (2023) compared four computerized spatial perspective taking tasks including the SOT. Based on systematic psychometric analyses, the SOT was shown to be a reliable and valid measure of perspective taking ability, demonstrating good internal consistency and construct saturation. Previous studies have shown that the correlation between the SOT and Roadmap tasks is approximately 0.3 - 0.5 (Friedman et al., 2020; Hegarty and Waller, 2004), suggesting they measure a common underlying construct, namely spatial perspective taking ability. However, these two tasks only ask participants to estimate directions without taking actions in physical spaces. To navigate proficiently from map-based information or imagined perspectives, people must estimate not only the direction but also the distance to a target. Then they need to turn their body and move (i.e., walk) to the target based on these estimations. Locomoting to a target based on estimated directions and distances could reflect people's perspective taking ability differently than asking people to draw directions using an arrow in a circle or to select left or right on paper. Moreover, another spatial process, path integration, may be necessary for accurate task performance.

1.2. Measures of path integration ability and its relation to navigation

Path integration is a critical navigational ability that involves continuously updating one's position in the absence of external visual landmarks. This process relies on the vestibular system and proprioception (i.e., self-motion or body-based sensing), in addition to visual optic flow to execute a path to a goal location (Loomis et al., 1993; Chrastil, 2013). For example, in the Triangle Completion task (TCT; see Fig. 2(a)–(b)), participants are led on paths defining two sides of a triangle in an immersive virtual environment and are tested on how accurately they can locomote to complete the triangle (Loomis et al., 1993). Path integration is theorized to rely on the specialized cell types in the brain that relate to these self-motion processes. Head direction cells in retrosplenial cortex, thalamus, and entorhinal cortex track a navigator's orientation in the environment (Chen et al., 1994; Cho and Sharp, 2001; Taube, 1995), whereas grid cells in entorhinal cortex track metric distances and directions (Fyhn et al., 2004; Hafting et al., 2005). In humans, fMRI investigations of grid cell-like signals have focused on the angular properties of grid cells (i.e. hexadirectional codes; Doeller et al., 2010). Together this information can help define place cells in the hippocampus, which respond to particular locations in the environment (O'Keefe and Dostrovsky, 1971).

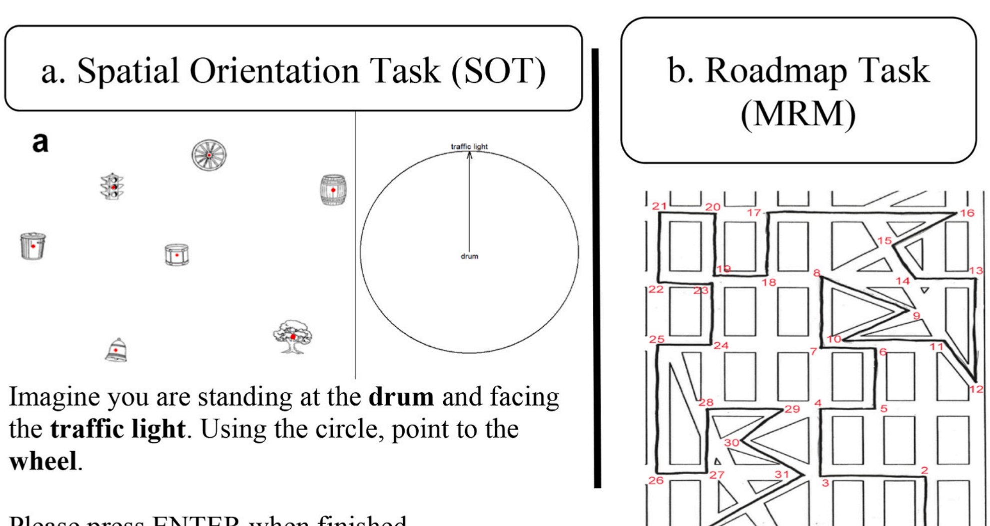

Fig. 1. Computerized spatial perspective taking tasks. (a) A sample question from the Spatial Orientation Test (SOT). Participants view a layout of objects on a screen. They are asked to imagine standing at one object and point to a second object while facing a third object (Friedman et al., 2020; Hegarty and Waller, 2004). Angular error is the angular difference between the marked angle and the correct angle to the target. (b) The Money Roadmap Task (MRM): Participants are shown a travel path on a map of a town. From a consistent overhead viewpoint, they indicate whether each successive turn is to the left or right, starting at the red dot in the lower right corner (Money et al., 1965; Zacks et al., 2000). Score is the total number of correct turns marked in 20 s.

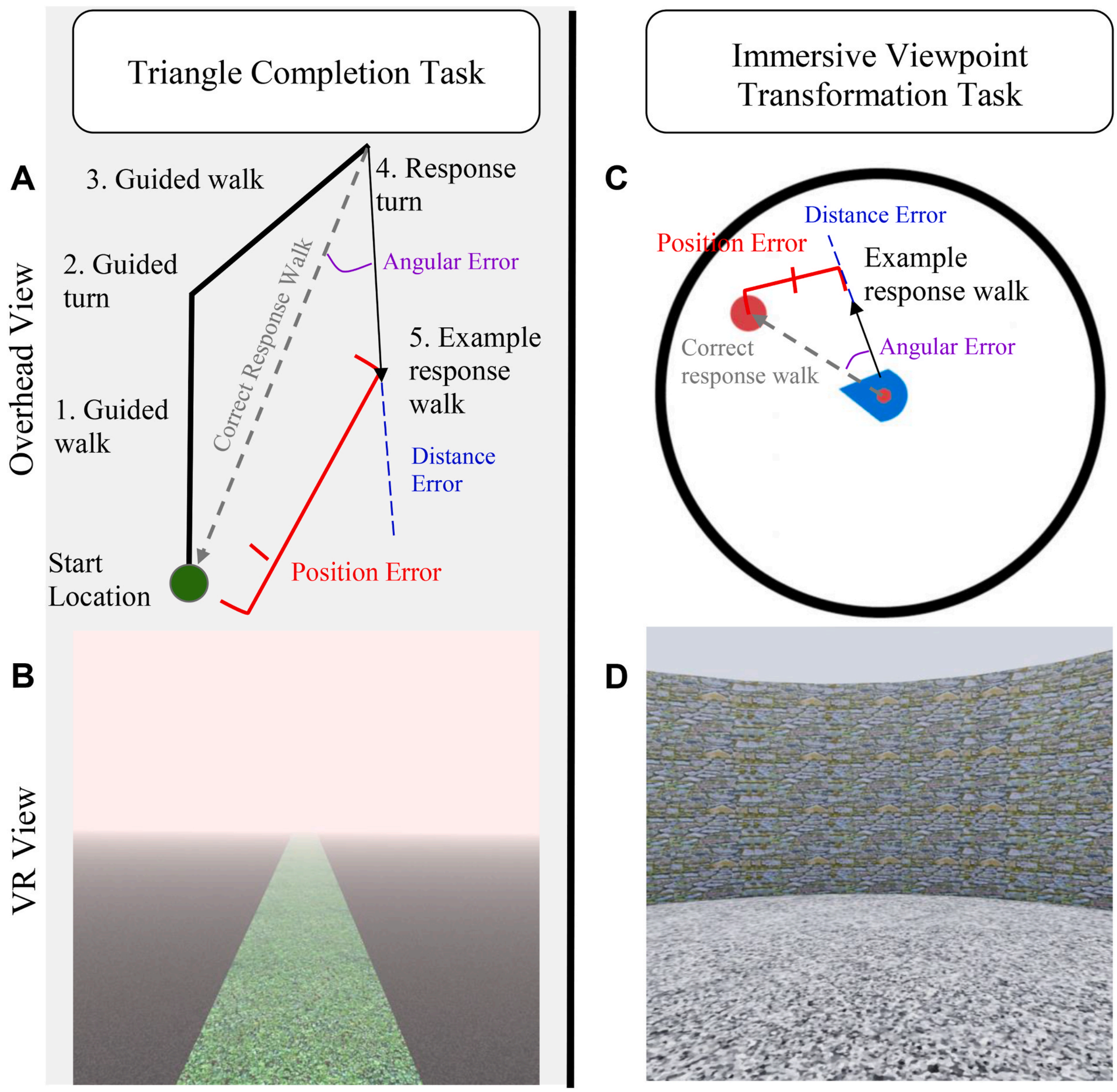

Fig. 2. Virtual Reality tasks. (a) A sample trial from the Triangle Completion task (TCT), which probes path integration accuracy. Participants first follow a preliminary guided path, then a guided turn, and finally a secondary guided path before being asked to turn and then walk to their start location (Loomis et al., 1993). Position error is the straight-line distance between where they ended and the actual start location of the triangle. (b) The virtual environment is a featureless desert with guided paths and turns shown on the ground. (c) A sample trial for the Immersive Viewpoint Transformation Task (iVTT). Participants are shown a map for 2 s, indicating the location and orientation of the participant at the start of the trial, and the location of their goal. Then the participant is returned to the first-person view at the center of the arena. They must then turn and walk to where they think the goal is located, and click the trigger of the handheld controller when they believe they have reached the target (d) The first-person view of the arena, including the boundary wall, that participants see during the response phase. (He et al., 2022).

Ample studies have highlighted the role of path integration in navigation ability (e.g., Campos et al., 2014; Chance et al., 1998; Grant and Magee, 1998; Loomis et al., 2002; Waller et al., 2002) and suggested a close connection between perspective taking and path integration (Gunalp, 2021; McNaughton et al., 2006; Ruginski et al., 2019). However, this connection has not been directly assessed because common measures of perspective taking in the literature do not involve physical locomotion. Further, executing a trajectory is susceptible to errors (Chrastil and Warren, 2017), suggesting that path integration could contribute to locomotion errors in reaching a target after viewing a map.

1.3. The immersive Viewpoint Transformation Task

The Immersive Viewpoint Transformation Task (iVTT), introduced by He et al. (2022), involves both perspective taking and locomotion to a map-specified target. This task is designed as the simplest measure of how individuals incorporate both perspective taking and path integration in daily map-based navigation. In the iVTT, participants initially view a 2D top-down map of a circular arena, devoid of landmarks (Fig. 2 (c)). This map displays a pointer and a target location. Participants are asked to imagine facing the direction indicated by the pointer and to encode the target location. After 2 s, the map disappears, and participants are then immersed in the virtual circular arena in which the wall is visible but the target is invisible (Fig. 2(d)). Participants are asked to turn in space and physically walk to the target location with the walls of the arena still visible as they walk (He et al., 2022). This task captures an ecologically valid process used during daily map-based navigation, where individuals rely on map information to guide their movement , albeit in a simple open environment. Such a transformation of map information to real-world navigation has been extensively explored in previous research on individual differences in learning the layout of environments from maps versus other learning media (e.g., videos, text, etc.) (e.g., Ai et al., 2023; Fehringer et al., 2025; Malanchini et al., 2020; Pazzaglia and Taylor, 2007; Richardson et al., 1999; Starrett et al., 2019). However, these studies often concentrate on the learning and wayfinding aspects of this task without separately examining the process of transforming from a map view to action and are typically conducted in desktop virtual environments, which do not provide body-based cues (e.g., proprioceptive, vestibular, etc.) that contribute to spatial updating in real world navigation.

He et al. (2022) systematically varied task parameters in the iVTT such as the size of the angle to be turned and the distance to be traveled. They also administered an extended version of the SOT with more trials with varied angles, and conducted a direct comparison of these different performance measures with angular error for the same angles on the Spatial Orientation Task (SOT) at the trial level, revealing a significant correlation between participants' angular error on the iVTT and angular error on the SOT ($r = 0.69$). Participants reported employing embodied strategies in both tasks, specifically using their body axes as anchors to facilitate direction estimation. These results suggested that the two tasks rely on common perspective taking abilities.

In contrast, the correlation between angular error in the SOT and distance error in the iVTT was small and non-significant ($r = 0.12$) suggesting that these errors stem from distinct cognitive processes. Although angular error and distance error in the iVTT were somewhat correlated, suggesting that they share common variance, the authors speculated that distance error in the iVTT also reflected a path integration ability that is distinct from perspective taking ability, as measured by the SOT. However, He and colleagues did not include an independent measure of path integration ability in their study. The present study aimed to determine whether perspective taking, as measured by the SOT, and path integration ability, as measured by the triangle completion task, independently predict performance on the iVTT. Further, it is not clear whether there are dissociable behavioral readouts of head-direction cells (e.g., angular estimation) or grid cells (e.g. distance estimation). By modeling the distinct contributions of perspective taking and path integration tasks, this work is well-suited to inform future studies of the neural mechanisms supporting these two processes.

Another novel contribution of the present study was to develop an efficient, reliable and valid measure of individual differences in map-based navigation, as measured by the iVTT task. Three changes were made to revise this individual-differences measure. First, the original study of the iVTT (He et al., 2022) included 48 trials, some of which involved a travel direction close to the four body axes (0°, 90°, 180°, and 270°). In such trials, participants tended to depend on these axes, leading to more homogenous behavior (less variance) across participants, so these trials did not discriminate between more and less able individuals. The present study omitted these trials. Second, we selected only trials involving a perspective shift of at least 90°, as trials with smaller perspective shifts have been found to be solved by mental rotation (i.e., imagining the map rotating) rather than perspective taking (imagining turning one's body to the direction to be assumed) (Hegarty and Waller, 2004) and perspective shifts of at least 90° tend to be the most difficult for participants (Gunalp et al., 2021; Kozhevnikov and Hegarty, 2001). Third, trials involving large travel distances were adjusted to be further from the boundary walls, reducing the use of boundaries as definite anchors. These changes produced a measure of individual differences that included a subset of 24 trials from He et al.'s (2022) original 48 trials and was intended to be a more valid measure of processes unique to map-based navigation (rather than other processes such as mental rotation or referencing boundaries).

1.4. Strategy usage

A final goal of the present study was to explore strategy differences in the iVTT. While most other studies only examine error patterns to infer strategy differences, our analysis also included self-report data, signed errors (undershooting vs. overshooting the target location), and movement trajectories for granular analysis. We examined participants' self-reports of the strategies they used to complete the tasks (which had not been collected by He et al. (2022)). We also analyzed participant's movement trajectories in the iVTT, which can also inform strategy, e.g., whether people first turn and walk in a straight line, or walk a curved path to the correct location. Additionally, the iVTT targets both perspective taking and path integration. Thus, the present study is the first to consider strategy use in a task involving both abilities.

1.5. The present study

In the present study, we compared individual differences measured by the Immersive Viewpoint Transformation Task (iVTT), Spatial Orientation Task (SOT), Roadmap Task (MRM), and Triangle Completion task (TCT). In preregistrated analyses (https://osf.io/x4mf7) we examined overall correlations between these tasks to investigate whether they capture individual differences on the same dimension or different dimensions.

H1. We predicted that SOT absolute angular error and MRM performance (total number of correct turns) would correlate with iVTT position error and angular error because all of these are measures of perspective taking.

H2. We predicted that angular, distance, and position error in the TCT would correlate with their respective errors in the iVTT because they both involve path integration.

H3. We predicted that in a regression analysis, a measure of perspective taking (absolute angular error in the SOT) and a measure of path integration (position error in the TCT) would be independent predictors of position error in iVTT.

Lastly, we explored how strategy contributes to individual differences in the iVTT. Measures of strategy included strategy reports, measures of undershooting and overshooting the target, and directness of the path taken. We treated strategy as exploratory factors.

2. Method

This study is part of a comprehensive investigation of individual differences in human navigation ability in which over 40 navigation and cognitive tasks are used to measure human variability in navigation performance and skills. Participants completed the larger study in 5-6 sessions over the course of 1-4 weeks, for a total of 10-12 h of testing. For the present study, we selected one questionnaire, two immersive environment tasks, and two desktop-based tasks to measure the relationship between perspective taking, path integration and map-based navigation ability.

2.1. Participants

A total of 279 participants (age: 17 - 35) were recruited from the University of California, Irvine and University of California, Santa Barbara communities to participate in the larger study. Of these, 211 completed all of the measures of interest in this study. Participants were excluded if they completed less than 75% of trials on any given task. Data from one participant was excluded because they did not appear to understand the directions of the iVTT correctly, leaving 210 (Female: 122, Male: 88, $M_{Age} = 21.20$, SD = 3.25) in our analyses.

A series of *a priori* power analyses was conducted to estimate the required sample sizes for both the correlational analysis (H1, H2) and the main regression analysis (H3) (Faul et al., 2007). We examined the correlations among nine measures (iVTT: position error, absolute angular error, absolute distance error, iVTT combined z-score; SOT absolute angular error; MRM total number of correct turns; TCT position error, angular error, distance error) and conducted a regression analysis with two main predictors (perspective-taking and path integration ability). Given that multiple comparisons were involved in the correlational analysis, we applied the Bonferroni correction to control for Type I error. For 36 pairwise comparisons, the adjusted alpha level is 0.0014. The analysis[1] indicated that at least 174 participants were needed to detect a correlation as small as 0.3 with a power of 80% at this adjusted alpha level. This meant that for the regression analysis, a sample of 174 participants should allow us to detect an effect size as small as $f^2 = 0.038$ (small to medium; Cohen, 1988) for each of the two main predictors with 80% power at an alpha level of 0.05. Thus, with a sample size of at least 210 participants, we exceeded the power needed to test our hypotheses.

2.2. Displays and equipment

2.2.1. Immersive virtual reality (VR) systems

Experimental sessions utilizing immersive VR took place either at the Center for Ambulatory Virtual Environment Research in Navigation (CAVERN) on the University of California, Irvine campus or at the Research Center for Virtual Environments and Behavior (ReCVEB) on the University of California, Santa Barbara campus. Virtual Environments (VEs) were built to fit in both CAVERN and ReCVEB, yielding a maximum of 7 m × 7 m size environments. At both sites, experiments were displayed using an HTC VIVE Pro Eye VR head-mounted display (HMD) with Dual OLED 3.5" diagonal display (1440 × 1600 pixels per eye or 2880 × 1600 pixels combined), a 90 Hz refresh rate, and a 110° field of view capable of delivering high-resolution audio through removable headphones. In addition to the HMD, the VR interface included a HTC VIVE wireless handheld controller for interacting with the experiment and four HTC Base Station 2.0 infrared tracking sensors for large-scale open space tracking. Each system was equipped with wireless room tracking via a 60 GHz WiGig VIVE Wireless adapter. Both the UC Irvine and UC Santa Barbara VR systems were run on an HP OMEN 30L GT13-1365xt desktop computer powered by an eight-core, 3.60 GHz Intel core i7 11700K central processing unit (CPU), an NVIDIA GeForce RTX 3080 Ti graphics processing unit (GPU) with 12 GB of dedicated memory, and 32 GB of system memory.

VEs were built and rendered in Unity; tasks were programmed in Unity using custom scripts and scripts modified from the Landmarks Unity package (Starrett et al., 2021). Specifics of each environment are described with each navigation task. These VEs provided complexity and ecological validity, as well as vestibular and proprioceptive information while maintaining experimental control over the navigational factors of interest.

2.2.2. Desktop-based tasks

Desktop-based tasks and the post-task surveys were displayed on desktops. On the University of California, Irvine campus, desktop experiments were displayed on a 23-inch Acer G6 Series monitor with 1920 × 1080 resolution at a 60 Hz refresh rate. The Acer Predator Orion 5000 610 rgb desktop computer is powered by a 3.60 GHz Intel Core i7-9700K central processing unit, an Nvidia GeForce RTX 2070 graphics card with 8 GB of dedicated memory, and 16 GB of system memory. On the University of California, Santa Barbara campus, these desktop tasks were displayed on a 24-inch Dell Professional P2412HB LED monitor with 1920 × 1080 resolution at a 60 Hz refresh rate. The Dell OptiPlex 7070 desktop computer is powered by a 3.00 GHz Intel Core i7-9700 central processing unit, an AMD Radeon RX 550 graphics processing unit, and 16 GB of system memory.

2.3. Experimental tasks

2.3.1. Immersive Viewpoint Transformation Task (iVTT)

The iVTT (He et al., 2022) is an immersive VR map-based navigation test. The ambulatory VE for this task was a virtual desert with a circular walled arena. Each trial included a map presentation (see Fig. 2(c)) and a navigation phase (see Fig. 2(d)). First, the participant was shown a map for 2 s, indicating the location and orientation of the participant at the start of the trial, and the location of their goal. Then, during the navigation phase, the participant was returned to the first-person view at the center of the arena (see Fig. 2(d)), which showed the boundary of the arena but no landmarks. They then turned and walked to where they thought the goal was located, and clicked the trigger of the handheld controller when they thought they had reached the target. Critically, the heading orientation of the participant on the map was never aligned with the actual facing direction of the participant. In order to successfully reach the goal, the participant must transform the perspective from an overhead viewpoint to a first-person viewpoint, update their heading with respect to the orientation in the map, infer the distance to be walked by scaling the map to the perceived size of the arena, and walk to the target location. See Table 1 for an informal task analysis of this and other tasks.

There were 24 trials in total, each varying along three main trial attributes: Perspective Shift, Travel Direction, and Travel Distance (Fig. 4(d)). Perspective Shift is the divergence of the imagined heading from the vertical direction, ranging from 90° to 180°, counterbalanced between right and left sides. Travel Direction is the direction of travel to the target, after the perspective shift has taken place. This ranges from 0° to 180°, counterbalanced between right and left. Travel Distance is the distance between the starting location and the target, ranging between 1.5 and 2.5 m. These attributes were not specifically tested here (see He et al., 2022), but the specific ranges of perspective shifts and travel direction were chosen to maximize trial difficulty and the ability to discriminate between individuals with more and less ability. Five practice trials were given; the first two included feedback on the location of the target (no feedback was given during the main task) and allowed participants the chance to calibrate their movements to the scale of the room. Participants were given unlimited time to complete the test trials.

Outcome measures for each participant were averaged across trials. Measures of performance include position error, absolute angular error, and absolute distance error. Position error - the main performance measure - was measured as the distance from the estimated location to the target's actual location. Absolute angular error and absolute distance error (see Fig. 2(a)) were used to parse out the influence of perspective-taking ability and path integration. Absolute angular error - ranging from 0° (best) to 180° (worst) - measured the angular disparity between the direction in which participants moved and the correct direction. Absolute distance error measured the disparity between how far from the origin the participant moved and the correct distance from the origin. We averaged the z-scores of the absolute angular and absolute distance error to create *iVTT combined z-score*, which we examined along with position error as measures of overall iVTT performance. Lower combined z-score and position error from the iVTT indicate better perspective taking ability.

Additional measures (signed angular error, signed distance error, and trajectory directness) were explored to examine possible strategy differences in performance. Signed angular error had a possible range from −180° to 180° with values further from 0° indicating bias. A positive value indicated that the participant overestimated the target direction, while a negative value indicated an underestimation. Signed distance error measured bias, with a positive value representing overshooting the target and a negative value representing undershooting. Trajectory directness measures how far a participant meanders from the

[1] Power analysis was performed prior to data analysis. See preregistration: https://osf.io/x4mf7.

Table 1
Task analysis for Immersive Viewpoint Transformation task (iVTT), Spatial Orientation Task (SOT) and Triangle Completion Task. Processes common to two of the tasks are in bold and italics.

	iVTT	SOT	TCT
Mental Processes	Encode the perspective indicated by the blue pointer ***Shift perspective and mentally represent the direction to the target object from that perspective*** ***Mentally represent the direction and distance to the target object***	Encode the perspective to be imagined based on the starting object and the facing object ***Shift perspective and mentally represent the direction to the target object from that perspective***	Update position and orientation while being led on two sides of a triangle ***Mentally represent the direction and distance to the start location***
Physical Processes	***Physically turn and walk to the mentally represented target location***	Rotate arrow on an arrow circle to indicate mentally represented angle	***Physically turn and walk to the mentally represented start location***

direct line between the origin and their estimated location and was calculated by drawing a straight line from the origin to the participant's estimated location and measuring the average perpendicular distance from this line to the participant's trajectory.

2.3.2. Spatial Orientation test (SOT)

Participants were given the computerized version of the SOT created by Friedman et al. (2020) based on the original Spatial Orientation test (see Fig. 1(a); Kozhevnikov and Hegarty, 2001; Hegarty and Waller, 2004). In this test of perspective taking, participants viewed a layout of objects on a screen. They were asked to imagine standing at one object and to point to a second object while facing a third object (See Table 1 for an informal task analysis). The imagined facing direction differs from their actual direction, measuring spatial perspective taking ability. Three practice trials were given, and participants were allowed 5 min to complete 12 test trials. The outcome measure is the absolute angular error - ranging from 0° (best) to 180° (worst). Absolute angular error was averaged across trials for each participant, and lower values indicated better perspective taking ability (Hegarty and Waller, 2004; Friedman et al., 2020). It was measured as the disparity between the participant's estimated angle and the correct angle.

2.3.3. Money Roadmap test (MRM)

In this test of perspective taking, participants were shown a travel path on a map of a town (see Fig. 1(b); adapted as a computerized version from Zacks et al.,'s (2000) modified version of the original task developed by Money et al., 1965). Without turning the map or their head, they indicated whether each turn is to the left or right. There were 32 turns in the route, and the participants had 20 s to respond. The outcome measure is the total number of correct turns - with a possible maximum of 32.

2.3.4. Triangle completion task (TCT)

The Triangle Completion Task tests path integration ability (see Fig. 2(a)–(b); adapted as a virtual version from Loomis et al.'s (1993) seminal version of the task). In the task, participants follow two legs of an outbound path, and then must turn and walk directly back to the home location (see Table 1 for an informal task analysis). First, they walk forward on the long fog-covered path until a sound cue tells them to stop. They then turn in place on a circular area (radius 2 m) as directed by a sound cue, and a new path appears. They then walk forward on this second path until they are told to stop. They must then turn in place at the center of another circular area, also with a radius of 2 m but with a distinctly darker hue compared to the first circular area (to indicate it is the response portion), until they think they are facing the start location, at which point they click the trigger once. A new 50 m fog-covered path, with the same distinct hue, appears in the same direction they are facing, and they walk forward on this new path until they think they have reached the start location, at which point they click the trigger a second time. Footprints then appear, marking the location of the next trial. We used five triangle types, with leg lengths ranging from 2 m to 5 m and internal turn angles between 30° and 120°, including right, scalene, acute, obtuse, and equilateral triangles. There were six repeats of each triangle type (three left turning triangles, three right turning triangles, combined for analysis) for a total of 30 trials, with varying starting locations in the room to prevent external cues from providing information about the start location. Triangle types were presented in a random order, with left and right turns alternating. Trials were excluded if participants turned in the wrong direction (indicating misunderstanding or inattention), experienced interruptions or confusion, bumped into a wall, or encountered a glitch during the angle estimation turn. Participants were given four practice trials without feedback to get used to the task.

Following trial-level exclusions, outcome measures for each participant were averaged across the remaining valid trials. These measures include absolute angular error, absolute distance error, and position error. Absolute angular error - ranging from 0° (best) to 180° (worst) - measures the angular disparity between the direction in which participants turned to face the starting location and the correct direction. Absolute distance error measures the disparity between how far the participant walked on the triangle's final leg and the true length of the triangle's final leg. Position error is measured as the straight-line distance between the endpoint and the home location. Lower error values indicate better path integration ability.

2.3.5. Post-VR experience survey

After completing the immersive VR tasks (iVTT and TCT), participants were asked about the difficulty of the task and any strategies they used. They were also asked their experience with the immersive environment, including usability and motion sickness.

2.4. Procedure

Participants were tested over five sessions, which included many other tasks in addition to the ones described here, each lasting approximately 2 h. The time between each session ranged between one day and two weeks, with the entire experiment completed within one month. At the start of the first session, participants were given information about the study. Once they provided their informed consent, experimenters began with an introduction to the immersive VR equipment. Each of the five sessions started in CAVERN or ReCVEB with a calibration session in immersive VR and one or two immersive VR tasks. Before each immersive VR task, participants sat at a desktop computer and read the task instructions from a slide deck. After answering any questions, the experimenters helped them don the HMD, calibrated it for the distance between the participant's pupils, handed them the controllers, and read the task instructions. In between immersive VR tasks, participants completed questionnaires about the VR experience on a desktop computer, which allowed them to take a short break from immersive VR. Participants were in immersive VR for less than an hour total per session.

All participants completed all tasks in the same set order. Thus, any order effects or influence of one task upon another would apply relatively equally to all participants. We attempted to put tasks in an order that would minimize any interference between tasks. The MRM was conducted in Session 2, the SOT and TCT in Session 3, and the iVTT in Session 4.

2.5. Analysis

The hypotheses and analysis plan were pre-registered on Open Science Framework prior to the analysis (https://osf.io/x4mf7). We first examined the psychometric properties of the measures of individual differences to determine whether they demonstrated adequate distinguishing power and internal reliability (Munns et al., 2023; Newcombe et al., 2023). These properties are foundational for further correlational and regression analyses. Specifically, we computed split-half reliability to evaluate internal consistency of the measures, and we examined the measures for normality. Extreme values were winsorized to three standard deviations of the mean. We opted to not transform the data (as stated in the preregistration) but instead use Spearman correlations rather than Pearson correlations, because these do not assume normality.

We then conducted correlational analyses to assess hypothesized pairwise correlations among the perspective taking measures, the triangle completion measures, and the viewpoint transformation measures, to test Hypotheses 1 and 2. This analysis aimed to provide insights into the strength and direction of associations for further analyses below. In addition, we assessed iVTT position error, iVTT combined z-score (average of the z scores for absolute angular error and absolute distance error), and the relationship between them to determine the best single measure of iVTT performance to be used in our regression analysis.

To test Hypothesis 3, a linear regression analysis[2] was performed with the average position error of iVTT as the dependent variable. The predictors were a measure of perspective taking (SOT angular error) and path integration ability (TCT position error). This analysis aimed to determine how much variance each ability contributed to the overall performance in iVTT.

Finally, we explored individual differences in strategy use in the iVTT based on self-reports, movement trajectory, systematic behavior bias, and task features to examine how strategy use contributes to task performance.[3]

3. Results

3.1. Descriptive statistics

Descriptive statistics and reliabilities are reported in Table 2. All measures of the iVTT showed good internal consistency (Spearman-Brown split-half reliabilities between 0.896 and 0.969), and all items showed good distinguishing power. The distributions of the iVTT measures suggested that there were some outliers, so all measures were winsorized, that is, outliers were set to three standard deviations above or below the measure's mean (Dixon, 1960).

3.2. Correlations

We predicted that SOT absolute angular error and MRM performance would correlate with iVTT position error and angular error because all of these are measures of perspective taking (Hypothesis 1). Spearman's rank correlations[4] between the measures and the results of significance testing are presented in Table 3. Note that all measures were error measures, except for the Roadmap task, which measured the total number of correct turns. Therefore, negative correlations between the Roadmap task and the other variables are expected.

As predicted, measures of perspective taking were correlated with iVTT angular and position errors (Table 2). Specifically, SOT angular error had medium-sized correlations with iVTT angular error ($\rho = 0.35$) and iVTT position error ($\rho = 0.39$). Roadmap performance had medium-sized correlations with iVTT angular error ($\rho = -0.37$) and iVTT position error ($\rho = -0.42$). This supports our first hypothesis and suggests that these scales all measure a common ability, namely perspective taking. Because the SOT more closely measures the perspective aspects of the iVTT (translating from a top-down to an in-person view and adopting a different perspective within that view), we used SOT angular error as our measure of perspective taking in subsequent analyses.

Next, we predicted that our measures of iVTT performance (angular error, distance error and position error) would correlate with the corresponding measures for the TCT. Consistent with Hypothesis 2, iVTT angular error had small, but significant, correlations with TCT angular error ($\rho = 0.28$), iVTT distance error had a small correlation with TCT distance error ($\rho = 0.26$), and iVTT position error had a small correlation with TCT position error ($\rho = 0.24$). These results support the view that processes of updating angle, distance, and consequently position, are shared across the two tasks. In addition to finding shared variance in these measures, we also found that the correlation between iVTT absolute angular error and TCT absolute distance error did not survive Bonferroni correction. This result supports the view that there is variance in the angular measures that is not shared with the distance measures of these tasks.

3.2.1. Measure of performance on the iVTT

Correlations between position error, angular error, distance error and average z scores of these measures are shown in Table 2 and were compared based on a Fisher's r-to-z transformation on the correlations and a two-tailed *z*-test. Although position error is strongly correlated with both angular and distance error, it is significantly more correlated with angular error ($z = 5.07$, $p < .01$, Fisher's r-to-z test). This suggests that error in a participant's turn contributes more to position error than error in how far they walk. The combined z-score, which weighs these variables equally, does not reflect this. As a result, we used iVTT position error as the dependent variable in our regression analysis.

3.3. Regression analysis

We predicted that a measure of perspective taking and a measure of path integration would be independent predictors of iVTT position error (Hypothesis 3). As noted, SOT was used as the measure of perspective taking and position error was used as the summary measure of TCT for consistency with how we measured iVTT. As predicted, the perspective taking measure and the path integration measure independently and significantly predicted iVTT position error. These results are shown in Table 4 and visualized in Fig. 3. Notably SOT accounted for 17.3% of the variance in iVTT position error over and above TCT, and TCT accounted for an additional 1.77% of variance over and above SOT, with 2.1% shared variance. A stepwise regression analysis demonstrated that the Roadmap task score did not significantly contribute to the model after accounting for SOT angular error and TCT position error ($F = 2.41$, $p = .122$).

[2] Note. We used the SOT as the predictor variable, rather than a composite of both the SOT and the Roadmap task, as stated in the preregistration, because the SOT more directly measures the common perspective taking processes with the iVTT. The preregistered analysis is in Table S2.

[3] Note. We did not include an analysis of sex differences as we stated in the preregistration. This analysis will be addressed in another paper focusing on sex differences from the larger dataset.

[4] We report Spearman's rank correlations, which do not assume normality, because data distributions were non-normal. However, the results do not change substantially if we used Pearson correlations (reported in the Supplementary Table S1).

Table 2
Descriptive statistics for all measures at the participant level.

	Mean	SD	Min	Max	Skewness	Kurtosis	Split-Half Reliability
iVTT Absolute Angular Error	17.33	12.73	6.85	67.59	3.15	9.57	0.96
iVTT Absolute Distance Error	0.32	0.11	0.12	0.77	1.36	2.26	0.82
iVTT Position Error	0.89	0.60	0.36	3.03	2.58	6.40	0.97
iVTT Combined Z-Score	0.00	0.75	−1.06	2.56	1.48	2.01	–
SOT Absolute Angular Error	21.86	13.23	3.83	73.75	1.36	2.20	0.61
Roadmap Total Correct	11.55	5.51	2	30	0.56	−0.03	–
TCT Absolute Angular Error	30.61	12.55	14.53	74.29	1.58	2.68	0.90
TCT Absolute Distance Error	0.81	0.19	0.37	1.41	0.56	0.35	0.66
TCT Position Error	2.07	0.60	1.09	4.10	1.27	1.72	0.89

Note. Values are calculated after winsorizing to within three standard deviations. Angular errors are reported in degrees; distance and position errors are reported in meters. The iVTT target ranged from 1.5 to 2.5 m away from the origin; the TCT outbound triangle legs ranged from 2 to 5 m.

Table 3
Observed Spearman correlations between all measures (n = 210).

	1	2	3	4	5	6	7	8
1. iVTT Absolute Angular Error	–							
2. iVTT Absolute Distance Error	**.24****	–						
3. iVTT Position Error	**.79****	**.52****	–					
4. iVTT Combined *z*-Score[a]	**.62****	**.86****	**.79****	–				
5. SOT Absolute Angular Error	**.35****	0.08	**.39****	0.22**	–			
6. Roadmap Total Correct	**−.37****	**−.25****	**−.42****	**−.34****	**−.46****	–		
7. TCT Absolute Angular Error	**.28****	0.18*	**.25****	**.23****	0.15*	**−.26****	–	
8. TCT Absolute Distance Error	0.19**	**.26****	**.29****	**.29****	0.18**	**−.23****	**.45****	–
9. TCT Position Error	**.23****	0.16*	**.24****	0.20**	0.14*	−0.23**	**.89****	**.61****

Note. *: $p < .05$, **: $p < .01$, bolded correlations are significant after a Bonferroni correction at $p = .0014$.
[a] iVTT combined z-score is the average z-score of iVTT angular and distance error.

Table 4
Regression Analysis on iVTT position error, with SOT angular error and TCT position error as predictors.

Model Summary					
R Square 0.21		Adjusted R Square 0.20			F-statistic 27.93
Variable	Unstandardized Coefficients		Standardized Coefficient		
	B	Std. error	Beta	*t*	p > |t|
Constant	0.198	0.14		1.43	0.154
SOT Angular Error	0.019	0.003	0.421	6.74	<0.001**
TCT Position Error	0.134	0.06	0.135	2.16	0.032*

Note. *p < .05, **: p < .01.

3.4. Bimodality in IVTT position error

Some trials in the iVTT show a bimodal distribution of position errors. In these cases, there exists a large peak at the correct angular response and a small peak at the value of where the correct angular response would be without a perspective shift (i.e., the participant falsely assumes that they should turn and walk to the target as if they are facing the top of the circle). This error is illustrated in specific trials in the heatmap diagrams (see Fig. 4). The correct location, and the location that ignores the perspective shift are plotted for each trial, and the heatmaps show a cluster of responses around each. Most of these errors were made by a small number of participants across multiple trials: 12 participants made this error on at least half of trials and 9 of these made the error on all 24 trials. While Hartigan's dip test (Hartigan and Hartigan, 1985) indicated that the data did not significantly depart from a unimodal distribution, 12 (~5.7% of total) participants is a non-trivial number of people who systematically made this error. We consider whether this bimodality is due to misunderstanding the task or to failure of perspective taking in the discussion section. We conducted the regression analysis with and without these participants and the results did not differ appreciably, so we opted to keep these participants' data in the analysis.

3.5. Exploratory analyses

3.5.1. Signed errors

Signed angular and signed distance errors for the iVTT were calculated. Participants tended to overturn (mean signed angular error = 7.06°, *SD* = 7.97°) and to underestimate distance (mean signed error = −0.06 m, *SD* = 0.25). One sample t-tests indicated that both signed angular ($t = 12.85$, $p < .01$) and distance ($t = -3.73$, $p < .01$) errors significantly departed from 0. The underestimation of distance is consistent with the results of He et al., 2023), but a significant signed error for angle was not found in that study.

3.5.2. Self-reported strategies

Most (204 of the 210) participants provided a response to the strategy questionnaire. Two of the authors independently categorized the written reports as one of six strategies, blind to the subject's performance. Table 5 indicates the number of participants who reported a specific angular strategy, a specific distance strategy, a top-down strategy, a first-person strategy, using the wall, and/or a mental rotation strategy. The table includes examples of responses indicating these strategies. Inter-rater reliability (Cohen's Kappa, κ) was high (above 0.8) for all except for the first-person strategy (which had κ = 0.602); strategies with discrepancies resolved by consensus. Some participants (n = 79) responded, but did not mention using any particular strategy, so those responses were included in a 'no strategy' category.

Participants who reported using a specific angular strategy had lower position error (M = 0.77, SD = 0.43) than those who did not report a specific angular strategy (M = 0.94, SD = 0.65; $t = -2.44$, $p = .02$). Similarly, those who reported using a specific distance strategy had

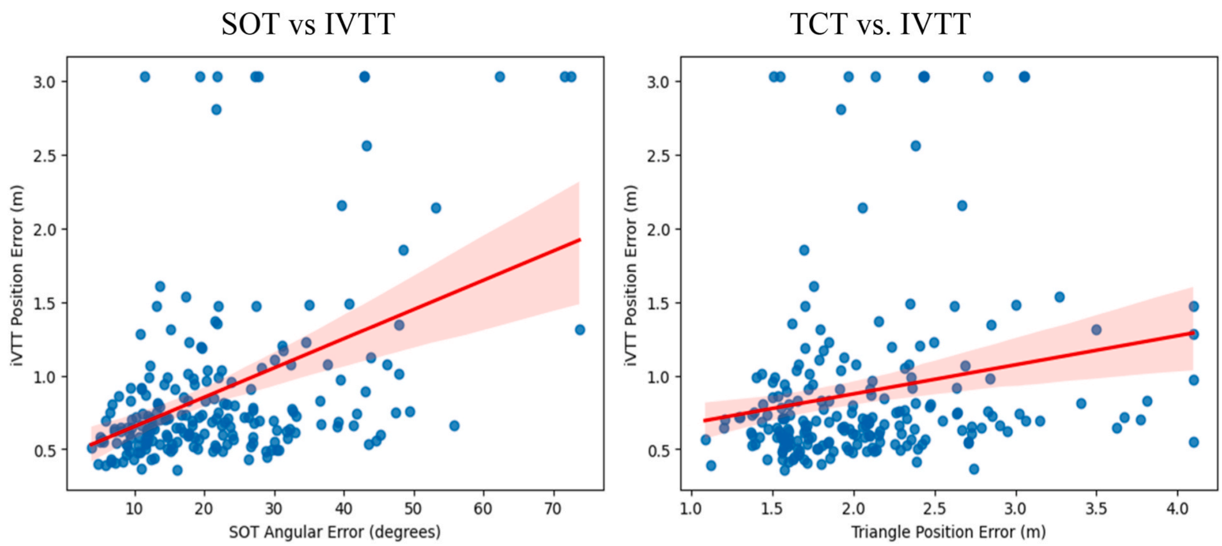

Fig. 3. Scatterplots with regression lines for variables in the regression analysis.

lower position error (M = 0.74, SD = 0.42) than those who did not (M = 0.94, SD = 0.64; $t = -2.57$, $p = .01$). Those who reported using a first-person or top-down strategy did not perform differently from those who did not mention one of these strategies. The self-reports indicate that only a small number of participants (n = 15) mentioned mental rotation while more participants (n = 32) indicated that they used the wall as a border reference for gauging the distance. Neither group performed differently from participants who did not mention these strategies.

3.5.3. Movement trajectories in the iVTT

Examination of participants' movement trajectories in the iVTT indicated that some participants appeared to first turn and walk in a straight line to their final destination, while others walked a more curved path or readjusted direction as they walked (Fig. 5). We calculated the mean deviation ($M = 0.05$ m, $SD = 0.02$ m) from a straight line on a given trial for each participant (i.e., a measure of how directly participants walked to their end location).

Larger deviation from a straight line was correlated with greater angular error ($\rho = -0.16$, $p = .02$) and less distance error ($\rho = 0.19$, $p < .01$), but not position error ($\rho = 0.08$, p = .24). In other words, participants who walked a direct line also tended to perform better on the angular component of the task, but worse on the distance component.

4. Discussion

Map-based navigation ability is used any time someone needs to relate information from a map to their surroundings to guide their movement to a target location. One aim of this research was to examine the relative contributions of perspective taking and path integration to map-based navigation using the simplest possible environment and task. We replicated the significant correlation of the iVTT with perspective taking ability found by He et al. (2022). A new finding of this study is that performance on the iVTT was also correlated with a path integration task (the Triangle Completion task) and in a regression analysis, a perspective taking measure and a path integration measure independently predicted iVTT performance. These results indicate that, as predicted, individual differences in both perspective taking and path integration contribute to viewpoint transformation ability and help establish the validity of the measure. A second aim was to develop an efficient psychometric measure of this ability, by including a smaller set of the most diagnostic items from the original Immersive Viewpoint Transformation Task (iVTT; He et al., 2022). Like the original measure, our revised measure, which is half the length of the original test, has high internal reliability, and shows a range of performance, indicating that it discriminates well between individuals with different ability levels.

4.1. Contributions of perspective taking and path integration to map-based navigation

iVTT angular and position error correlated with the Spatial Orientation Test (SOT), replicating the results of He et al. (2022) with a more efficient measure of viewpoint transformation ability. While the correlations in this study were lower (e.g., the correlation of angular errors on the SOT and iVTT was 0.36, compared to 0.69 in the earlier study), the measures used here had fewer trials, optimized for individual differences here, and the internal reliability of the SOT was lower (0.61) here than in the previous study (0.80). The correlation of iVTT with another measure of perspective taking, the Roadmap test (MRM) adds to its validity as a measure of perspective taking ability. However, the perspective taking aspect appears to primarily affect the angular component (not the distance component) of the iVTT, as SOT angular error did not correlate significantly with iVTT distance error, consistent with He et al. (2022).

An important novel contribution of the present study was the inclusion of the Triangle Completion task (TCT) as a measure of path integration and the demonstration that the TCT predicts iVTT performance independently of the SOT. Notably, after Bonferroni correction, the angular TCT measure was significantly correlated with the angular iVTT measure, and the distance TCT measure was significantly correlated with the distance iVTT measure, but not vice versa. It is important to note, however, that the difference between these correlations was not significant. Regardless, this finding suggests a relative dissociation between distance and angle in path integration, in line with some previous work (Chrastil and Warren, 2021), as well as in map-based navigation. The contribution of path integration to map-based navigation further establishes its relevance to other aspects of navigation. Although there have been suggestions that path integration contributes to survey knowledge, it is not as clear how it contributes to other navigation abilities. In particular, updating one's position and orientation while walking to a remembered goal (i.e., executing a path trajectory, Chrastil and Warren, 2017, 2021), rather than solely encoding an environmental layout, is an important aspect of navigation. Our current results suggest a role for path integration in map-based navigation, at least when physically walking to a target, which situates path integration as part of a broader navigation system.

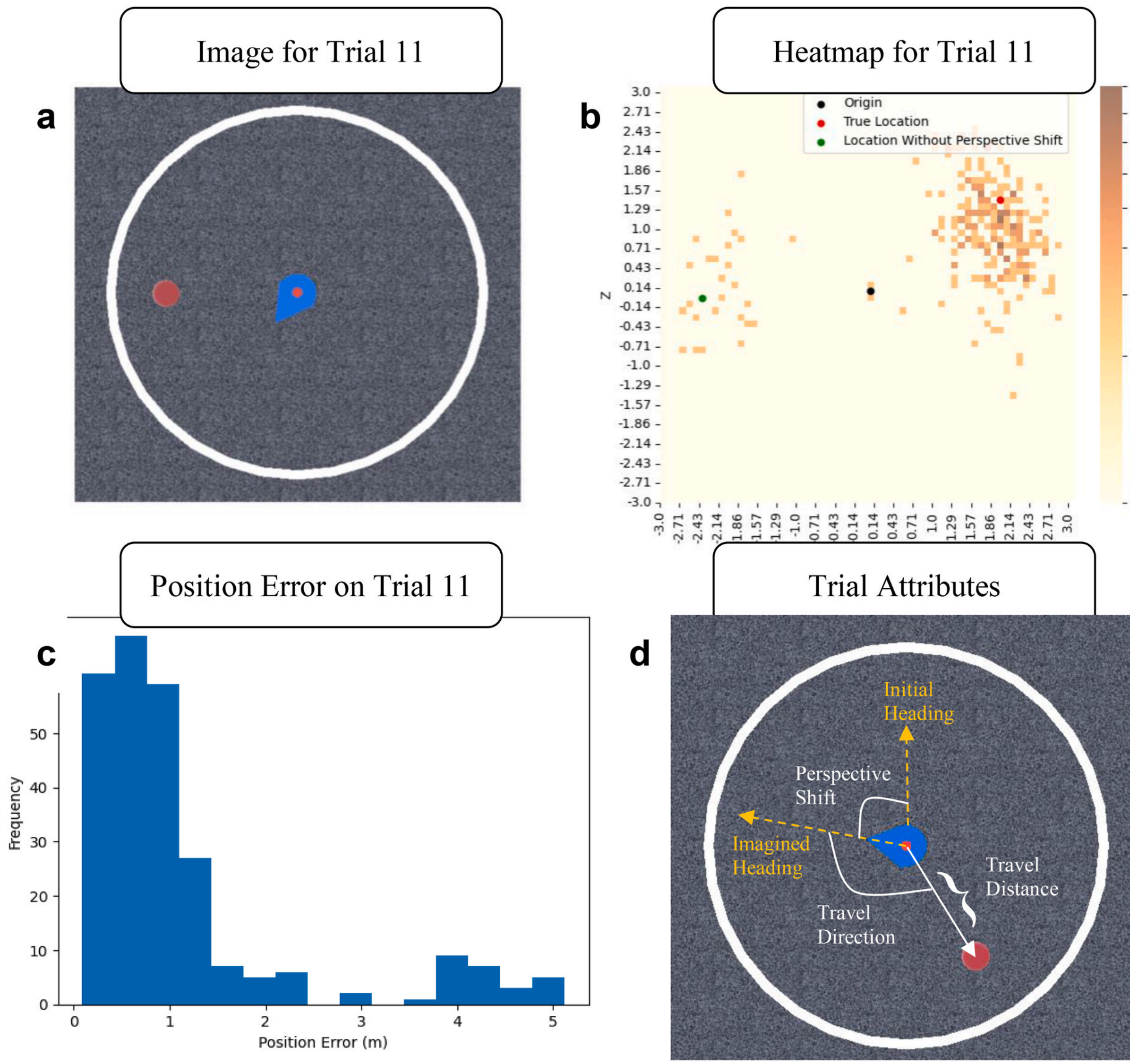

Fig. 4. Example iVTT trial. (a) Image of what participants saw during the map phase of the task. In this case, the participant should turn about 45° clockwise to reach the target. However, if the participant treated the arrow as pointing directly ahead, they would turn about 90° counterclockwise. (b) Heatmap of responses (darker squares represent locations where more participants responded). The black dot represents where participants begin. The red dot is where the true location of the target would be. The green dot is where the target would be if the participants failed to perspective shift. (c) Histogram of participant position error in meters for this trial. (d) Trial attributes of the iVTT.

Although both perspective taking and path integration predicted iVTT performance, perspective taking was a stronger predictor. A possible explanation is that the translation (distance) component of the iVTT, which is not shared with the SOT, was not as challenging as the angular component. The distances from the origin to the target location were not large (less than 2.7 m) meaning that participants only had to update their position over a short distance; however, these distances were not much shorter than in previous studies of Triangle Completion which showed errors in executing the path to home (Loomis et al., 1993; Chrastil and Warren, 2021). In the current version of the iVTT, it appears that perspective taking plays a larger role than path integration on iVTT accuracy, although studies with more variety of environments would help fully characterize their roles. It is also important to note that the triangle completion task involves processes not shared with the iVTT task, including encoding the lengths of the first two sides of the triangle and the angle, and integrating this information to infer the path to the start location (Loomis et al., 1993). In future research, it would be advisable to examine the contribution of a simpler path integration task, for example, one that that just involves walking directly to a prespecified location in the absence of visual cues.

Connecting with how distance and direction might be processed in the brain, there are separable mechanisms for head direction (via head direction cells in the thalamus, entorhinal cortex, and retrosplenial cortex; Chen et al., 1994; Cho and Sharp, 2001; Taube, 1995) and for distance (via grid cells in the entorhinal cortex; Fyhn et al., 2004; Hafting et al., 2005), with partial overlap of the two in entorhinal cortex. This separation in the brain is consistent with the dissociation between distance and angle that we found here. Future work could test this dissociation more directly using functional neuroimaging. In addition to head direction, retrosplenial cortex is thought to also support perspective transformations (Byrne et al., 2007), suggesting that there could be a partial relationship between the angular components of path integration and the perspective taking aspects. However, two processes supported by the same brain region does not necessarily mean that they overlap. This question should be tested in the future.

Table 5
Examples of strategy reports.

Category	N	Example
Specific angular strategy	56	"I tried to judge my position with the 90/180 angle, to see how far [the target] is [from] my position to the 90 or 180 angle."
Specific distance strategy	45	"determine distance through 3 categories, short medium and long"
Top-Down	16	"I imagined looking at myself from above"
First-Person[a]	44	*Visualization:* "I tried to reimagine the map from my point of view and think about where the red dot would be from my position." *Analytical:* "My first step was figuring out if it was to my left or to my right, in terms of in front of and behind me."
Wall as Gauge	32	"I used the distance from the wall to measure where I was."
Mental Rotation	15	"I mentally turned the map that was given to me until it was facing the same direction I was."
No Strategy Mentioned	79	"no strategies. just tried to 'feel' the blue circle and remember where the red dot was"

[a] First person strategies were originally classified into visualization and analytical strategies, but were combined due to low inter-rater reliability when coding analytical strategies ($\kappa = 0.44$). Examples of each are included in the table.

4.2. A new measure of map-based navigation

Recently, researchers have called for the need to develop comprehensive and robust measures of human spatial abilities, and pointed to the paucity of measures of navigation ability (Uttal et al., 2024). A second contribution of this research is the development of a new psychometric measure of map-based navigation, the iVTT, which is efficient, reliable and discriminates between more and less able individuals. In contrast with the iVTT, most previous research on map-based navigation, has been experimental in nature and has focused on specific challenges of map-based navigation, such as map misalignment (e.g. Levine, 1982) or more generally on the perspective-taking aspects of map based navigation, like the SOT and Roadmap test included here. Other studies have examined map-based navigation in desktop or phone-based virtual environments (Coutrot et al., 2018; Gunalp, 2021; Fehringer et al., 2025; Malanchini et al., 2020; Pazzaglia and Taylor, 2007; Starrett et al., 2019), which do not allow for body-based cues central to path integration in everyday navigation. In contrast, the iVTT offers an ecologically valid measure of how people encode and transform map-based information to guide action to goal locations.

4.3. Failures to shift perspective

A minority of participants (approximately 5%) had responses indicating that they did not perform the perspective shift on a large number of iVTT trials, instead responding as if they had to turn and walk to the target as if they were facing the top of the circle. One explanation of this pattern is that participants misunderstood the task and did not realize they had to assume a different perspective. However, some of these participants walked to the true location on several of their attempts. Second, these participants only made this mistake on the perspective shift aspect of the task. Recall that the iVTT involves an initial perspective shift, a travel direction aspect (the angle you turn after accounting for the perspective shift), and a travel distance aspect (walking out from center after deciding which direction) (Fig. 4(d)). No participants routinely and systematically made large errors on the travel direction aspect, and only one participant did so for the travel distance aspect, suggesting that participants were paying attention to the task directions and taking the task seriously. This finding further supports that perspective taking and executing the path are dissociable cognitive processes in this task. Third, only one of these 12 participants indicated any sort of confusion in the self-reported strategy post-task.

Our results suggest that perspective shifting is a difficult task that some participants can achieve only some of the time. One possibility is that these participants were unable to imagine or maintain the alternative perspective indicated by the pointer, which could include the inability to put the new perspective into action. Perspective taking errors of this type have been characterized as inability to inhibit sensorimotor signals indicating one's current perspective (May, 2004), especially when someone has to make a body-based response (Avraamides et al., 2007), which was the case with our task.

4.4. iVTT strategy differences

Previous studies have demonstrated that people use different strategies in perspective taking tasks, notably mental rotation (i.e. mentally rotating the map with respect to the environmental frame of reference) rather than imagining changing their egocentric perspective with

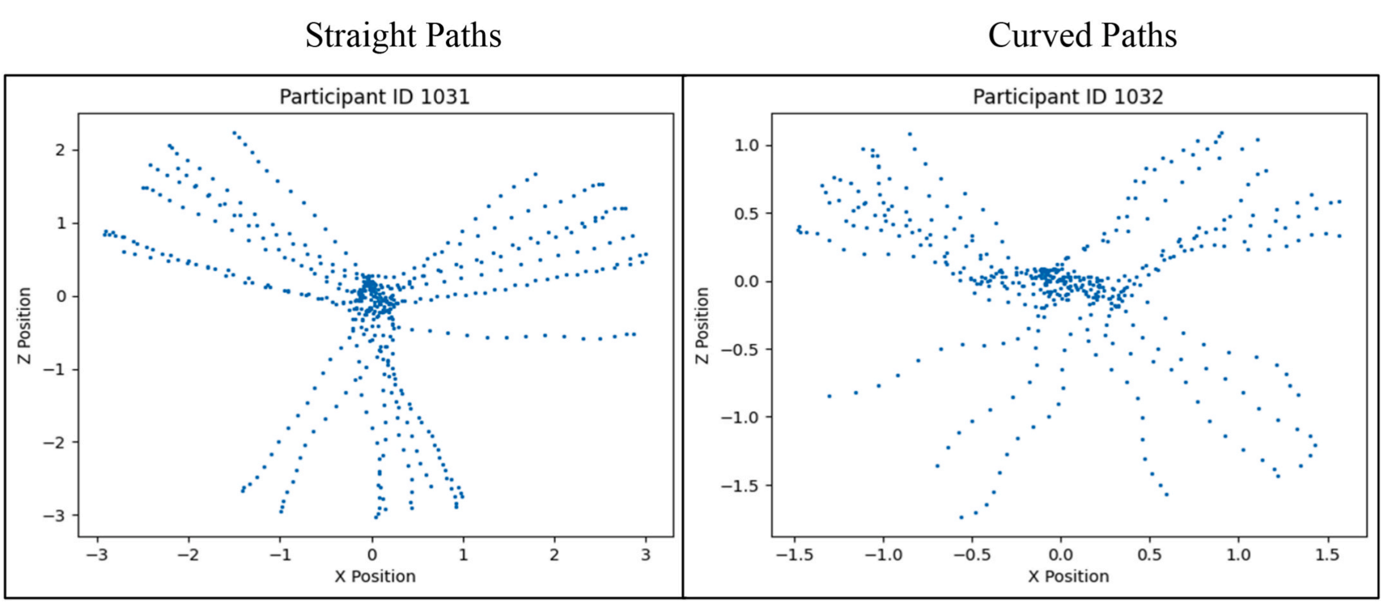

Fig. 5. Examples of movement trajectories are plotted for all 24 trials to demonstrate individual differences in directness. The left plot depicts a participant who walked in straight lines towards their target locations, while the right plot depicts a participant who walked in more curved lines.

respect to the environmental frame of reference (cf. Zacks and Michelon, 2005). However, only a few participants (7%) reported mental rotation as a strategy here, suggesting that our task primarily measures a true perspective taking process. This is perhaps not surprising, as the immersive design and requirement to make a physical response (walking) may necessitate taking an egocentric perspective. Moreover, only a minority of participants mentioned referencing the wall, and using this strategy conferred no advantage to performance on the task.

In addition to perspective taking, a striking variation in strategy was that some participants walked in a straight line, suggesting that they computed the direction of their path before walking, while others took curved or wavy paths, suggesting that they continued to compute the direction to the target while walking. Walking in a straight line (which was associated with less error) might indicate more confidence (i.e., less uncertainty) regarding the angle of rotation, and developing a conscious strategy may have increased this confidence. It could also be an indication that people taking straight paths are dissociating distance and angle into separate elements, whereas curved paths indicate that they are attempting to resolve both at the same time. The identification of this conscious strategy may offer an opportunity for training map-based navigation. In particular, this training could be applied to older adults, who have been found to struggle most with maps due to the cognitive difficulties of transforming between top-down, allocentric and first-person, egocentric viewpoints, as these cognitive abilities degrade with age (Ai et al., 2023; Fabiani et al., 2016).

4.5. Limitations and future directions

A limitation of the current study is that the navigation task was relatively simple, involving locomotion to a single target in an open arena. Another limitation is that the physical space in which people had to move was relatively small (approximately 6 × 6 m) because it was constrained by the size of the laboratories in which the study was conducted. As a result, participants did not have to walk very far to the target direction, and thus this study might have underestimated the contribution of path integration ability to the iVTT task. In future research, it will be important to study map-based navigation ability in larger and more complex environments (cf., Coutrot et al., 2018, 2022; Fehringer et al., 2025) and to relate the iVTT to navigation in these spaces. Importantly, for ecological validity, these studies need to be conducted in ambulatory virtual or real environments in which participants have access to full body-based cues involved in path integration. It is also clear that the iVTT, SOT and TCT involve spatial working memory, so it will also be important to examine the extent to which the shared variance in these tasks can be accounted for by working memory. Finally, a number of questions emerged related to how the brain might support these cognitive functions, which are important to resolve in the future.

4.6. Conclusion

To date, studies of individual differences in human navigation have focused primarily on the ability to learn the layout of a novel environment (Hegarty et al., 2006; Wolbers and Hegarty, 2010). The ability to use a map to guide locomotion to a goal location is an ecologically valid task used during everyday navigation that has received less attention in the literature on individual differences in human navigation. Here, we developed a novel psychometric measure of this ability in immersive ambulatory virtual reality, based on previous experimental research (He et al., 2022) and established its reliability and validity in relation to measures of perspective taking and path integration. The ability to isolate this skill gives us a new tool in the toolkit of measuring spatial abilities, contributing to the cognitive science of human variation in spatial navigation (cf. Newcombe et al., 2023). Characterizing the strategies of more able navigators on this task can inform the training of navigation skills and the development of GPS navigation devices that better align with human abilities.

CRediT authorship contribution statement

Charley Jetter: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Chuanxiuyue He:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Alina S. Tu:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis. **Michael J. Starrett:** Writing – review & editing, Validation, Software, Formal analysis. **Elizabeth R. Chrastil:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mary Hegarty:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Consent to participate

All participants gave their written, informed consent prior to their inclusion in the study.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the Institutional Review Boards at the University of California, Irvine and the University of California, Santa Barbara.

Data and code availability

Upon publication, task materials, data, and analysis code will be made available on the Open Science Framework, https://osf.io. Portions of the design and analysis plan were registered at the Open Science Framework; these are publicly available at https://osf.io/x4mf7.

Declaration regarding generative AI

No generative AI was used in the preparation of this manuscript.

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Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose. The authors have full control of all primary data and have agreed to allow the journal to review this data if requested.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2026.109476.

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