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The necessity of motoric engagement in enhancing route memory

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Abstract

The relative contribution of decision-making and motor engagement at encoding, on route memory, was examined using virtual reality (VR). During encoding, participants explored 12 virtual environments for 40 s each. Navigation strategy during encoding was manipulated within-subjects. On Active trials, participants made decisions about their route of travel. On Guided trials, they followed a predetermined path overlaid on the road, removing the need for decision-making. On Passive trials, participants simply viewed a set route, without initiating decision-making nor engaging movement during encoding. Following exploration of each environment, participants were asked to 're-trace their steps' using the exact route they had just travelled. We also manipulated type of VR implementation (Desktop VR, Headset VR) between subjects. Movement in a Desktop-VR group was controlled via keyboard input, limiting motoric engagement. Movement in a Headset-VR group occurred using a VR-compatible steering wheel, requiring relatively greater motoric engagement. We found an effect of navigation strategy only in the Headset-VR group: route memory was significantly better following Active and Guided relative to Passive trials. Memory did not differ following Active relative to Guided trial types, suggesting that decision-making does not underlie the memory benefit. We suggest route memory is enhanced when initiating physical movement during encoding.

KEYWORDS

active navigation, decision-making, motor control, route memory, virtual reality

BACKGROUND

Prior work shows that people differ greatly in their navigational proficiency (Chrastil & Warren, 2012 for review; Weisberg & Newcombe, 2016). For example, some people can use a map to form a Birds-eye view of spatial routes, which enables them to integrate familiar and novel paths to assist navigation (Gaunet et al., 2001). Other people, however, are more reliant on navigational apps such as Google Maps™, which provide turn-by-turn instructions, to help guide them to their destination faster (Dahmani & Bohbot, 2020). When examining memory for routes and the spatial layout of an environment, several studies have consistently shown that active navigation during encoding results in better performance relative to a passive tour of an environment (see Chrastil & Warren, 2012 for review; Maguire et al., 2006). Active encoding consists of both cognitive (mental manipulation of spatial information, allocation of attention and decision-making) and physical (motor control for locomotion, proprioceptive and vestibular sensory information) components that are believed to be combined to create a multi-modal representation of the path travelled (Chrastil & Warren, 2012). Passive encoding, in which the person simply views a route without motoric engagement or decision-making about where to turn, leads to consistently poorer retention. That is, acquisition of spatial knowledge is limited when individuals passively view routes, as in the case of a passenger who is simply observing a path relative to a driver who initiates their own decisions about where to explore and how to arrive at a location (Chrastil & Warren, 2012). Some suggest that engaging in decision-making during encoding is the key factor benefitting later memory (see Chrastil & Warren, 2012 for review; Weisberg & Newcombe, 2016). However, it remains uncertain whether it is the lack of decision-making that accounts for poorer memory following passive viewing or lack of motoric engagement. In the current study, we examined whether altering the level of motor engagement at the time of encoding modulates memory for routes travelled.

Some researchers argue that decision-making is vital to effectively learn about spatial layouts and acquire graph knowledge (Carassa et al., 2002; Farrell et al., 2003; von Stülpnagel & Steffens, 2012). For example, Bakdash et al. (2008) discovered that pointing accuracy to target locations was similar whether participants encoded virtual environments through active navigation (requiring motor and decision-making processes) or through decision-making alone without motor control. In other words, merely using motor control did not enhance spatial memory. Similarly, Chrastil and Warren (2015) assessed route learning using a 'shortest route task' in which participants needed to find the shortest path to a target landmark. Although this task assessed the ability to integrate knowledge of different familiar paths to navigate new routes (i.e. graph knowledge), they too found decision-making to be an important factor in spatial memory. In contrast, research by Day and Fitzpatrick (2005) and Smith (2017) has demonstrated that engaging in body-based movements, which involve proprioceptive and vestibular systems, during exploration, enhances memory for spatial information on a subsequent retrieval test. Similarly, we have also shown that self-motion cues encompassing the integration of proprioceptive, vestibular and visual information are important for retaining route knowledge (Sivashankar, Fernandes, et al., 2024; Sivashankar, He, et al., 2024).

In the current study, we manipulated the need for decision-making during the encoding of a new route within virtual reality (VR), as well as the motoric demands for movement, to determine their relative influences on memory. Movement was initiated either within Desktop viewing of environments (using a QWERTY keyboard for movement and mouse control for rotational viewing) or within a VR headset using a VR-compatible steering wheel that allowed for greater motoric involvement. Our goal was to determine the degree to which motoric engagement is necessary to enhance memory for routes.

Method of implementation: Desktop versus headset-based viewing within VR

Recent advancements in VR technology have introduced a new variable to consider when assessing spatial memory: the type of VR device used to interact with the virtual environment. The type of VR apparatus determines not only the display modality (on a computer monitor in Desktop viewing, or 360-degree integrated viewing with head-mounted VR), but also the level of motor engagement with the virtual environment. Simply put, not only is the field of view (FOV) different in these implementations but also is the motoric interaction evoked by the system (Jerald & Marks, 2016; Roettl & Terlutter, 2018; Wilson & Soranzo, 2015). For example, in Desktop VR, participants explore virtual environments primarily using a keyboard to move through the environment and a mouse to control the camera view (i.e. to observe around an environment). On the other hand, exploring a virtual environment using headset-based VR is quite different. Movement is typically controlled with VR paddles, or in the case of the current study, using a VR-compatible steering wheel to control the direction of movement (e.g. turning the wheel changes the direction in which the virtual environment moves), and pedals to control acceleration and deceleration. Critically, the level of motor engagement required by the latter VR system generates inertial cues about one's movement and position in space that are then relayed to the brain (Murcia-López & Steed, 2016; Waller & Nadel, 2013). Inertial cues can play an important role in spatial navigation by providing information about movement and orientation relative to one's body (Jerald & Marks, 2016; Loomis & Knapp, 2003). These cues include proprioceptive feedback from sensory receptors in muscles and joints, vestibular information from the inner ear that detects head position and motion, and accelerative cues that indicate changes in velocity (Jerald & Marks, 2016). Self-motion cues integrate these inputs to help individuals perceive their trajectory and orientation in space. When combined with visual cues, these inertial cues are believed to enhance spatial awareness and navigation capabilities (Jerald & Marks, 2016). In VR, replicating realistic inertial feedback can improve immersion and accuracy, demonstrating the importance of these cues in both real and virtual environments for navigation.

When examining the role of spatial navigation using different VR implementations, it is also essential to consider the interactive influence of one's sense of presence and immersion. Presence fosters a sense of 'being there', which not only enhances the encoding of spatial information by grounding the experience in a perceived real-world context, but may also increase the attention devoted to the virtual environment (Makowski et al., 2017). Further, it is hypothesized that attention mediates the positive benefits of presence on memory (Makowski et al., 2017; Smith & Mulligan, 2021). It is reasonable to presume that under headset-based viewing, the level of presence evoked by a virtual environment would be higher than that simulated under Desktop viewing. Therefore, in the current work we measured self-rated presence, post-VR immersion, to determine its influence on subsequent memory performance.

Past research has also shown that spatial learning is most effective in immersive conditions and that presence could mediate the effect of immersion on the acquisition of spatial knowledge within virtual environments (Parong et al., 2020). For instance, Cadet and Chainay (2020) found that using a more immersive Headset-VR device (similar to the one used in the current study) resulted in better memory performance and heightened presence compared to Desktop-VR implementation. Researchers also suggest that immersion plays a critical role in enhancing spatial memory by engaging multiple sensory and motor modalities (Bampouni et al., 2024; Makowski et al., 2017; Smith & Mulligan, 2021). In other words, non-immersive devices are believed to restrict the full motor and sensory experience that can be evoked by active navigation tasks. Conversely, immersive Headset-VR systems that enable motor control and head movement are suggested to provide bodily based (idiothetic) motor cues, which are essential for spatial memories, like route knowledge, which rely on an egocentric frame of reference.[1]

Current study

In this study, we sought to examine whether a change to the method of implementation of environments within VR (Desktop viewing vs. Headset-based VR with steering-wheel compatibility) would alter memory for routes. In our previous research, we created encoding conditions that differentially

[1]An egocentric frame of reference is a spatial representation system where locations and orientations are defined relative to the individual's own body, encompassing coordinates linked to the eyes, head and torso (Ruggiero et al., 2009).

required decision-making and motor control, and compared the influence of these navigation types on memory for the route travelled (Sivashankar, He, et al., 2024; Sivashankar, Fernandes, et al., 2024). Navigation type during encoding was manipulated within-subjects and required either actively self-initiating decision-making about the route of travel (Active navigation) or simply following a visually guided pre-determined route (Guided navigation). In both conditions, volitional control of movements occurred using handheld controllers that engaged head, body and arm movements to advance through streets (using an HTC-VIVE™ VR system). In a third navigation type, participants passively viewed set routes within VR (Passive navigation) without the need to initiate decisions about the route of travel nor engage in motoric exploration. Our findings indicated that both actively self-initiated and visually guided navigation conditions significantly improved the accuracy of route memory compared to the passive condition. This suggests that limiting decision-making at encoding does not hinder route memory performance. Instead, we argued that motor engagement, involving head, body and arm movements during encoding, plays a more pivotal role in enhancing subsequent route memory than decision-making (Sivashankar, Fernandes, et al., 2024; Sivashankar, He, et al., 2024). In the current study, we aimed to determine whether our pattern of findings would replicate when varying the level of motor engagement allowed by different VR implementations: Desktop VR and Headset VR. Such an investigation is important not only for understanding the cognitive mechanisms underlying spatial memory, but also to offer insight into the best protocols using VR technologies to examine human navigation.

A second goal of our work was to document the relationship between individual differences in navigation abilities, preferences and motivations for various encoding types, and to determine how trait-level curiosity influences memory performance. To this end, we asked participants to complete a questionnaire to assess their everyday navigation skills using the *Santa Barbara Sense of Direction Scale* (*SBSODS*; Hegarty et al., 2006). Further, we measured variations in self-reported motivation and preference for each navigation strategy (Passive, Guided and Active) and examined whether this influenced route memory. Previous studies have highlighted a role of motivation and curiosity in enhancing spatial memory across various age groups, including children, younger adults and older adults (Gruber et al., 2014; Sakaki et al., 2018; Sivashankar, Fernandes, et al., 2024; Sivashankar, He, et al., 2024). For instance, Gruber et al. (2014) proposed that motivation enhances memory encoding by boosting attention, promoting exploration and encouraging information-seeking behaviour. This neurocognitive framework emphasizes the interaction between motivation and the brain's reward networks, suggesting that motivation triggers a state of curiosity that enhances memory through dopamine release within the hippocampal memory system (Lisman & Grace, 2005). Moreover, research has shown that hippocampal volume and blood flow increase during 'active' navigation tasks—when motor control and decision-making are involved—highlighting a positive association between active explorative strategies and spatial memory (Javadi et al., 2017; Konishi & Bohbot, 2013; Maguire et al., 2000). Given these findings, we hypothesised that hippocampal-mediated memory for travelled routes (Jansen-Osmann & Wiedenbauer, 2004) would improve when motivation levels are higher during encoding. Here, we aimed to determine whether participants' self-reported motivation and their preference for each navigation strategy influenced route memory.

In addition, participants completed the *Five-Dimensional Curiosity Scale* (*5DC*). This questionnaire assesses participants' inherent qualities of curiosity related to joyous exploration, deprivation sensitivity, stress tolerance, social curiosity and thrill seeking (Litman, 2005). In our past research, we demonstrated a significant link between curiosity and route memory performance in children (Sivashankar, Fernandes, et al., 2024; Sivashankar, He, et al., 2024). In this study, we aimed to explore whether individual differences in the emotional states elicited by curiosity, such as feelings of joy versus fear, might affect route memory. Such an examination has broader implications for understanding the influence of curiosity on memory. Lastly, we measured simulator sickness (Kennedy et al., 1993; *Simulator Sickness Questionnaire*) and participants' sense of presence in VR (Schubert et al., 2001; *Igroup Presence Questionnaire*) to assess the perceived realism of the virtual environments and to explore whether these aspects directly influenced or mediated memory performance.

METHODS

Participants

In our previous research, we detected a significant main effect of navigation condition in a one-way repeated measures design, using a sample of 50 participants (Sivashankar, Fernandes, et al., 2024; Sivashankar, He, et al., 2024). Given that the current work extends our prior research and aims to detect a similar effect of encoding strategy on route memory, but using different VR apparatuses, we sought to maintain a comparable sample size for this study. This approach ensured that our sample size was both theoretically grounded and empirically informed. In the present study, 54 undergraduate students (16 males, 38 females; $M_{age} = 22.0$ years, $SD = 2.20$) from the University of Waterloo were recruited on a volunteer basis to be in our Desktop-VR group. Another independent sample of 54 undergraduates (16 males, 38 females; $M_{age} = 24.0$ years, $SD = 3.20$) was recruited to be in our Headset-based VR group. The Research Ethics Committee approved all study procedures. Written informed consent was obtained from all participants prior to experimentation. Data collection for the Desktop-VR group began in January of 2023 and was completed by July of 2023. Data collection for the Headset-VR group began in September of 2023 and was completed by February of 2024. See Table 1 for descriptive statistics on individual difference measures from participants in each group. We did not collect information about the racial/cultural makeup or the socioeconomic status of our participants.

TABLE 1 Individual difference measures from participants in the Desktop-VR and Headset-VR groups.

Group and measures	Mean (*SD*)
Desktop-VR Group	
Santa Barbara Sense of Direction Scale (*SBSODS*)	4.23 (0.88)
Headset-basedVR Group	
Santa Barbara Sense of Direction Scale (*SBSODS*)	4.14 (1.04)
Simulator Sickness Questionnaire (*SSQ*)	6.17 (5.08)
I-Group Presence Questionnaire (*IPQ*):	
Presence	4.72 (1.51)
Spatial presence	4.32 (0.71)
Involvement	3.91 (0.47)
Experience realism	2.85 (1.42)
Total mean IPQ	3.75 (0.57)
Five-Dimensional Curiosity Scale (5DC):	
Joyous exploration	5.02 (1.23)
Deprivation sensitivity	4.37 (1.42)
Stress tolerance	4.54 (1.41)
Social curiosity	5.45 (1.04)
Thrill seeking	4.41 (3.90)

Note: For the Desktop-VR group, scales assessing simulator sickness, presence and curiosity were not administered.

Materials

VR application

A computer-run VR application was designed on the 3D Unity © engine (ver. 2019.4.4f1; see specifications on https://www.vive.com/ca/), using the software Mapbox (https://www.mapbox.com/).[2] Environments in our VR program were chosen to be equivalent in environment sizes. Google Maps Street™ View was then used to decide specific streets within an environment to include in our VR program. Environments were all topographically (i.e. structural organization of the environment) similar, with an average area of 100,000 square meters (measured using Google Earth™ polygon tracing) with a minimum of 4 and a maximum of 20 intersections (point at which two or more roads converged). Since we created the environments to simulate how the cities appear in the real world, some environments contained a greater number of intersections than others. We believe this is an advantage to our study because real-world cities naturally vary in structural topography. The diversity in layout within our map allowed us to more realistically assess the relationship between key factors known to impact navigation, such as intersections (Moser et al., 2008). We then modified the specifications of the environments to allow integration with Desktop-VR and Headset-based VR systems. The VR application included 12 virtual environments created by entering the longitudinal and latitudinal coordinates of various cities around the world (e.g. Abu Dhabi, Chicago, Grenoble, London, Manhattan, Prague, Rio de Janeiro, San Francisco, Singapore, Sydney, Tokyo, Windsor) into the Mapbox Environments SDK for Unity © engine. The speed of travel during all encoding conditions was controlled at 8 m/s.[3]

We replaced the VR controls with suitable analogues for the desktop version of the experiment: The SteamVR plugin, which enabled the use of the VR headset as the in-game player camera, was replaced with a static camera attached to a player object in Unity. The controls for the viewing angle and direction of the camera were shifted to the computer mouse's position and movement inputs to compensate for the removal of head rotation. Further, the player's movement was remapped from VR trackpad controls to the WASD keyboard keys (i.e. the four directional arrow keys, placed on the left side of the keyboard to allow the right hand to more comfortably use the mouse).

We then adapted the Desktop-VR version of the experiment to function with the Headset-based VR group, with movement controlled using a VR-compatible steering wheel. To do this, we again remapped the input controls onto a different hardware system. The ability to turn left and right was assigned to a steering wheel using the [Input System Unity plugin Version 1.6.1] Unity plugin, with the degree of wheel rotation modulating the magnitude of the turn. Moving forward was assigned to the accelerator, while the brake pedal was used to pause at any given time during the exploration phase. Finally, as mentioned above, the velocity at which participants moved within each exploration of an environment was set at 8 m/s (analogous to a vehicle going approximately 30 km/h). Each participant explored all 12 environments. Encoding/Navigation strategy was blocked by type (4 Passive, 4 Guided and 4 Active), with order counterbalanced and presented within-subjects.

Individual difference measures administered post-VR immersion

Desktop-VR group

Spatial orientation ability of participants was evaluated with the Santa Barbara Sense of Direction Scale (*SBSODS*; Hegarty et al., 2006). Each participant rated their endorsement of 15 statements

[2]See Sivashankar and colleagues (2024) for a detailed explanation of how we created virtual environments using Mapbox and 3D Unity © engine, and for information pertaining to the topographical features of the environments (e.g. square footage, number of intersections, types of landmarks).

[3]We collected data on meters travelled as a proxy for distance covered, under the assumption that travelling faster would likely result in covering a greater distance. Our correlation analysis did not reveal a significant association between meters travelled during encoding, and route memory performance, in either group, $r(52) = .22$, $p = .467$ (Desktop-VR) and, $r(52) = .26$, $p = .423$ (Headset VR).

about spatial orientation in everyday life, such as 'I am good at giving directions', indicating whether they strongly agreed or disagreed, using a 7-point Likert-scale. After reverse scoring the items, the responses were summed and divided by 15 to derive an average score between 1 and 7. Participants then rated their motivation and preference to explore each navigation type (Passive, Active and Guided), on a 7-point Likert-scale, with increasing numbers reflecting greater motivation or preference (e.g. 'please rate your motivation to explore environments in VR during active exploration'; 'Please rate your preference to explore environments in VR during active exploration').

Headset-based VR group

Participants completed the *SBSODS* and rated their motivation and preference to explore each navigation type. We also measured simulator sickness using the *Simulator Sickness Questionnaire* (*SSQ*; Kennedy et al., 1993) to evaluate oculomotor discomfort, disorientation, nausea and fatigue experienced because of VR exposure. We scored this questionnaire by assigning each question a value based on the response. Each 'None' response received a score of 0, each 'Slight' response received a score of 1, each 'Moderate' response received a score of 2, and each 'Severe' response received a score of 3.[4] We then administered the *Igroup Presence Questionnaire* (*IPQ*) to determine the extent to which participants felt present while exploring the VR environments (Schubert et al., 2001). Participants were instructed to rate each statement (e.g. 'In the computer-generated world, I had a sense of being there', I felt present in the virtual space) from a scale of 1 (not at all) to 7 (very much). Finally, participants completed the *Five-Dimensional Curiosity Scale* (*5 DC*). This questionnaire assesses participants' inherent qualities of curiosity related to joyous exploration, deprivation sensitivity, stress tolerance, social curiosity and thrill seeking (Litman, 2005).

Measures

Calculation of route overlap as a measure of route memory

The primary dependent variable of interest was accuracy in re-tracing the same route at retrieval that had been travelled during the encoding of each environment. To obtain this measure of spatial memory performance, the deviation in distance between the routes travelled by each participant at encoding and retrieval, for each of the 12 environments was calculated to produce a deviation distance measure.[5] That is, for every map, we collected 40 pairs of X, Y coordinates every second, during both initial exploration (encoding) and during retrieval, reflecting a participant's position in a map. Using the *Pythagorean theorem*, the Euclidean distance was calculated [$C = \sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2)}$] between each of the 40 X, Y coordinates from encoding and retrieval (Liberti et al., 2014). We then calculated the average distance (C) value to obtain the mean deviation distance between encoding and retrieval for each map, explored by a participant. A higher value signified that there was greater deviation between the paths making up encoding and retrieval; hence, poorer memory for the route travelled at encoding (see Figure 1, Panel (a), for perfect route overlap between encoding and retrieval, and Panel B, for route overlap representing significant deviation). Finally, we computed the mean route overlap across the four environments in each of the three conditions to obtain a single route overlap value that was the most representative of route memory following Passive, Guided and Active explorations.

[4]Based on a large sample of *SSQ* data gathered from military pilots, it is suggested that total scores can be associated with negligible (<5), minimal (5–10), significant (10–15) and concerning (15–20) symptoms (Kennedy et al., 1993).

[5]Mean deviation distance was computed for each map explored (12 environments in total) separately for each condition (i.e. 4 Passive, 4 Guided, 4 Active environments, for each participant).

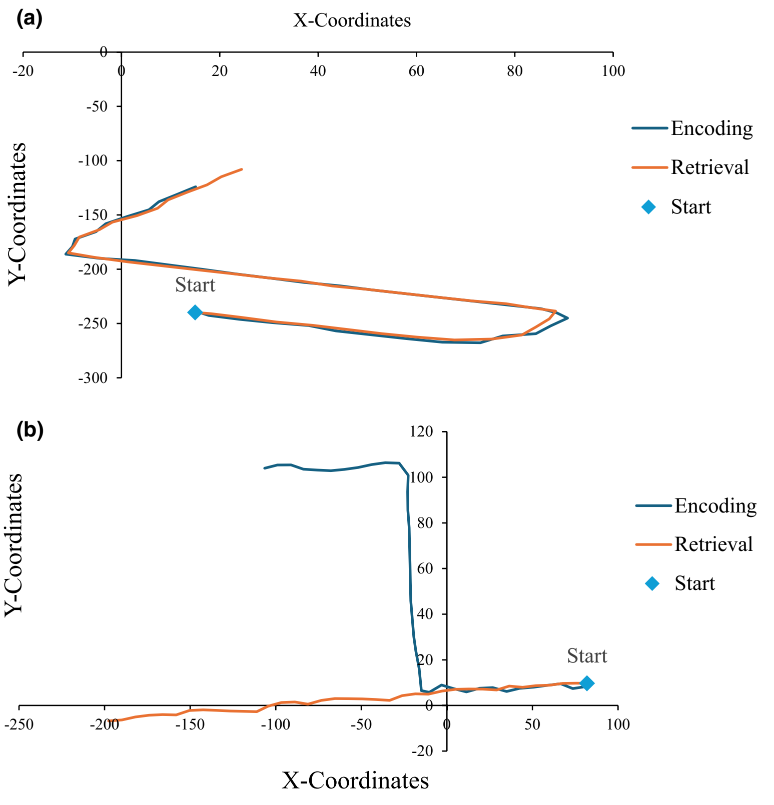

FIGURE 1 Panel (a). Example of paths travelled in one of the virtual environments at encoding and retrieval, showing perfect route overlap (good memory for route travelled at encoding). Panel (b). Example of paths travelled in one of the virtual environments at encoding and retrieval, showing significant path deviation (poor memory for route travelled at encoding).

Transparency and openness

The data necessary to reproduce the analyses presented here and VR environments are https://osf.io/qunkf/?view_only=3a5b3bf266d5485a85197f266319ae98. All analyses were carried out in *JASP* statistical software (Version 0.19.1).

Procedure

Desktop-VR group

Participants first completed a practice phase to help them learn which keyboard buttons to use to navigate within the virtual space. Throughout the entire VR experiment, participants were seated in a comfortable chair that could turn a full 360°, placed in the centre of a testing room. They were instructed to use the WASD keyboard keys to control movement: the W key was used to move forward, A to turn left, S to move backward and D to turn right. Further, participants could adjust their camera-viewing angle—and, consequently, their forward movement direction—by moving the mouse. We advised participants to take as much time as needed in the training phase to become comfortable with the virtual environment. Immediately following the training phase, the experimental session began.

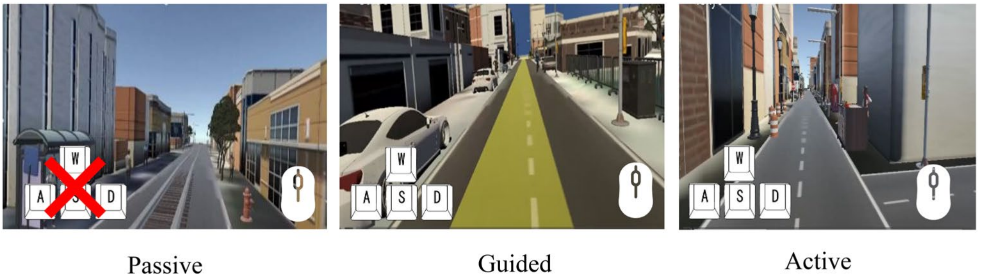

FIGURE 2 Display seen in the Desktop-VR group. From left to right: Passive, Guided and Active navigation types.

There were two phases for each of the 12 environments: an exploration/encoding phase (40 s), followed immediately by a retrieval phase (40 s), in which participants were asked to re-trace the exact route they had travelled during encoding. Navigation type during encoding was blocked (4 environments using Passive, 4 environments using Guided and 4 environments using Active navigation) and manipulated within-subject, with order counterbalanced.

The Passive condition was created by recording 360-degree videos showing a set path travelled within each environment. During passive viewing (see Figure 2), participants were provided with the following instructions: 'You will passively explore this environment. During passive exploration, you will experience a tour of the environment leading you to a gold star'. Here, participants did not exert any motor control for movement (no pressing of the keyboard), nor decide the path of travel, but could control their view using the mouse. The Guided condition was created using Mapbox Directions API to automatically generate the optimal path between two waypoints. One end of the waypoint was attached to a fixed location (the gold star), while the other waypoint was attached to the participant so that the path could be updated in real time. This path was coloured in Yellow (see Figure 2) and overlaid onto the road so that it was highly visible to participants. During Guided exploration, participants received the following instructions 'You will be guided during exploration of this environment. During guided exploration, you will follow a yellow-line directing you to a gold star'. Simply put, participants only exerted motor control by pressing [W] key to accelerate within the environments, but did not decide the path of travel, as they simply followed the yellow line directing them to their end-point. During Active exploration (see Figure 2), participants were free to choose the route they travelled to find a gold star. That is, participants exerted motor control via keyboard button press and decided the path of travel, thus engaging both motor and decision-making processes. Before beginning each new exploration, an instruction appeared on the screen indicating the condition type. Immediately after encoding (40 s) a given environment, participants were placed back at the same starting position and were asked to re-trace (move themselves) along the route they had taken during initial exploration. The total time spent in exploration was approximately 30 min. The researcher then administered the scales (*SBSODS*, preference and motivation).

Headset-VR group

The procedure was identical to that outlined above, but with movement on Active and Guided trials controlled using a VR-compatible steering wheel. During these trials, participants directed their gaze and oriented their head, body and the VR-compatible steering wheel towards a desired path of travel. That is, both active and guided navigation types required the participant to rotate their head to look towards a desired path (e.g. rotating the head to the left prior to a left turn), along with rotation of their body and the steering wheel, to turn left or right at intersections (participants remained seated while they rotated in the swivel chair). In addition, participants had control over acceleration using their foot to depress a metal pedal (see Figure 3).

RESULTS

Route memory performance

We conducted a 2 (Group: Desktop VR vs. Headset VR) × 3 (Navigation Condition: Passive, Guided and Active) mixed Analysis of Variance (ANOVA), with the first factor being between- and the second factor a within-subject manipulation, on Route Overlap scores. There was a main effect of Navigation Condition, $F(1.61, 170.10) = 14.96$, MSE = 303.76, $p < .001$, $\eta^2_p = .12$. Both Active ($M = 27.88$, $SD = 4.53$) and Guided navigation ($M = 28.36$, $SD = 3.56$) improved route memory performance compared to Passive navigation ($M = 38.18$, $SD = 4.78$). There was no difference between Active and Guided performance. There was no effect of Group (Type of Device), $F(1, 106) = 0.47$, MSE = 417.07, $p = .495$, $\eta^2_p = .00$. As predicted, we also observed a significant Group × Navigation Condition interaction (see Figure 4), $F(1.61, 170.10) = 9.32$, MSE = 303.76, $p < .001$, $\eta^2_p = .08$. To understand the interaction, we conducted separate one-way ANOVAs for each Group.

FIGURE 3 Display during Headset-based VR. From left to right: Passive, Guided and Active navigation types.

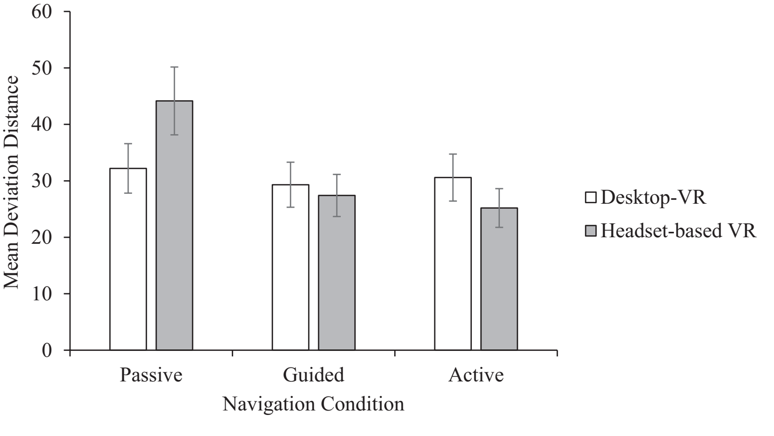

FIGURE 4 Route overlap (measured by deviation distance between path travelled at encoding and retrieval) score in Passive, Guided and Active conditions. Lower deviation distance values indicate better memory for routes travelled. Error bars represent the standard error of the means.

Desktop-VR group

We conducted a one-way repeated measures ANOVA to examine the effect of Navigation Condition on Route Overlap score as the dependent variable. There was no significant effect of Navigation Condition,[6] $F(1.46, 77.41) = 0.32$, MSE = 485.04, $p = .658$, $\eta^2_p = .006$ (see Figure 4 for means).

Headset-VR group

We conducted another one-way repeated measures ANOVA to examine the effect of Navigation Condition on Route Overlap score as the dependent variable in Headset -VR Group.[7] Here, we observed a significant effect of Navigation Condition on Route Overlap Memory score, $F(2, 108) = 45.22$, MSE = 130.78, $p < .001$, $\eta^2_p = .46$ (see Figure 4 for means). We then conducted paired sample *t*-tests to compare Route Overlap scores across each Condition (Passive, Guided and Active). Passive exploration resulted in the highest mean deviation in route overlap accuracy relative to Active and Guided Navigation Conditions, $t(53) = 8.21$, $SE = 2.18$, $p < .001$, $BF_{10} = 2.72$, $d = 1.11$ and $t(53) = 7.23$, $SE = 2.18$, $p < .001$, $BF_{10} = 2.19$, $d = 0.98$, respectively.[8] There was no significant difference between Active and Guided exploration on Route Overlap accuracy, $t(53) = -1.01$, $SE = 2.18$, $p = .932$, $BF_{01} = 6.38$, $d = -0.18$.

Self-reported motivation

We conducted a 2 (Group: Desktop VR vs. Headset VR) × 3 (Navigation Condition: Passive, Guided and Active) mixed ANOVA, with the first factor being between- and the second factor a within-subject manipulation, on self-reported Motivation. There was a main effect of Navigation Condition, $F(2, 212) = 16.63$, MSE = 2.42, $p < .001$, $\eta^2_p = .14$. That is, motivation was higher in both Active ($M = 5.52$, $SD = 1.48$) and Guided conditions ($M = 5.09$, $SD = 1.57$) relative to Passive ($M = 4.32$, $SD = 1.90$). There was no effect of Group, $F(1, 106) = 1.85$, MSE = 3.23, $p = .177$, $\eta^2_p = .02$. There was a significant Navigation Condition × Group interaction (see Table 2 for descriptives), $F(2, 212) = 4.55$, MSE = 2.42, $p = .012$, $\eta^2_p = .04$. To understand the interaction, we conducted separate one-way ANOVAs for each Group.

Desktop-VR group

We conducted one-way repeated measures. There was a significant effect of Navigation Condition on self-reported Motivation $F(2, 106) = 18.93$, MSE = 2.47, $p < .001$, $\eta^2_p = .26$. Participants reported greater

[6]Mauchly's test indicated that the assumption of sphericity had been violated ($p < .05$) thus; a Greenhouse–Geisser correction was applied.

[7]To assess whether the route memory advantage observed in the Active and Guided navigation conditions in the headset-VR group persists after controlling for exploratory behaviour, we also fit a linear mixed-effects model that yielded the same pattern reported here. We modelled route overlap scores as the dependent variable, with Navigation Condition (Passive, Guided, Active) as a fixed effect, and included trial-level behavioural covariates: log-transformed distance travelled, total stop time within intersections, path complexity and number of turns. Random intercepts were included for Participant.

[8]Bayes factors were calculated using the Bayes-Factor package in JASP, enlisting a default Jeffreys–Zellner–Siow (JZS) prior with a Cauchy distribution (center = 0, $r = .707$). This package compares the fit of various linear models. Bayes factor interpretations follow the conventions of Lee and Wagenmakers (2014). Bayes factors in favour of the alternative (BF_{10}) or null (BF_{01}) models are presented in accordance with each preceding report of null hypothesis significance testing analyses (i.e. based on a $p < .05$ criterion). A $BF_{10} > 1$ is interpreted as evidence in favour of the alternative hypothesis, while $BF_{01} > 1$ is interpreted as evidence in favour of the null.

We chose to report Bayes Factors alongside traditional p-values for two main reasons. First, we wanted to provide the reader with both results so that they could better interpret the evidence being reported. Second, reporting Bayes Factors allows for the evaluation of evidence that is consistent with the null hypothesis, lending to more meaningful interpretation of null results.

TABLE 2 Mean motivation and preference scores in each VR Group, following each navigation condition. Standard deviation in parentheses.

Group and condition	Motivation	Preference
Desktop VR		
Passive	3.83 (1.80)	4.02 (1.93)
Guided	5.02 (1.50)	5.19 (1.53)
Active	5.67 (1.40)	5.19 (1.93)
Headset-based VR		
Passive	4.80 (1.85)	3.72 (1.99)
Guided	5.17 (1.63)	5.13 (1.68)
Active	5.37 (1.52)	5.15 (1.80)

motivation to explore environments under Active and Guided (see Table 2 for descriptives) relative to Passive, $t(53)=5.93$, $SE=0.31$, $p<.001$, $BF_{10}=63285.12$, $d=0.81$ and $t(53)=4.06$, $SE=0.29$, $p<.001$, $BF_{10}=142.97$, $d=0.55$, respectively.[9] Notably, participants endorsed Active Navigation as eliciting higher motivation for exploration relative to Guided, $t(53)=2.13$, $SE=0.31$, $p=.038$, $BF_{10}=1.18$, $d=0.29$.

Headset-VR group

There was no effect of Navigation Condition on self-reported Motivation (see Table 2 for descriptives), $F(2, 106)=1.93$, MSE $=2.37$, $p=.151$, $\eta^2_p=.04$.

Self-reported preference

We conducted a 2 (Group: Desktop VR vs. Headset VR) X 3 (Navigation Condition: Passive, Guided and Active) mixed ANOVA, with the first factor being between- and the second factor a within-subject manipulation, on self-reported Preference. There was a main effect of Navigation Condition, $F(1.86, 195.09)=14.82$, MSE $=4.08$, $p<.001$, $\eta^2_p=.12$,[10] but no effect of Group, $F(1, 105)=0.62$, MSE $=2.49$, $p=.434$, $\eta^2_p=.00$. There was no Navigation Condition X Group interaction (see Table 2 for descriptives), $F(1.86, 195.09)=0.25$, MSE $=4.08$, $p=.763$, $\eta^2_p=.00$. In both Groups, participants preferred to explore environments under Active and Guided navigation (see Table 2 for means) relative to Passive, $t(106)=4.70$, $SE=0.27$, $p<.001$, $BF_{10}=333.20$, $d=0.68$ and $t(106)=4.73$, $SE=0.27$, $p<.001$, $BF_{10}=56{,}609.03$, $d=0.69$, respectively. There were no significant differences in preference ratings between Active and Guided, $t(106)=-0.04$, $SE=0.27$, $p=1.00$, $BF_{01}=9.33$, $d=-0.00$.

Assessment of path complexity

We examined whether taking a longer route during encoding (reflecting the topographical properties of the environment) could have influenced route memory. We computed a measure of path complexity for each route taken at encoding. We applied an angle-based measure (see Data S1 for a detailed description of the equation) to quantify turns taken while exploring each environment. That is, we recorded each participant's position within each environment at each 1-s time-point during

[9]All t-tests reported in this paper have been Bonferroni-corrected for multiple comparisons.

[10]Mauchly's test indicated that the assumption of sphericity had been violated ($p<.05$) thus; a Greenhouse–Geisser correction was applied.

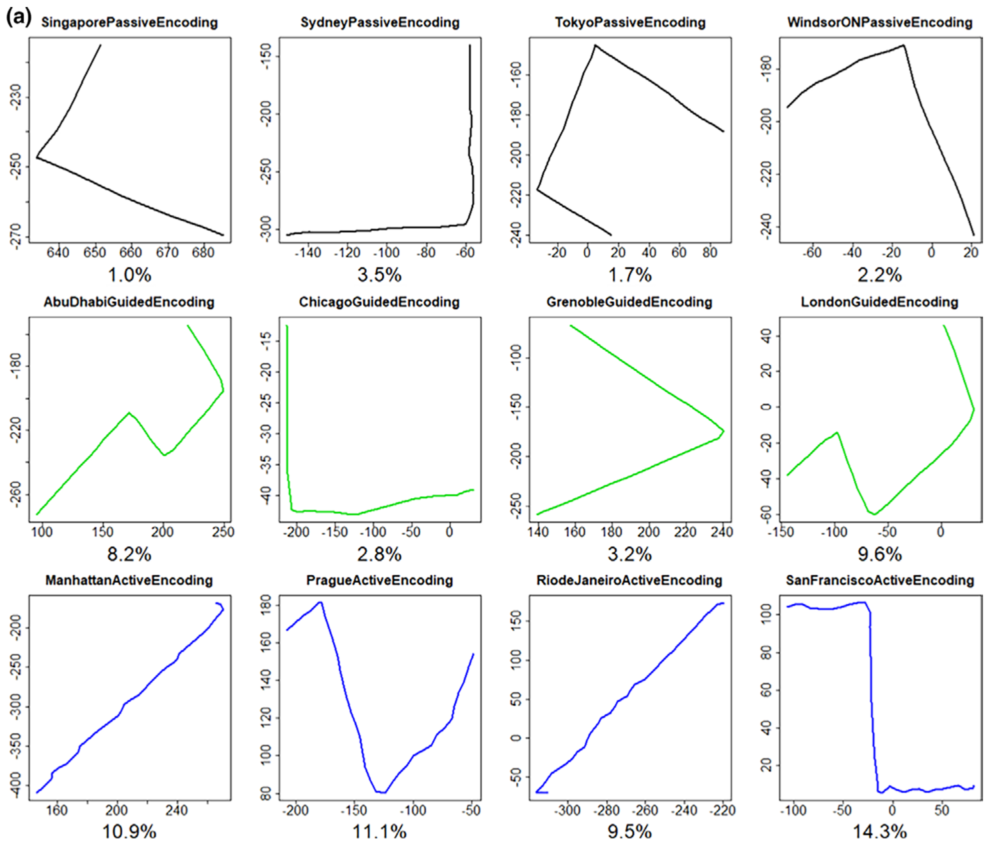

FIGURE 5 Panel (a). Path complexity and percentage score (shown underneath) from a sample participant from the Desktop-VR group, with Passive trials shown in black, Guided trials in green and Active trials in blue. Panel (b). Path complexity and percentage (shown underneath) from a sample participant from the Headset-VR Group, with Passive trials shown in black, Guided in green and Active in blue.

their 40-s exploration. We then derived displacement vectors between positions at each consecutive time-point. Next, we calculated the angle between each pair of consecutive displacement vectors and normalised these angles to represent a complexity score between 0 and 1, such that a 0-degree turn (straight path) has a complexity of 0, and a 90-degree turn or greater has a complexity of 1. Finally, we tabulated the average of the individual turn complexity scores to determine the overall path complexity in percentage for each environment within each navigation condition. Figure 5 shows path complexity percentages for all twelve environments explored in a sample participant within Desktop (Panel A) and Headset VR (Panel B); Active navigation trials are shown in blue, Guided in green and Passive in black. We tabulated and averaged these scores across all participants, separately by Navigation condition and Group.

We conducted a 2 (Group: Desktop VR vs. Headset VR) X 3 (Navigation Condition: Passive, Guided, Active) mixed ANOVA, with the first factor being between and the second factor a within-subject manipulation, on Path Complexity scores. There was a main effect of Navigation Condition, $F(1.69, 179.44)$[11] $= 38.80$, MSE $= 7.96$, $p < .001$, $\eta^2_p = .27$, but no effect of Group, $F(1, 106) = 2.06$, MSE $= 0.01$, $p = .154$, $\eta^2_p = .02$. The Navigation Condition X Group interaction was also

[11]Mauchly's test indicated that the assumption of sphericity had been violated ($p < .05$) thus; a Greenhouse–Geisser correction was applied.

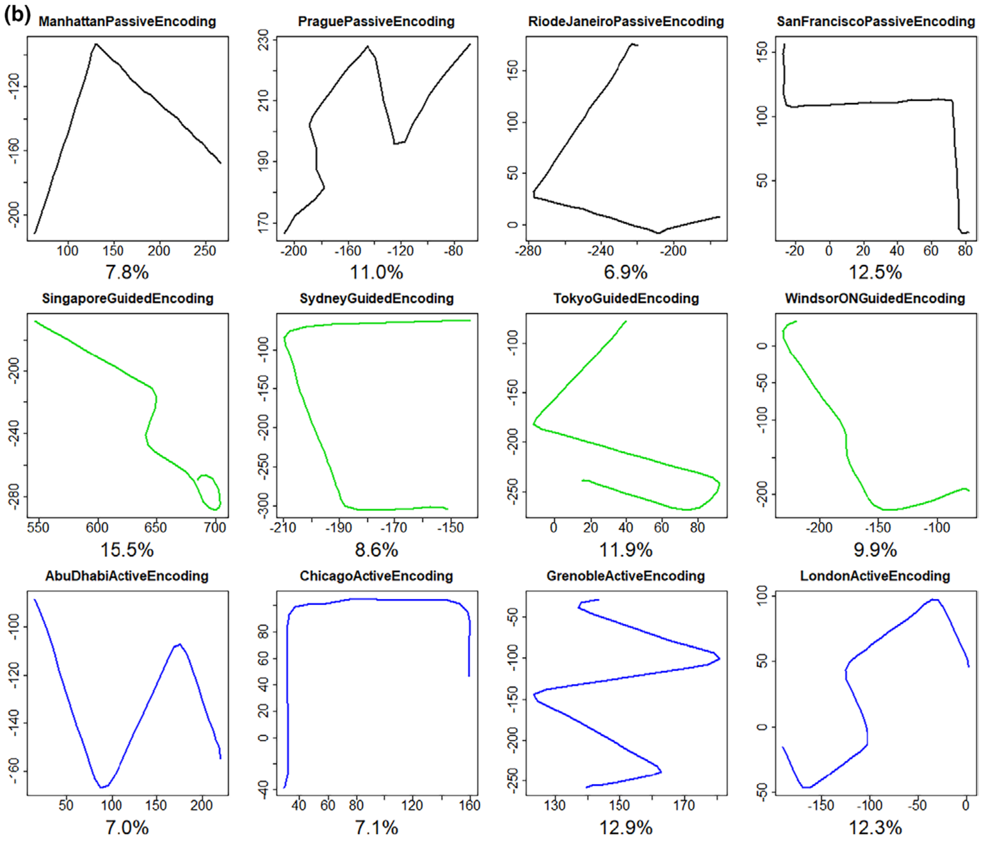

FIGURE 5 (Continued)

non-significant, $F(1.69, 179.44) = 1.95$, $MSE = 7.96$, $p = .152$, $\eta^2_p = .01$. In both Groups, paths explored during the Active condition ($M = 8.8\%$; $SD = 0.03$) were significantly more complex than in the Passive condition ($M = 6.3\%$; $SD = 0.01$), $t(106) = 7.13$, $SE = 0.01$, $p < .001$, $BF_{10} = 18.70$, $d = 0.85$. A similar pattern of results was found when comparing Guided ($M = 9.2\%$; $SD = 0.03$) and Passive conditions, $t(106) = 8.05$, $SE = 0.01$, $p < .001$, $BF_{10} = 43.16$, $d = 0.96$. We did not, however, find a significant difference in path complexity between Active and Guided encoding conditions, $t(106) = -0.92$, $SE = 0.01$, $p = 1.00$, $BF_{01} = 0.21$, $d = -0.11$.

Correlation analyses revealed no significant relationship between Active [$r(106) = -.03$, $p = .738$], Guided [$r(106) = .16$, $p = .095$] and Passive [$r(106) = -.10$, $p = .287$] path complexity and route memory performance.[12] These results provide strong evidence that the length of the route taken during encoding, reflecting the topographical properties of the environment and detours, did not influence route memory.

Correlations with individual difference measures

Given our goal of determining whether route memory performance in each of the navigation conditions was related to various individual difference factors (see Table 1 for descriptives for all

[12]Pearson correlation analyses were collapsed across Group (Desktop VR and Headset VR).

TABLE 3 Pearson correlations in each group showing association between route memory following each navigation condition and various individual difference measures.

Variables	Group and condition					
	Desktop–VR			Headset–VR		
	Active	Guided	Passive	Active	Guided	Passive
1. Intersections crossed during encoding	−.27*	.04	—	−.13	.04	—
2. Number of stops at intersections during encoding	.14	.21	—	.16	−.46*	—
3. Total time at intersections during encoding	−.04	.02	—	−.29*	.23	—
4. Stop count during encoding	.21	.25	—	.06	−.34*	—
5. Preference	−.12	−.03	−.20	−.37**	−.09	−.16
6. Motivation	−.26	.17	−.04	.00	−.06	−.31*
7. *SBSDS*	−.04	−.05	.13	−.11	−.12	.15
8. Total presence	—	—	—	.08	.01	−.13
9. Prescence	—	—	—	−.03	.03	−.12
10. Spatial prescence	—	—	—	.08	.09	−.21
11. Involvement	—	—	—	−.11	−.10	.03
12. Experienced realism	—	—	—	.06	.19	−.06
13. Joyous exploration	—	—	—	.12	−.31*	-
14. Deprivation sensitivity	—	—	—	.00	−.21	.29*
15. Stress tolerance	—	—	—	.02	.19	−16
16. Social curiosity	—	—	—	−.28*	−.12	.10
17. Thrill seeking	—	—	—	−.23	.06	.18
18. *SSQ*	—	—	—	.01	.19	.21

Note: We did not compute correlations between variables (e.g. intersections crossed, joyous exploration) and route overlap following the passive condition. Since route memory was calculated as deviation in distance, a negative correlation indicates a boost in memory (a reduction in deviation distance).

*$p < .05$. **$p < .01$.

measures described below), we examined a range of variables. These included intersections, stop count, preference, motivation, spatial navigation proficiency (measured by SBSODS),[13] sense of presence in VR (measured by IPQ), simulator sickness (measured by SSQ) and curiosity (measured by 5 DC). To assess these relationships, we ran a series of Pearson correlations. *IPQ* and *5 DC* were further separated into subcategories: *IPQ* consisted of presence, spatial presence, involvement and experience realism; 5 DC consisted of joyous exploration, deprivation sensitivity, stress tolerance, social curiosity and thrill seeking. See Table 3 for correlation coefficients along with significance values.[14]

[13]We also conducted a 3 (Navigation Condition: Active, Guided, Passive; within-subjects) × 2 (*SBSODS* group: Low vs. High; between subjects) mixed- ANOVA to determine whether self-rated spatial ability moderated route memory performance. The mixed-design ANOVA was carried out using a median-split of the *SBSODS* scores to classify participants into “High” and “Low” spatial ability groups. Findings revealed a significant main effect of Navigation Condition on route memory, $F(2, 104) = 44.20$, $p < .001$, replicating the pattern of improved memory in Active and Guided conditions relative to passive. The main effect of *SBSODS* group was not significant, $F(1, 53) = 0.96$, $p = .331$. The SBSODS Group × Condition interaction was also non-significant, $F(2, 104) = 1.76$, $p = .177$. Together, these analyses suggest that the mnemonic advantage conferred by Active and Guided navigation conditions does not depend on self-reported spatial ability.

[14]We also examined whether Navigation Condition interacted with *SBSODS*, total *IPQ*-Presence and *SSQ* in influencing route overlap. No significant interactions emerged.

Intersection traversed and dwell time at encoding

We found a negative association between the number of intersections traversed and route overlap deviation score, following Active exploration in Desktop-VR. In Headset-based VR, we found a similar relationship between total time spent at intersections (proxy for dwell time) and route overlap deviation following Active exploration.

We also detected a negative association between the number of stops made during intersections and along with travelled route with route overlap deviation following Guided exploration in Headset-based VR (see Table 3). This relationship underscores the value of pausing at critical junctures while following GPS instructions. We suggest that stopping at intersections to encode landmarks enhances spatial memory retention, possibly by allowing individuals to encode spatial cues. This can be particularly helpful when navigating new routes, adjusting to changing conditions, or seeking shorter paths under time constraints.

Motivation and preference reports

We found a significant negative association between route overlap scores following Passive exploration and motivation in Headset VR, but not in Desktop VR. We also found that preference for Active exploration was negatively correlated with route overlap deviation for this condition in Headset VR, but not in Desktop (see Table 3). Collectively, these findings indicate that in highly immersive virtual reality environments, an individual's intrinsic judgements about the surroundings can augment spatial knowledge.

Curiosity

We found a positive association between deprivation sensitivity and route overlap deviation following passive exploration in the headset-based VR group (see Table 3). The items that make up the ‘deprivation sensitivity’ measure reflect the negative feelings (e.g. anxiety and frustration) that one experiences when the right information is concealed from them. When deprivation sensitivity is present, people experience discomfort and annoyance until they resolve information gaps (e.g. Litman, 2005). It is interesting to observe that participants who scored high on this measure also had poorer memory for routes travelled at encoding during passive exploration (i.e. higher route memory deviation). In contrast, we found joyous exploration and social curiosity to be negatively associated with route overlap deviation following guided and active explorations, respectively. These results do indeed highlight the dual nature of curiosity, showing that while a positive state of curiosity (i.e. joyous exploration and social curiosity) can boost cognitive performance, a negative state (i.e. deprivation sensitivity) of curiosity may impair it.

Predictors of route memory performance

A forward stepwise regression analysis was conducted (separately for Desktop- and Headset-based VR groups) to identify the strongest predictors of route memory performance following Active, Passive and Guided exploration. We included the following measures in our model, as predictors: intersections crossed at encoding, distance travelled, total time spent within an intersection, path complexity, motivation, preference, scores on the *Santa Barbara Sense of Direction Scale* (*SBSODS*), the *Igroup Presence Questionnaire* (*IPQ*), the *Simulator Sickness Questionnaire* (*SSQ*) and the *Five-Dimensional Curiosity Scale* (*5DC*).

Desktop-VR group

For the Active condition, the final model was statistically significant, $F(2, 51) = 4.43$, $p = .017$ and explained approximately 12% of the variance in route memory performance (adjusted $R^2 = .115$). The first variable entered into the model was intersections crossed at encoding, which significantly predicted route memory following Active exploration, $\beta = -7.99$, $t = -2.43$, $p = .019$. This means that a one-unit increase in intersections crossed at encoding leads to a 7.98 decrease in deviation distance (better memory). The second variable entered was motivation, which also significantly predicted route memory performance, $\beta = -3.37$, $t = -2.12$, $p = .039$. Here, we can also infer that a one-unit increase in motivation ratings leads to a 3.36 decrease in deviation distance (better memory).

For the Guided condition, the final model was statistically significant, $F(1, 52) = 4.72$, $p = .034$ and explained approximately 7% of the variance in route memory performance (adjusted $R^2 = .066$). We only found self-report scores on the *Santa Barbara Sense of Direction Scale* (*SBSODS*) to significantly predict route memory, $\beta = -8.64$, $t = -2.17$, $p = .034$. This means that a one-unit increase in *SBSODS* self-ratings leads to an 8.64 decrease in deviation distance (better memory).

For the Passive condition, a similar stepwise regression analysis was performed to identify predictors of the outcome variable. However, no variables met the criteria for inclusion in the final model. As a result, the model did not include any predictors, and the variance explained was effectively zero ($R^2 = .00$).

Headset-VR group

For the Active condition, the final model was statistically significant, $F(2, 48) = 7.52$, $p = .001$ and explained approximately 21% of the variance in route memory performance (adjusted $R^2 = .207$). The first variable entered into the model was preference, which significantly predicted route memory following Active exploration ($\beta = -1.98$, $t = -3.18$, $p = .003$). This means that a one-unit increase in preference ratings leads to a 1.98 decrease in deviation distance (better memory). The second variable entered was the social curiosity subscale from the five-dimensional curiosity scale, which also significantly predicted route memory performance ($\beta = -2.77$, $t = -2.53$, $p = .015$). This indicates that a one-unit increase in the curiosity subscale leads to a 2.77 decrease in deviation distance (better memory).

For both Guided and Passive conditions, a similar stepwise regression analysis was performed to identify predictors of the outcome variable. However, no variables met the criteria for inclusion in the final model. As a result, the model did not include any predictors, and the variance explained was effectively zero ($R^2 = .00$).

Exploratory mediation analysis

To determine whether the effect of navigation type on route memory in both Desktop and Headset VR groups was mediated by self-reported motivation to explore under each navigation type, we conducted two mediation models (see Figures 6 and 7) using SPSS Process macro (Hayes, 2018). As confirmed by indirect paths based on 5000 bootstrap resamples, motivation did not emerge as a significant mediator in either the Desktop or Headset-VR groups.[15]

[15] We also sought to determine whether measures such as curiosity, presence, preference and *SBSODS* mediated the relationship between encoding strategy and route memory performance. No significant mediation effects emerged.

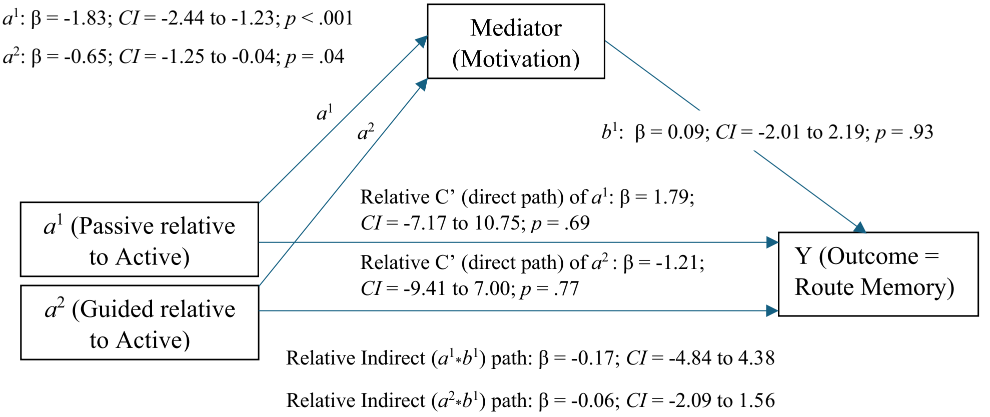

FIGURE 6 Mediation model for Desktop-VR group examining whether the effect of navigation type (Active as reference; Passive, Guided) on route memory was mediated by self-reported motivation to explore under each navigation type. Standardised Linear Regression Coefficients (*β*) along with confidence intervals (based on 5000 bootstrap resamples) and *p*-values are shown.

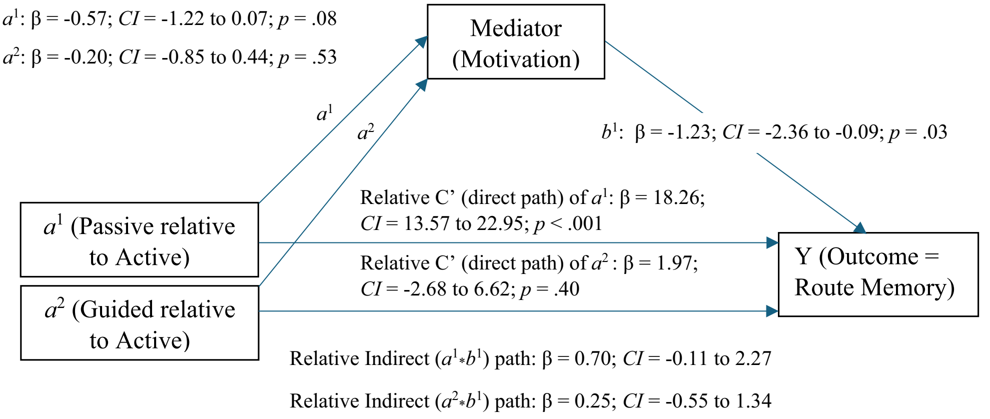

FIGURE 7 Mediation model for Headset-VR group examining whether the effect of navigation type (Active as reference; Passive, Guided) on route memory was mediated by self-reported motivation to explore under each navigation type. Standardised Linear Regression Coefficients (*β*) along with confidence intervals (based on 5000 bootstrap resamples) and *p*-values are shown.

DISCUSSION

In the current research, our objective was to examine the relative contribution of decision-making and motor engagement at encoding on route memory using VR. We manipulated the need for decision-making during encoding of a new route, as well as the motoric demands for movement, to determine their relative influences on memory. Movement was initiated using a QWERTY keyboard and finger movement to navigate keys during Desktop viewing of environments, with limited motoric engagement, or within a VR headset using a compatible steering wheel that allowed for greater motoric involvement. Using headset-based VR but not Desktop VR, we found that route memory was significantly better following Active and Guided relative to Passive trials. Importantly, we showed that memory did not differ following Active relative to Guided trial types, suggesting that decision-making does not underlie the memory benefit. Taken together, these findings suggest that motoric engagement, more so than decision-making, is necessary to enhance memory for routes. Our results highlight the importance of active engagement and self-motion cues in spatial navigation, supporting the idea that more immersive and physically engaging navigation experiences lead to better retention.

That we observed a significant effect of encoding strategy in the Headset-based VR but not in the Desktop version underscores the importance of self-motion cues in enhancing route memory. In the Desktop version, participants navigated along routes via keyboard button presses alone, which represents a comparatively reduced engagement of motor activity. In addition, we speculate that movement via keyboard button press limited the level of realism afforded by the virtual environment and, in turn, made it challenging for participants to track their position within the virtual environment. Typically, past studies investigating route memory have shown that active navigation at encoding leads to better memory than passive (Chrastil & Warren, 2012). However, some studies report no differences between these conditions; importantly, this has occurred in studies that implemented Desktop VR (Gaunet et al., 2001; Wilson, 1999; Wilson et al., 1997). Given that we observed similar route memory performance across the three encoding trial types in our desktop but not Headset-based VR group, we propose that the limited motor and sensory feedback in the former likely accounts for this finding in other work (Roettl & Terlutter, 2018; Smith, 2017). For example, Roettl and Terlutter (2018) examined how variations in VR display (desktop vs. immersive VR systems) and user interface (e.g. steering wheels, handheld controllers) could influence users' ability to navigate and remember spatial information. One of their key findings was that immersive VR systems provide precise spatial cues about the virtual environment compared to Desktop viewing. Further, Smith (2017) explored the role of self-motion cues in spatial navigation, particularly focusing on how the vestibular and proprioceptive systems contribute to route memory and navigation performance. Participants who received more robust self-motion cues performed better in navigation tasks, demonstrating improved route memory and spatial orientation relative to those with limited or no self-motion cues. The current study supports Smith's (2017) finding, as we too detected the memory benefits of active and guided navigation, but only in the Headset-based VR group. Overall, these findings highlight that effective spatial navigation, particularly when remembering route information, is strengthened by the integration of multiple self-motion cues.

In animal research, particularly with rodents, it has been demonstrated that motion cues are vital for forming and maintaining spatial representations (Vorhees & Williams, 2014). For example, animal studies have shown that impairments to the vestibular labyrinths, key components of the vestibular system, lead to deficits in performance on the Morris Water Maze task (Zheng et al., 2009). Comparable results have been observed in humans, with findings demonstrating that age-related vestibular loss negatively impacts older adults' ability to perform route-learning tasks (Coto et al., 2021). For example, studies in humans have shown that vestibular-based self-motion cues can enhance egocentric route learning (Jabbari, 2022) and body-based information becomes more important as the difficulty of the spatial task increases. Furthermore, a review by Burgess (2008) highlighted the role of the hippocampus and associated neural networks in processing motion cues to support spatial orientation and navigation. These studies collectively underscore the importance of motion cues not only in route memory but also in spatial cognition more broadly.

Possible neural mechanisms underlying navigation

The effect of navigation strategy in the Headset-based VR study, but not in the Desktop VR, signifies that an immersive experience matters to performance on egocentric spatial tasks such as route memory. Egocentric navigation is said to depend on inertial cues that engage the dorsal striatum, facilitating encoding of routes and procedural memories (Vorhees & Williams, 2014). Inertial cues include proprioceptive feedback from sensory receptors in muscles and joints, vestibular information from the inner ear that detects head position and motion, and accelerative cues signalling changes in velocity, all of which contribute to the perception of self-motion (Jerald & Marks, 2016). When interpreting the findings of the current study in the context of prior research we infer that the route-learning task used here also heavily depends on the striatal and other motor regions of the brain. Route memory involves sequences of decisions such as 'go straight, turn right, then turn left', which require specific actions at key intersections (Ruddle et al., 2011). Since participants were required to re-trace the exact route during retrieval, their memory likely depended on striatal regions, as it is involved in recalling sequences of actions, mediated by this region (Burgess, 2008). Although the Guided condition removed the need for decision-making, it still provided participants with sufficient inertial cues, including proprioceptive, vestibular and visual flow information. It is the information that we believe participants utilized later to retrieve the exact route taken during encoding. Another notable observation in our data is that route memory performance in the Guided condition differed significantly from that in the Passive condition (in the Headset-based VR group). This finding once again suggests that the motor information available during Guided exploration was sufficient to enhance memory compared to Passive exploration. Moreover, the lack of a significant benefit of navigation strategy on route memory performance in desktop but not Headset-based VR implementation provides additional evidence that environments offering enhanced self-motion cues can better support route memory.

The critical role of test type at retrieval to spatial knowledge

Previous research has employed various methods to examine the relative contributions of decision-making and motor processing to spatial memory, including map drawing, landmark recognition and pointing accuracy to target objects (Gardony et al., 2013; Münzer et al., 2006; von Stülpnagel & Steffens, 2012; see Chrastil & Warren, 2012 for review). These studies suggest that decision-making is more beneficial than motor control for enhancing spatial performance. It may be that the processes shown to be beneficial to performance vary depending on the type of test used to assess memory.

When assessing survey knowledge,[16] it is plausible that following explicit instructions from a GPS during guided navigation could divide attention and impair performance on global memory tests (e.g. map drawings). Gardony et al. (2013) argue that guided navigation can impair attention by requiring participants to hold instructions in working memory while navigating, leading to reduced attention to landmarks and alternative routes. In this way, survey knowledge is hampered. In line with this, Chrastil and Warren (2015) emphasize that decision-making is essential for acquiring topological graph knowledge, which involves understanding the connectivity of an environment to facilitate detours or novel routes during testing. In contrast, route memory tasks, such as the one employed here, require remembering specific action sequences at particular locations within a route (Chrastil & Warren, 2012). Participants were simply asked to reproduce the path taken during encoding. Our selection of the memory task may have led to an increased reliance on motoric engagement rather than decision-making. This underscores the importance of considering the type of test used to evaluate memory when making claims about the processes critical for spatial-based memory.

Regardless, based on our current findings, we propose that self-generated movements are a crucial factor in enhancing memory for spatial routes, potentially more so than decision-making about the travel path. However, it is important to note that our results may be limited to contexts in which memory assessment involves accurately reproducing one's steps (motor-based memory task). Future research should investigate whether guided navigation during encoding provides less benefit when the memory assessment requires more conceptual or topographical knowledge. To this end, our future work is investigating the impact of guided navigation on various measures of survey-based spatial memory, in both younger and older adults, such as map drawings of routes traversed and landmarks observed at encoding.

[16] Survey knowledge is configural "maplike" knowledge that includes metric distances and directions between locations. Local survey knowledge is based on a set of landmarks that are all visible from most places in the environment, whereas global survey knowledge must be constructed from subsets of landmarks visible from different locations (Appleyard, 1970).

The role of individual differences in spatial navigation

Our findings also underscore the role of individual differences in shaping spatial navigation performance across immersive and non-immersive virtual environments. Specifically, in Desktop-VR, participants who crossed more intersections during Active exploration exhibited better route memory performance. Similarly, in Headset VR, the total time spent at intersections during Active exploration was negatively associated with route overlap deviation (indicating better memory performance). These results align with prior animal research indicating that intersections serve as salient spatial boundaries, helping to contextualize cognitive maps (Moser et al., 2008). Notably, in Headset VR, pausing at intersections and along the route during Guided navigation was linked to improved memory. This reveals that brief pauses may facilitate the encoding of spatial cues and ultimately enhance spatial memory, even when navigation is guided. These findings are further supported by the regression results, which revealed that in Desktop-VR, route memory in the Active condition was predicted by the number of intersections traversed, while Guided memory was predicted by navigation proficiency measured by *SBSODS* scores.

Further, intrinsic qualities such as motivation and preference also played a significant role in shaping memory outcomes. In Headset VR, a stronger preference for Active exploration was linked to, and predicted, higher route memory performance in this condition. This is consistent with the higher preference ratings observed for Active relative to Passive encoding strategies. These regression results, however, were not detected in the Desktop-VR group, even if participants preferred Active and Guided conditions relative to Passive. Collectively, these results emphasize that aligning navigation strategies with user preferences could positively impact memory performance, especially in highly immersive settings. On the other hand, motivation predicted better route accuracy following Active exploration in the Desktop-VR group, which is reflected in the higher motivation ratings observed for this condition relative to Guided and Passive. We speculate that in low-immersion settings, such as Desktop-VR and in Passive conditions that reduce user engagement, maintaining attention may be difficult, limiting route memory.

Further, positive dimensions of curiosity such as joyous exploration and social curiosity were associated with improved memory following Active and Guided exploration, respectively. While negative dimensions such as deprivation sensitivity were linked to poorer memory following Passive conditions. Regression models further supported these observations, with social curiosity predicting route memory performance following Active exploration in the Headset-VR group. This suggests a dual effect: curiosity can either enhance or hinder spatial encoding depending on its emotional valence and whether the environment allows for information-seeking behaviour. Indeed, the Prediction, Appraisal, Curiosity and Exploration (PACE) framework proposed by Gruber and Ranganath (2019) proposes that an anxious state could lead to behavioural inhibition, potentially diminishing memory performance. In line with this, Brunyé et al. (2009) showed that spatial representations formed during high arousal states tend to have more global configural details about the broader inter-landmark structure of an environment. In contrast, a low arousal state diminished participants' ability to accurately compare distances between landmarks that are relatively far as opposed to close to one another. These results show that various emotional and arousal experiences can differentially influence how we encode and retrieve spatial information, highlighting the nuanced role of emotions in cognitive processes related to navigation and memory.

Constraints on generality

We recognize that experiencing VR environments while sitting down, as did the participants in our study, limits the sensory and motor cues gained about one's location in space when exploring an unfamiliar environment, relative to walking. However, our research paradigm still allows for participants to engage in motor actions to dictate the path of travel (i.e. to enable head and body rotation, and tuning of the steering-wheel controller) and utilize vestibular information received from head rotation (see

Chrastil & Warren, 2012 for review; von Stülpnagel & Steffens, 2012). Further, seminal reviews and research in the field of spatial navigation have also manipulated motor control similarly (see Chrastil & Warren, 2012 for review; Chrastil & Warren, 2013; von Stülpnagel & Steffens, 2012). Thus, we believe that our manipulation of motor control is one that sufficiently reflects current definitions of motor actions outlined by the field. Nonetheless, future studies could allow for greater motor engagement by having participants actually walk while immersed in VR to better simulate the inertial cues (i.e. cues that provide information about linear and angular acceleration) evoked when exploring new surroundings (Waller & Nadel, 2013). Studies should also directly measure head movements to determine whether a greater rotation of the head, indicative of visual observation, could influence subsequent spatial memory.

Another dependent variable to consider in future work, when examining the influence of navigation strategies on spatial memory performance, is roaming entropy. This is an index of the variability in an individual's territorial coverage, and it is demonstrated as a good measurement of participants' motivation during the study phase of VR (Cen et al., 2024). Future research could incorporate roaming entropy as an objective measure of exploration to assess whether higher entropy (i.e. exploration covering many zones within an environment) corresponds to increased curiosity and motivation, ultimately enhancing spatial memory performance. Including such measures would help disentangle the interplay between exploration strategies, motivation and memory retention, adding an important dimension to our current findings.

Finally, we believe that it is also important to consider the authenticity of spatial environments when examining spatial memory. In the current work, we made considerable effort to enhance ecological validity. We used virtual environments that mimic real-world streets, carefully designing street layouts and incorporating landmarks unique to each city (e.g. a red telephone booth in London). Environments were counterbalanced across participants, making it unlikely that structural differences between environments systematically influenced the results. Notably, very few previous studies examining route memory have incorporated such realistic urban simulations. Therefore, we believe that our approach provides a realistic estimate of navigational experience compared to typical VR paradigms. However, future research can further enhance the realism of virtual environments by including auditory features like sirens, car honks and pedestrians to mimic the complexity of real-world navigation. We also acknowledge that route memory was evaluated shortly after exploration of virtual environments, and it will be of theoretical and practical importance to learn whether the same pattern of results emerges when memory is assessed hours or days later. While these questions extend beyond the scope of this study, future research can explore these factors to develop a more comprehensive understanding of route memory.

CONCLUSION

Our findings indicate that self-generated motoric engagement, needed in both active and guided navigation conditions, enhances the formation of route memory relative to passive observation. That is, we have demonstrated that self-motion cues, such as head rotations, full-body 360-degree turns and forward movement via handheld controller, during initial exploration of a virtual environment support route knowledge. Decision-making, in comparison, seems to play a lesser role as memory did not differ across navigation conditions that required it (Active) versus not (Guided). Moreover, the selective finding of a memory benefit in the Headset-based VR, but not the Desktop-VR group, provides additional evidence that environments offering the opportunity for motor engagement better support route memory. Our findings also have implications for the development of navigation systems for humans. Relying on external GPS devices (analogous to the guided condition in the current study) for navigation is unlikely to impair memory for the routes, as others have suggested (Bakdash et al., 2008; Gardony et al., 2013), provided that the motor system is engaged during the initial encoding phase.

AUTHOR CONTRIBUTIONS

Yadurshana Sivashankar: Conceptualization; investigation; writing – original draft; funding acquisition; methodology; validation; visualization; writing – review and editing; software; formal analysis; project administration; data curation; resources. **Philip He:** Writing – review and editing; software; visualization. **Patrick Tsapoitis:** Software; writing – review and editing. **Evan Skorski:** Data curation; writing – review and editing. **Myra A. Fernandes:** Investigation; funding acquisition; writing – review and editing; supervision; resources; methodology; validation; visualization.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data necessary to reproduce the analyses presented here and VR environments are publicly accessible on the OSF website through this link: https://osf.io/qunkf/?view_only=3a5b3bf266d5485a85197f266319ae98. All analyses were carried out in *JASP* statistical software (Version 0.19.1) and *SPSS*.

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