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Abstract

Navigation aids limit the need for decision-making, possibly hindering memory for routes travelled. We manipulated type of navigation at encoding, within virtual-reality. In the Active condition participants self-initiated decision-making about routes, to find a target, and in the Guided condition followed a pre-defined path overlaid onto virtual streets. In both, they had volitional control using hand-held controllers, allowing head and body rotation in a swivel chair. In the Passive condition they viewed a pre-defined route, with no control of movement. At retrieval, participants were asked to reproduce their exact route from the initial starting point. Route memory was better following Active and Guided encoding than Passive. A visual navigation aid does not impair route memory if volitional movement is maintained.

Key words: Route Memory, Motor Control, Decision-making, Virtual Reality, Active Navigation, Guided Navigation

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1. Active and Passive Encoding of Spatial Knowledge

Successful navigation requires that we keep track of our location relative to our surroundings, and adapt dynamically to change (Dahmani & Bohot, 2020). Recent advances in technology have attempted to make this complex task simpler by offering users systematic turn-by-turn directions (Gardony et al., 2013). Given the prevalent use of navigational aids (such as Google Maps™), it is critical to examine whether reliance on such devices helps or hampers our memory for spatial routes (Dahmani & Bohot, 2020). Ishikawa (2019) has shown that the long-term use of navigational aids impairs performance on wayfinding, assessed by travel time, the number of stops, and travelling in the opposite direction to the end point. Global configural knowledge about the explored environment was also impaired (Ishikawa, 2019). To counteract these negative effects, some have suggested it would be beneficial for users to actively invest mental effort during a wayfinding task, to reduce the negative impact of automated visual- and audio-based navigation tools on memory for a route travelled (Parush et al., 2007). Further, Appleyard (1970) was one of the first researchers to show that passengers on a bus retain only route knowledge[1] of a city, whereas drivers who are actively making their own navigational decisions have much greater survey knowledge (i.e., a global representation of all routes encompassing a city; a birds-eye view).

In trying to understand factors that influence memory for routes travelled, past studies have suggested significant spatial memory benefits when encoding is ‘active’ rather than ‘passive’ (Chrastil & Warren, 2012; Jebara et al., 2014; Meade et al., 2019; Sauzéon et al., 2016).

[1] Route knowledge consists of a set of associations we make between a place and specific action sequences, that is, a set of turns at identifiable locations or decision points (see Chrastil & Warren, 2012 for review).

That is, route learning is significantly impaired 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 (see Chrastil & Warren, 2012 for review). These findings suggests that decision-making during encoding or initial exposure to a route influences later navigation proficiency (see Chrastil & Warren, 2012 for review; Weisberg & Newcombe, 2016).

In trying to explain the benefit of active over passive navigation to later spatial memory, past research suggests that active exploration consists of both a cognitive (mental manipulation of spatial information, allocation of attention, and decision-making) and a physical (motor control for locomotion, proprioceptive, and vestibular sensory information) component (Chrastil & Warren, 2012). It is unclear, however, which of these components drives the benefit of active exploration on subsequent memory for routes travelled. That is, is it the motor or the decision-making aspect of active navigation that is critical? Some suggest decision-making is a key component in successfully acquiring spatial knowledge about a map (Carassa et al., 2002; Farrell et al., 2003; Stulpnagel & Steffens, 2012). On the other hand, Day and Fitzpatrick (2005) and Smith (2017) have shown that body-based motor cues arising from proprioceptive and vestibular systems, engaged during encoding, are critical to spatial navigation. Spatial navigation requires the continuous integration of visual information, along with vestibular and proprioceptive cues, to enable both purposeful and safe navigation (for a review see Cullen & Taube, 2017).

Relatedly, it is unclear whether following directions provided by an external aid helps or hinders later route memory, as this type of guided navigation retains volitional control of movement, but removes decision-making (i.e., self-directed choice). During guided navigation, such as following systematic directions from a Global Positioning System (GPS), one is directed

about where to turn and when. Past studies have reported a negative impact on spatial memory performance following the use of a navigational device, particularly to survey knowledge (measured by a sketch map drawn of the explored environment), and item memory for landmarks (Dahmani & Bohbot, 2020; Gardony et al., 2013), suggesting that decision-making is key. For example, Munzer and colleagues (2006) found that a mobile navigation device that presented systematic route directions during navigation impaired later landmark and route knowledge, relative to the use of a physical map. The authors interpreted the benefit afforded by map-guided navigation (i.e., physical map) as due to the cognitive effort required by the participant. That is, a physical map required one to develop an integrated representation of landmarks represented along routes, and to transfer this information to route choices (decision-making) in the real environment. Engaging such cognitive processes is believed to have facilitated memory.

Similarly, Gardony and colleagues (2013) provided verbal navigation commands (e.g., “Forward”, “Slightly to the right in 100 ft”) every five seconds as participants explored virtual environments. These researchers found that the presence of a navigational aid impaired spatial memory assessed by recall of landmarks, and accuracy in later map drawings. They suggest that providing directional instructions in advance impairs participants’ ability to form a coherent mental representation of routes travelled and to successfully encode the nearby landmarks specific to that route and location. Put another way, listening and holding verbal commands in working memory during navigation is believed to compete for cognitive resources needed to retain an accurate representation of the spatial information.

In the current study, the way in which we provided directions during the guided navigation condition differed in two critical ways from past studies: first, participants received a visual cue (shown in the colour yellow, directly overlaid on the path to be taken) directing them

to the correct route to find the target object (a gold star). Second, participants did not need to hold verbal instructions in working memory, as they simply had to follow the visual cue that was always present in the form of an overlaid path. Importantly, we believe that our guided navigation condition better reflects how driving directions are provided in the real word, as navigational guidance in the form of a visual cue or verbal commands are always present and available to the driver (no working memory load). Thus, the aim of the current study was to investigate whether guided exploration, a navigation type that is analogous to following systematic directions from a GPS, hindered route memory. Guided exploration removes the need for decision-making during navigation, though in our study we retained the use of motor control over one's movement.

Another reason for exploring the utility of guided navigation is that the current literature suggests that exploiting the use of an external device, to reduce the information processing requirements of a task, has negative implications for one's memory performance. Risko and Gilbert (2016) define cognitive offloading as the use of physical action or affordances of the external environment to modify the cognitive demands required by a task. An example of a physical action is using fingers to solve simple arithmetic calculations or using gestures to convey meaningful information during speech (Novack & Goldin-Meadow, 2015; Sivashankar & Fernandes, 2022; Sivashankar et al., 2023). That is, offloading to the external environment involves using an external repository to hold information, or to help us retrieve information (see Risko & Gilbert, 2016 for review). Without an external aid one must register, rehearse, and maintain an internal representation of the information. Past research examining the negative impact of offloading on human cognition has found that memory for the offloaded information is poor in participants who saved to-be-remembered items on a computer, relative to individuals

who had to commit the target items to memory (Sparrow et al., 2011). Similarly, we too predicted that the presence of a navigational aid might impair memory for routes travelled, relative to when one explored without such an aid.

1.1 The Role of Decision-making in Active Exploration

Decision-making in particular has been predicted to be a key component in successfully acquiring spatial knowledge about an environment (Carassa et al., 2002; Farrell et al., 2003; Stulpnagel & Steffens, 2012). In a study conducted by Bakdash and colleagues (2008), participants' memory for the spatial layout of a virtual environment was assessed after encoding various environments in one of three ways: (1) active exploration involving both decision making and motor control, (2) deciding the path of travel with no volitional motor control [i.e., "backseat driver"] and (3) controlling a joystick for movement while receiving directions (no decision-making). During the test phase, spatial knowledge was measured by having participants point to target locations previously seen during exploration. Bakdash and colleagues (2008) found that pointing accuracy to target locations was comparable when the virtual environments were encoded under active navigation, and when decision-making was employed at encoding in the absence of motor control. In other words, simply exerting motor control did not benefit spatial memory. It is important to note, however, that the results observed by Bakdash and colleagues (2008) pertain specifically to memory for selective locations, as opposed to route memory, since participants had to simply point to target locations in a scene rather than demonstrate memory retention of a route.

Chrastil and Warren (2015) found decision making was a key component of active learning for the acquisition of topological graph knowledge. In their study, Chrastil and Warren (2015) assessed route learning using a "shortest route task", in which participants were required

to take the shortest route possible to reach a target landmark. This type of task, as described in their paper, does not assess the exact memory for a route travelled, but rather the ability to integrate knowledge of various known paths to take novel routes (i.e., graph knowledge). In contrast, the aim of the current study was to examine whether visually guided exploration in which a participant exerted motor control to explore a prescribed route, in the absence of decision-making, hindered route memory relative to active and passive navigation. This is an important question to address as navigation use has increased considerably in the recent years, and it is still unclear in the literature whether route memory, in particular, is dampened by the use of a navigation aid.

1.2 Current Study

In the current study, we were particularly interested in route memory, to better understand the possible consequences of following systematic directions from a GPS. Route memory requires the successful retrieval of precise place and specific action sequences at identifiable locations or decision points (Malley et al., 2018). To examine this research question, participants explored 12 environments within virtual-reality (VR) in one of three ways: (1) viewing a video of a pre-recorded path with no volitional motor control (hereafter referred to as 'passive'), (2) freely exploring an environment while making decisions about where to turn and how to arrive at a location (hereafter referred to as 'active'), or (3) receiving visual guidance to a final destination (hereafter referred to as 'guided'). The use of VR allowed us to simulate real-world environment layouts of cities around the world (e.g., Tokyo, New York), and to examine both the physical and cognitive contributions to route memory. To assess memory for routes travelled at encoding, participants were placed at the exact same starting position within each VR

environment, and were instructed to reproduce the path they had taken during initial exploration. This novel approach enabled us to accurately measure route memory in VR.

Given that route memory requires one to remember a set of turns at critical decision points (e.g., intersections), we hypothesized that removing decision-making during exploration would limit creation of a mental representation for the routes explored. For example, some researchers have noted that decision-making during navigation requires one to draw on previous experiences to inform navigational decisions (Shohamy & Daw, 2015). It is believed that the self-referential cues evoked by a requirement to decide, then enhances memory for those key decision points when called to retrieve. Further, it is well-known that the medial pre-frontal cortex (mPFC) plays a critical role in decision-making (Euston et al., 2012). Recent studies suggest the involvement of mPFC in strengthening hippocampal-dependent memories for events which require decision-making (Sul et al., 2010). The strong network connectivity between the ventral half of the hippocampus (critical for encoding spatial locations via place cells) and mPFC offers further anatomical evidence of this interaction (Preston & Eichenbaum, 2013; Shin et al., 2019). Thus, active navigation was predicted to confer the greatest benefit to route memory, followed by guided and then passive exploration.

However, it is important to note that efferent motor commands that determine the path of travel during volitional motor control are also suggested to be critical in mediating the benefit of active navigation to spatial learning (Chrastil & Warren, 2012). Notably, past work in humans has shown that successful representation of a cognitive map involving both landmark and route knowledge exclusively relies on the intact functioning of the vestibular system and other body-based motor cues (Jabbari et al., 2021; Waller et al., 2004). Thus, it is possible that memory in the guided condition would be similar to that in the active one if these motoric contributions

outweigh the cognitive, decision-making, contribution. Thus, we examined whether a navigation type that engaged the motoric system at encoding, in the absence of decision-making, conferred a benefit to memory proportional to active navigation.

We were also interested in documenting any individual differences in the influence of each navigation condition on memory. After participants completed the exploration and retrieval phases in VR, we asked them to complete a questionnaire probing for individual differences in everyday navigation proficiency as measured by the *Santa Barbara Sense of Direction Scale* (Hegarty et al., 2005; *SBSODS*). We also measured whether there were any differences in self-reported levels of motivation and preference to explore in one of the three navigation conditions (passive, guided, and active). Past studies have reported a critical role for motivation in enhancing spatial memory in children, younger, and older adults (Gruber et al., 2014; Sakaki et al., 2018; Sivashankar et al., 2024). For example, Gruber and colleagues (2014) have suggested that we better encode information that we are motivated to acquire because it better engages attention, promotes exploration, and leads to information-seeking behaviour, ultimately enhancing memory. This neurocognitive framework stresses the interplay between motivation and the so-called reward networks in the brain, whereby motivation induces a state of curiosity that enhances memory through the release of dopamine in the hippocampal memory system (Lisman & Grace, 2005). Further, prior studies have linked hippocampal volume and blood flow to 'active' navigation. That is, when motor control and decision-making are required at exploration (Javadi et al., 2017; Konishi and Bohbot, 2013; Maguire et al., 2000) these indices increase. In light of these findings, we believe that hippocampal-mediated memory for a route travelled (Jansen-Osmann & Wiedenbauer, 2004) would be better remembered if greater motivation is reported for a given navigation condition. We were specifically interested in

determining whether participants were more motivated to explore in the active and guided conditions, relative to passive, as this could be sufficient to explain any subsequent benefit to memory. Finally, we measured simulator sickness (Kennedy et al., 1993; *Simulator Sickness Questionnaire*) and one's sense of presence in VR to assess the "realness" of the virtual environments (Schubert et al., 2001; *Igroup Presence Questionnaire*). This too could indirectly influence memory performance for the routes travelled in VR.

2. Method

2.1 Participants

After conducting a power analysis using G*Power software (version 3.1), a sample size of 43 participants or greater was deemed necessary to achieve 90% power to detect a medium-sized (Cohen's $d = 0.5$) main effect in a within-subjects design (i.e., a one-way repeated measures), with an alpha level of 0.05 (Field, 2005). Fifty undergraduate students (30 males, 20 females; $M_{age} = 22.0$, $SD = 2.20$) from the University of Bordeaux in the New-Aquitaine region of France, were recruited on a volunteer basis to participate in the study. The Research Ethics Committee at University of Bordeaux and University of Waterloo approved all study procedures. Written informed consent was obtained from all participants prior to experimentation. Data collection took place between March and August of 2022.

2.2 Materials

2.2.1 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/). Mapbox generates game objects for roads and structures using

open-source geolocation data and 3D scans of buildings, requiring a GPS position and a zoom scale to specify the perimeter of the location that is being simulated. Unity © engine is a game development platform used by game designers to create virtual environments for players to explore. In our experiment, we paired a VR immersion plugin with 3D Unity © engine that generated game objects using geolocation data from real cities, creating an application that allowed participants to use VR headsets to virtually explore custom-created 3D environments based on real-world environment layout of selected cities.

The VR application included 12 Virtual Environments (VEs) 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. Our VR application allowed participants to explore VEs with a lightweight HTC VIVE headset (HTC Corporation; Valve Corporation) and handheld controllers, with continuous button press and heading rotation, for an easy-to-use control interface. Environments in our VR program were chosen to contain sufficient path complexity, and to be equivalent in environment sizes. Path complexity was operationalized to be the number of intersections (i.e., total possible turns) contained in each environment. 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[2]. Following environment selection, we integrated landmarks into each environment according to observations made from Google Maps™ Street View. These landmarks were 3D models of various objects that are commonly observed throughout a city, such as benches, trees, water fountains, bus stops, and traffic lights, downloaded from the free-to-use online source, Sketchfab (sketchfab.com). Finally, the velocity at which participants moved in VR was set at 8ms/sec (analogous to a vehicle going approximately 30 km/hr) within each exploration of an environment.

2.3 Measures

2.3.1 Calculation of route overlap as a measure of route memory

The primary dependent variable of interest was the accuracy in reproducing the same route at retrieval that had been travelled during encoding of environments. 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[3]. That is, for every environment, we collected 40 pairs of X, Y coordinates every second, during both initial exploration (encoding) and during retrieval, reflecting a participant's position in an environment. 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

[2] The mean number of intersections crossed at encoding during passive exploration was 12.0, guided was 12.1, and active was 9.7. There were no significant differences between the number of intersections traversed during each exploration type. Importantly, the number of intersections traversed at encoding for each condition did not correlate significantly with route memory performance (Active: $r(48) = -.09$, $p = .515$; Passive: $r(48) = .08$, $p = .570$; Guided: $r(48) = .14$, $p = .347$).

[3] Mean deviation distance was computed for each environment explored (12 environments in total) separately for each condition, i.e. 4 passive, 4 guided, 4 active environments, for each participant.

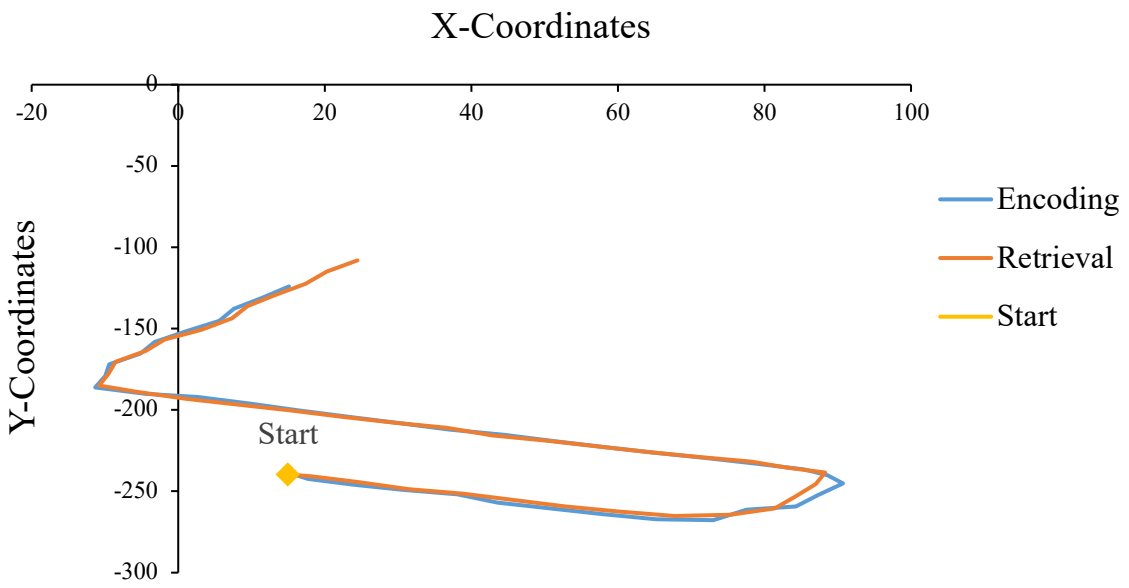
coordinates from encoding and retrieval (Liberti et al., 2014). We then calculated the average distance (*C*) value to obtain the mean deviation distance between Encoding and Retrieval for each environment, explored by a participant. A higher value signified that there was greater deviation between the 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; see Figure 1, Panel B, for paths 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 exploration.

2.3.2 Individual difference measures administered post VR-immersion.

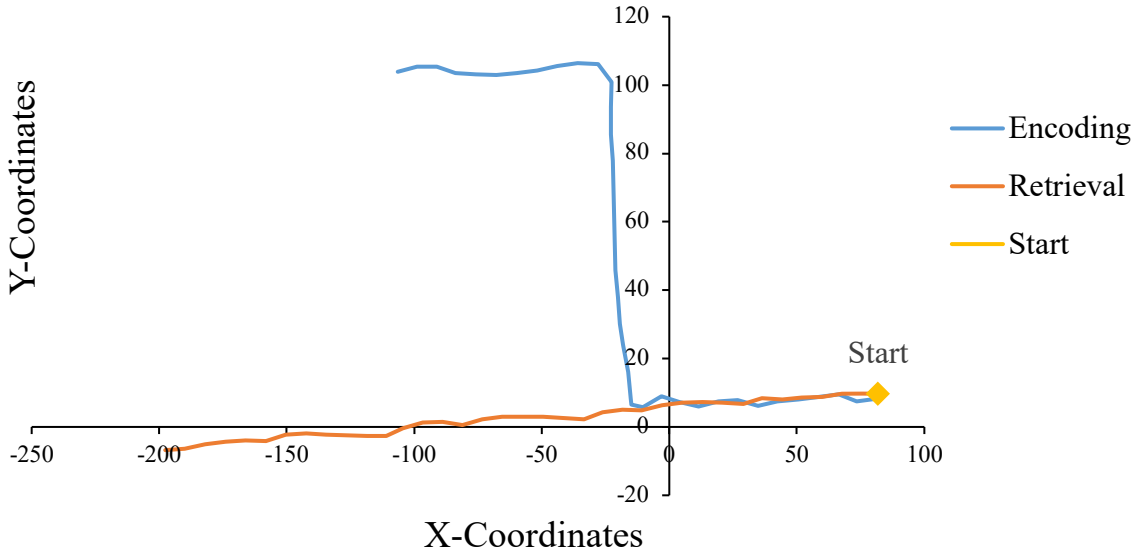
Spatial orientation ability of participants was evaluated with the *Santa Barbara Sense-of-Direction* (*SBSODS*) scale (Hegarty et al., 2005). Visuospatial ability was assessed to later determine whether inherent visuospatial skills influenced route memory performance, beyond our experimental manipulation. Each participant rated their endorsement of 15 statements 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 1–7. Participants then rated their motivation and preference to explore each condition (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”).

We also measured simulator sickness using the *Simulator Sickness Questionnaire* (*SSQ*; Kennedy et al., 1993) to evaluate oculomotor discomfort, disorientation, nausea, and fatigue experienced as a result 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. 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). Finally, we 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).

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).



2.4 Procedure

Throughout the entire VR experiment, participants were seated in a comfortable swivel chair that could turn a full 360°, placed in the center of a testing room. Following verbal instructions on how to use the VR headset, participants completed a practice phase with the VR equipment, designed to help them learn how to use the VR controllers to move within the virtual space. A single handheld VR controller was sufficient to navigate in the environment. To move forward, participants were instructed to press the Trackpad Button of the controller. To change their direction, participants had to rotate their head in the desired direction, as well as physically rotate in the spinning chair with their legs, while pressing the Trigger button on the VR controller, pointed in the direction of travel. We advised participants to take as much time as needed in the training phase in order to become comfortable with the environment. Immediately following the training phase, the experimental session began.

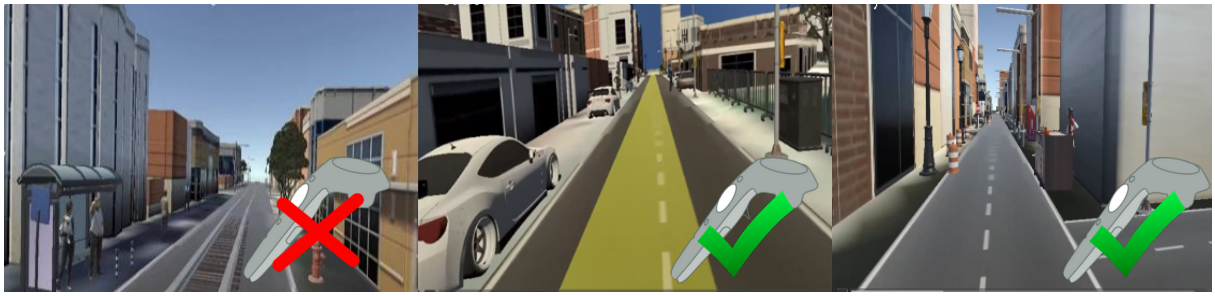
There were two main phases for each of the 12 environments: A study/encoding phase (40 secs), and then a retrieval phase (40 secs) which followed immediately, in which participants reproduced the exact route taken at encoding. During the study phase (i.e., the route of the path taken at encoding), participants explored each of the 12 environments within VR in one of three conditions: Passive, Guided, and Active. Condition was manipulated within-subject, with condition and order counterbalanced across participants.

The passive condition was created by recording 360-degree videos of a pre-defined path for each environment. Therefore, the path observed by participants in the passive condition differed to the paths travelled in the guided and active conditions. That is, we did not yoke the passive condition trials to a route travelled in the active or guided conditions. Participants observed the videos within VR to simulate the act of moving inside a vehicle from a passenger's seat. 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. You will be able to move your headset, but will have no control over the movement of your hand-held controllers”. To reiterate, participants did not exert motor control for movement, nor decide the path of travel. The guided condition was created using Mapbox Directions API to automatically generate the optimal path between two waypoints according to path data. Specifically, 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 colored in Yellow (see Figure 2) and overlaid onto the travelled path 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, during the guided exploration, participants exerted motor control using the VR controllers (along with head and body rotation) to move forward and follow the yellow line directing them to their end-point, but did not decide the path of travel. 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 using the VR controllers, and also decided the path of travel, thus, engaging both motor and decision-making processes. Therefore, the paths travelled in the guided and active conditions differed as the former path was experimentally controlled, while the latter was chosen by the participant. Prior to beginning each new exploration, an instruction appeared on the screen indicating the condition. Immediately after encoding (40 secs) a given environment, participants were placed back at the same starting position, and asked to reproduce (move themselves) along the route they had taken during initial exploration (encoding).

Each participant explored all 12 environments. Encoding conditions were blocked by type (4 environments of Passive, 4 environments of Guided, and 4 environments of Active). The order of the three condition blocks (Passive, Guided, and Active) was counterbalanced across participants. The total time spent in VR was approximately thirty minutes (including a break to reduce VR fatigue, before starting a new condition). After completion of the experiment in VR, the researcher administered the scales.

Figure 2. From left to right: passive, guided (movement was controlled via the handheld controller), and active (movement was controlled via the handheld controller) navigation conditions.



3. Results

3.1 Route Overlap (memory) Performance

We conducted a one-way repeated measures ANOVA (within-subject variable was Navigation Condition, Passive, Guided, and Active) examining Route Overlap score as the dependent variable. We observed a significant effect of Navigation Condition on Route Overlap Memory score[4], $F(1.50, 73.37) = 5.25$, $MSE = 490.29$, $p = .013$, $\eta^2p = 0.10$ (see Figure 3 for

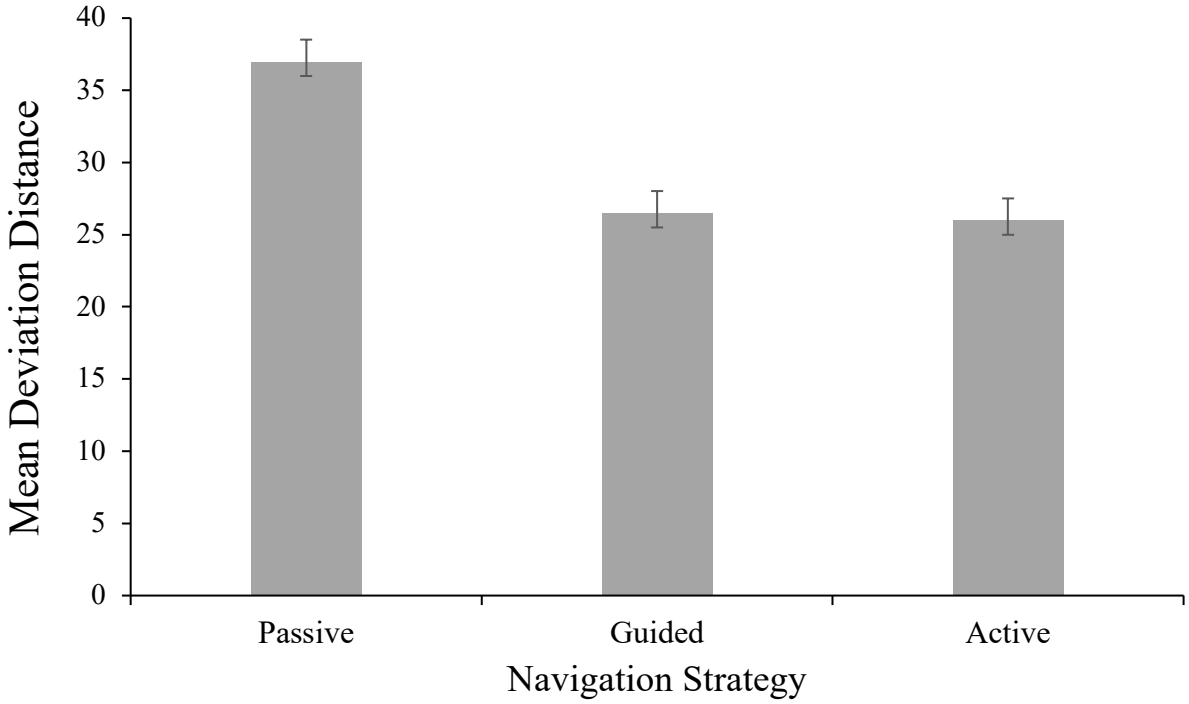
[4] Mauchly's test indicated that the assumption of sphericity had been violated ($p < .05$) thus; a Greenhouse-Geisser correction was applied.

means)[5]. We then conducted paired sample *t*-tests to compare Route Overlap score in each of the three Navigation Conditions (Passive, Guided, and Active). Passive exploration resulted in the highest mean deviation in route overlap accuracy relative to Guided and Active Navigation Conditions, $t(49) = 2.53$, $p = .015$, $BF_{10} = 2.72$, $d = 0.36$, 95% CI [0.07, 0.64], and $t(49) = 2.43$, $p = .019$, $BF_{10} = 2.19$, $d = 0.34$, 95% CI [0.06, 0.63], respectively.[6] There were no significant differences between Active and Guided exploration on Route Overlap accuracy, $t(49) = 0.20$, $p = .841$, $BF_{01} = 6.38$, $d = 0.03$, 95% CI [-0.25, 0.31].

Figure 3. Route overlap (measured by deviation distance between path travelled at encoding and retrieval) score across Passive, Guided, and Active conditions.

[5] In addition to route overlap, we also measured the number of stops made at encoding and retrieval for all three navigation conditions. We did not observe any significant correlations between route overlap score and this metric ($p > .05$). We, however, found a significant negative correlation between distance travelled at encoding and route memory in the Active condition, such that, as distance travelled increased, the deviation in route memory performance decreased (i.e., better memory; $r(48) = -.37$, $p = .008$). No such significant relation was found for Guided or Passive navigation.

[6] Bayes factors were calculated using the Bayes-Factor package for *R*, enlisting a default Jeffreys–Zellner–Siow (JZS) prior with a Cauchy distribution (center = 0, $r = 0.707$). This package compares the fit of various linear models. In the present case, Bayes factors for the alternative (BF_{10}) are in comparison to null models with subject-level random error. Bayes factor interpretations follow the conventions of Lee and Wagenmakers (2013). Bayes factors in favor 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.



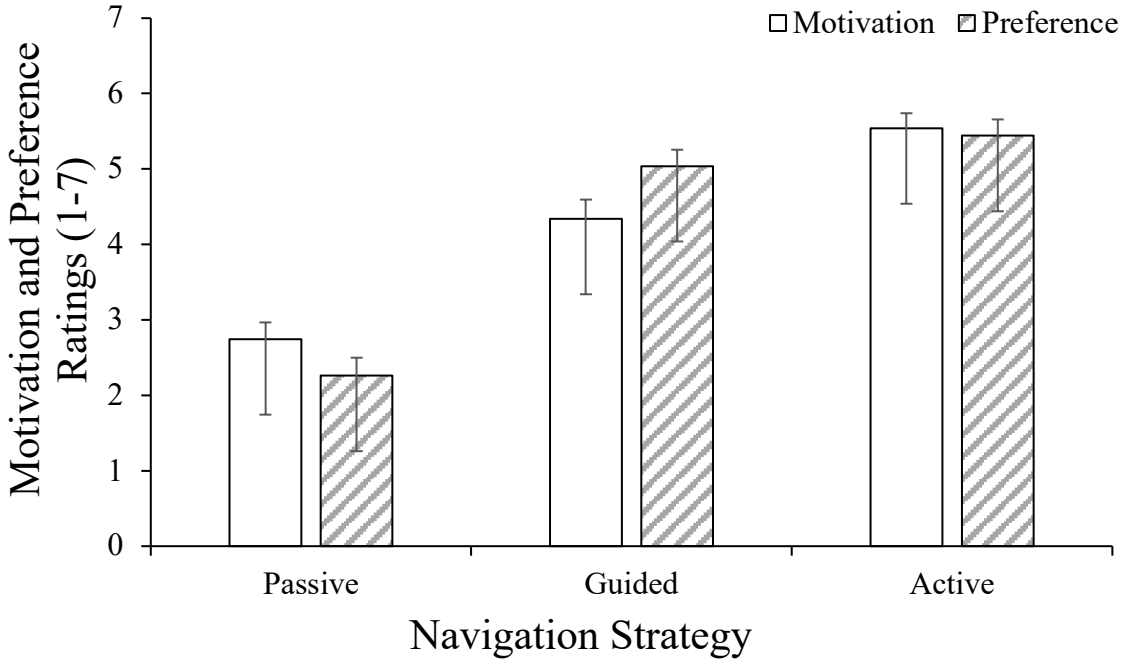
Note. Higher the score on the deviation distance, poorer the memory for routes travelled at encoding. Error bars reflect the standard error of the means.

3.2 Difference in Self-reported Levels of Motivation and Preference to Explore

We conducted one-way repeated measure ANOVAs to detect significant differences in motivation and in preference rating. As predicted, we observed a significant effect of Navigation Condition on self-reported motivation $F(2, 98) = 45.90$, $MSE = 2.15$, $p < .001$, $\eta^2p = 0.48$. Participants reported greater motivation to explore environments under Active and Guided Navigation Conditions (see Figure 4 for means) than Passive, $t(49) = 9.56$, $p < .001$, $BF_{10} = 9.57$, $d = 1.35$, 95% CI [0.96, 1.73], and $t(49) = 5.72$, $p < .001$, $BF_{10} = 2.487^{e4}$, $d = 0.81$, 95% CI [0.49, 1.13], respectively. Notably, participants endorsed Active Navigation as evoking greater motivation for exploration, relative to Guided, $t(49) = 3.92$, $p < .001$, $BF_{10} = 90.31$, $d = 0.55$, 95% CI [0.25, 0.85].

Using preference scores as the dependent variable we again observed a significant main effect of Navigation Condition, $F(2, 98) = 49.00$, $MSE = 3.06$, $p < .001$, $\eta^2p = 0.40$. Specifically, participants preferred to explore environments under Active and Guided navigation strategies (see Figure 4 for means) significantly more than in Passive, $t(49) = 8.19$, $p < .001$, $BF_{10} = 1.03$, $d = 1.16$, 95% CI [0.80, 1.51], and $t(49) = 8.90$, $p < .001$, $BF_{10} = 1.12$, $d = 1.26$, 95% CI [0.88, 1.63], respectively. There were no significant differences in preference rating between Active and Guided Navigation Strategies, $t(49) = 1.16$, $p = .252$, $BF_{01} = 3.46$, $d = 0.16$, 95% CI [-0.12, 0.44].We did not, however, find any significant correlations between motivation and preference scores and route overlap in any one of the three navigation conditions ($p > .05$).

Figure 4. Mean motivation and preference scores for Passive, Guided, and Active conditions.



Note. Error bars reflect the standard error of the means.

3.3 Correlation Between Route Overlap Score and Individual Difference Measures

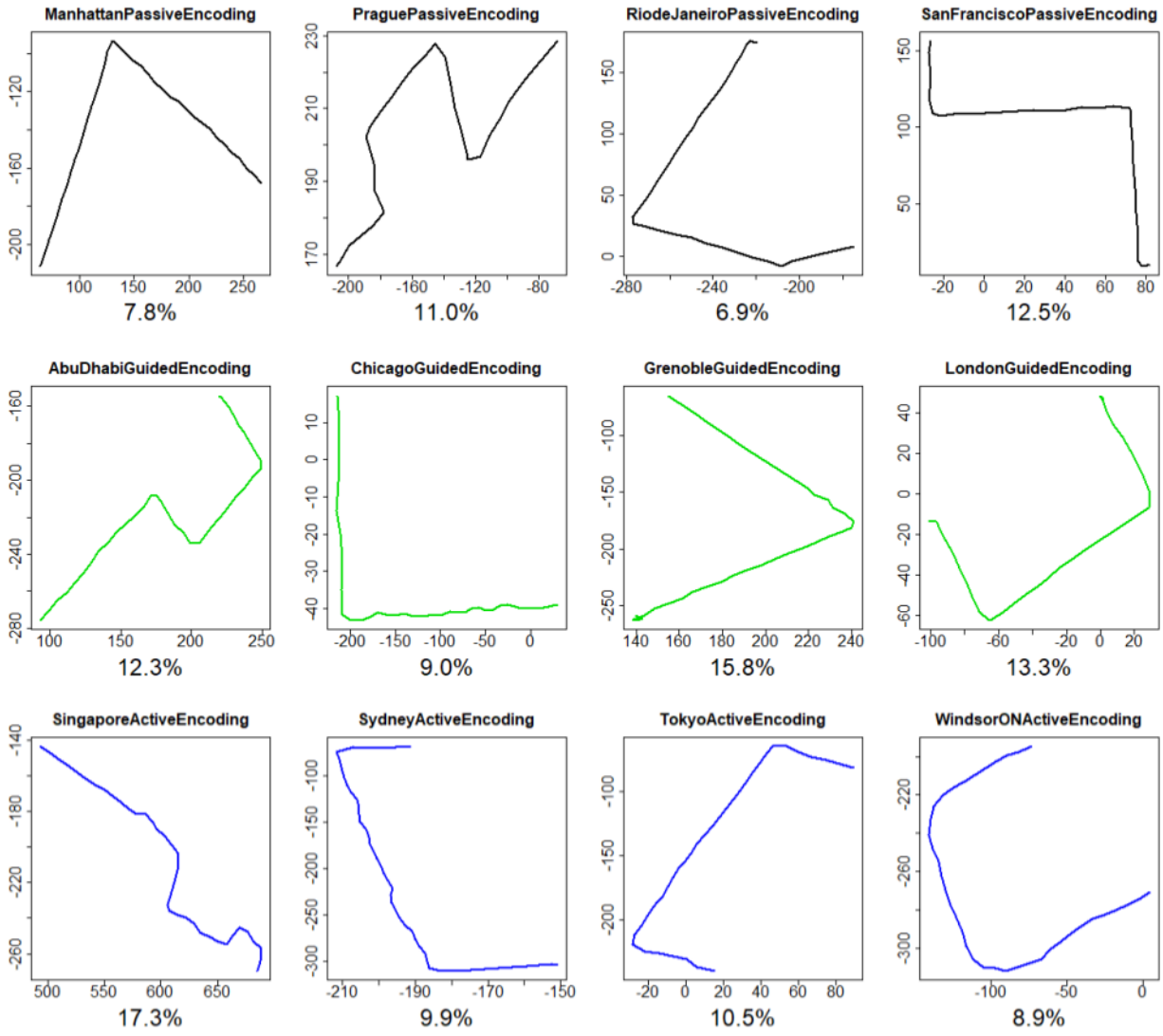
Given our goal of determining whether route memory performance in each of the navigation conditions was related to various individual difference factors pertaining to spatial navigation (measured by *SBSODS*; $M = 4.08$, $SD = 1.09$), sense of presence in VR (measured by *IP*Q; $M = 3.81$, $SD = 0.47$), and simulator sickness (measured by *SSQ*; $M = 11.60$, $SD = 8.65$), we ran a series of Pearson correlations. We did not observe any significant associations between route overlap (in Passive, Guided, and Active explorations) and inherent spatial navigation abilities of participants, VR sickness, and sense of presence ($p > .05$).

3.4 Assessment of Path Complexity Across the Three Exploration Conditions

We also considered whether differences in path taken across the three exploration conditions influenced subsequent memory for the route travelled. We applied an angle-based measure (see supplemental materials for a detailed description of the equation) of path complexity to each participant's encoding phase of each environment. That is, we recorded each participant's position within each environment, at each time-point during their 40-second 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 normalized 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 environments by condition. Figure 5 shows path complexity percentages for all twelve environments explored by a participant, with those explored in the Active condition shown in blue, in the Guided condition shown in green, and in the Passive condition shown in black.

We conducted a one-way repeated measures ANOVA comparing the percentage of path complexity across the three Encoding conditions (active, guided, and passive). We found a significant main effect of path complexity, $F(1.09, 53.18) = 6.64$, $MSE = 0.01$, $p = .011$, $\eta^2p = 0.12$. Bonferroni corrected t-tests revealed that the path explored during the active encoding condition ($M = 13\%$; $SD = 0.13$) was significantly more complex than that of the passive condition ($M = 7\%$; $SD = 0.01$), $t(49)= 3.64$, $p = .001$, $d = 0.72$, 95% CI [0.21, 1.22]. No other significant differences emerged. Correlational analyses also revealed no significant relationship between active, guided, and passive path complexity, and route memory performance ($p > .05$). In light of these findings, we do not believe that any variations in the path taken could have significantly influenced route learning.

Figure 5. Sample of a participant's path complexity and percentage (shown underneath) of each environment explored, with Passive condition shown in black, Guided condition in green and Active condition in blue.



4. Discussion

Past research suggests that active relative to passive exploration of an environment enhances memory. Past work also suggests that active navigation requires engaging 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 (Chrastil & Warren, 2012). It is unclear, however, whether following

directions provided by an external aid helps or hinders later route memory, as this type of guided navigation retains volitional control of movement, but removes decision-making (i.e., self-directed choice). In the current study, we created encoding conditions that differentially required decision-making and motor control, and compared the influence of these navigation conditions on memory for the route travelled. Navigation condition during encoding was manipulated within-subjects, and required either actively self-initiating decision-making about the route of travel, or simply following a visually guided route; in both conditions, volitional control of movements occurred using hand-held controllers that engaged head, body, and arm movements to advance through streets. In a third encoding condition, participants passively viewed pre-determined routes within VR, requiring no decision-making and motoric engagement. Of particular interest, in the 'guided navigation' condition, we examined whether motor control alone, in the absence of decision-making, would limit acquisition of route memory and render route memory, similar to that following Passive navigation. Relative to the passive condition, both actively self-initiated and visually-guided navigation similarly and significantly benefited the accuracy of route overlap between path travelled during exploration and retrieval. Our results show that visual navigational guidance during an exploration phase does not impair later retrieval of routes travelled. We suggest that motor engagement involving head, body, and arm movements during encoding, more so than decision-making about which route to travel, influences subsequent route memory. Our study has implications for understanding the consequences of following directions from a GPS guidance application.

Prior work in the field of spatial navigation shows that people differ greatly in their navigational proficiency, and this may also influence the benefit conferred by any particular navigation condition at the time of acquiring directions (see Chrastil & Warren, 2012 for review;

Weisberg & Newcombe, 2016). Given this, we examined whether individual differences influenced the effect of each Navigation condition on route memory. Participants rated their preference to explore environments under Active and Guided navigation similarly, and both more so than the environments in the Passive condition. In terms of motivation, participants reported the greatest motivation to explore environments under active, followed by guided and passive navigation conditions. These findings are in line with prior work showing that elevated states of curiosity evoked by exploratory activities or stimuli that are surprising, novel, and of intermediate complexity, foster both spontaneous exploration and active learning in children, as well as younger and older adults (Gruber et al., 2014; Sakaki et al., 2018). It is plausible that participants regarded both active and guided navigation to be activities of intermediate complexity and novel, as these navigation conditions required active exploration in VR, whereas passive exploration only required the observation of a pre-recorded path in VR. Although we found active and guided navigation to yield better memory performance, relative to passive, we did not detect a significant correlation between route overlap in these conditions and motivation and preference reporting. Future work could examine whether a relationship might emerge by gathering more precise moment-by-moment measurements of motivation and preference during the exploration phase. Another approach would be to experimentally manipulate participant' level of motivation and preference by asking them to explore an environment that is personally salient, or that is void of landmarks and simple in environment configuration.

4.1 Role of Motion Cues to Route Memory

The current work showed that decision-making about the path of travel at encoding did not confer a benefit to route memory, more than that conferred by motoric engagement. In the domain of spatial navigation, route memory has been shown to recruit the use of vestibular and

proprioceptive cues from head and body rotation to aid formation of an internal spatial representation of an explored environment (Jabbari, 2021). Precisely, past work has reported two distinct critical sources of information that humans rely on when navigating: these include landmark cues originating from the external environment, and self-motion cues stemming from body movement (Jabbari, 2021). In the context of self-motion cues, the vestibular system, which includes the semicircular canals of the inner ear, transduces inertial cues arising from physical motion, and is regarded as critical to spatial orientation (Day & Fitzpatrick, 2005; Smith, 2017).

We speculate that for one to successfully reproduce a route previously travelled, they would require continuous integration of body-based self-motion cues from the visual, vestibular and proprioceptive systems (Chrastil and Warren, 2012; see Cullen & Taube, 2017 for review). For example, continuous and sequential visual information received by the retina informs people about the flow of passing stimuli (i.e., optic flow) and helps one to perceive movement in space (Jabbari, 2021), while both vestibular and proprioceptive systems provide information about position of limbs in space during self-generated movement (Waller et al., 2004; Cullen & Taube, 2017). In addition, recent work by Zhu and colleagues (2022) examined eye movements and found that participants made greater saccades forward and backward along the intended path of travel (i.e., the path containing the reward). Critically, the number of sweeping eye movements increased with environmental complexity. These findings suggest that eye movements guide one's movement in space in a goal-directed manner, rather than in a bottom-up process that is purely driven by the saliency of a stimulus (Zhu et al., 2002). In relation to the findings of the current study, both active and guided navigation required the integration of oculomotor[7],

[7] We did not directly measure eye movements in the current study design, however, we reason that one would need to direct their gaze towards the intended direction, to be able to perceive and move in that direction.

vestibular and proprioceptive systems to guide eye movements and motion towards the path of travel. That is, one had to direct their gaze and orient their head, body, and the position of the VR controller towards a desired path to move in that direction. The failure to accurately carry out any one of these steps described above would prevent one from travelling in the desired direction. During passive navigation, however, one did not have to carry out a sequence of integrated self-generated motion involving gaze control, face and body rotation, as there was no motion required by the participant to move in passive exploration. Given that route memory was lowest in this condition, it appears that this factor is particularly important in explaining any boost to performance.

Moreover, work in mice and humans has shown the importance of context reinstatement to spatial navigation. Context reinstatement refers to the finding that in grid and place cells[8] of the medial entorhinal cortex and hippocampus (respectively), the spatial and temporal attributes of a space at encoding are reinstated just before retrieval (Lewis & Durrant, 2011; Jacobs et al., 2013). For example, we know from past work that place cells in the hippocampus do not show the same firing pattern in all locations that are perceptually identical to one another (Sharp, 1999). Rather, hippocampal place cells receive inputs from vestibular, proprioceptive systems, and visual motion to distinguish locations as A and B in order to modify patterns of cell firing (see Moser et al., 2008 for review). In our experiment, encoding and retrieval for any given city occurred in the same environment, and the subsequent retrieval phase required one to reproduce the path taken at encoding. From past work, we know that place cells use both visual and motor cues to reconstruct a spatial map of an explored environment (see Moser et al., 2008 for review).

[8] Place cells in the hippocampus encodes specific locations in space, whereas gird cells in the medial entorhinal cortex fire in response to spaces that represent a grid-like pattern (see Moser et al., 2008 for review).

Given this, we speculate there must be a reinstatement of place cell firing at retrieval that is reflective of the motor activity engaged at encoding (in addition to visual cues in the form of landmarks; Jabbari et al., 2021), to explain the benefit to route memory in both active and guided navigation. Based on our results engagement of motoric processing during initial navigation is particularly potent in enhancing route memory.

4.2 The Test at Retrieval

In the current study, we simply asked participants to reproduce the path taken at encoding, thus, we utilized a motor-based memory test that likely engaged the same processes as at encoding. In the past, researchers have used map drawing, landmark recognition, and pointing accuracy to target objects, to determine the relative contribution of decision-making and motor processing to spatial memory (Gardony et al., 2013; Munzer et al., 2006; Von Stülpnagel & Steffens, 2012; see Chrastil & Warren, 2012 for review). These studies have suggested that decision-making is superior to motor control in terms of improving spatial performance. In instances where survey knowledge is examined, it is indeed possible that the requirement to follow explicit instructions given by a GPS during guided navigation would divide attention, and impair memory on such global memory tests (e.g., on map drawings). In fact, Gardony and colleagues (2013) suggest that it is precisely attention that is impaired in the presence of guided navigation that limits performance on global knowledge tests, as participants need to hold instructions in working memory and navigate, thereby, failing to attend to landmarks and other routes making up an environment[9]. Further, Chrastil and Warren (2015) found that decision-making is an integral component in acquiring topological graph knowledge, where one must

[9] Survey knowledge consists of an integrated mental representation of all roads and landmarks encompassing an environment (i.e., a cognitive map), thus reflecting global knowledge for the environment explored (Chrastil & Warren, 2013).

know the various connecting routes of an environment to be able to detour and take novel routes to reach a target at test. Route memory on the other hand is a test in which one must remember particular action sequences at specific locations within a route (see Chrastil & Warren, 2012 for review). Hence, it is possible to remember specific turns solely based on one's initial motoric or procedural memory for the paths taken. In light of our findings, we suggest that self-generated movements are a critical component to enhancing memory for spatial routes, more so than decision-making about the path of travel; our results, however, might only apply when the assessment of memory involves 'reproducing' one's steps. Future work should consider whether guided navigation at encoding would provide less benefit when the assessment of memory is more conceptual or requires topographical knowledge.

5. Limitations

In the current study, motor control by the participant entailed head and body rotation, while seated in a chair that could turn a full 360°. We recognize that sitting limits sensory and motor cues about one's location in space when exploring a new environment, relative to walking. However, our research paradigm still allows for participants to engage sufficient motor command to dictate the path of travel (i.e., motor signals to enable head and body rotation, and pressing of trackpad on the VR controller) and utilize vestibular information received from head rotation (see Chrastil and Warren, 2012 for review; Von Stülpnagel & Steffens, 2012). Nonetheless, future studies could allow for greater motor engagement by having participants 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 et al., 2003). Similarly, it is also important for future research to investigate whether findings obtained using one type of immersive VR transfers to other encoding contexts such as

the use of a steering-wheel VR system, Desktop VR, or self-motion in real life which all differ in amount and intensity of motoric engagement.

Another limitation of the current study is that we did not control for the number of intersections in each map, as cities were created to resemble real-world map configuration. For example, past work revealed that pausing near intersections during active encoding was related to, and predictive of, route overlap accuracy, illuminating another cognitive component that contributes to the benefit of active navigation (Meade et al., 2019). Future studies could control for the number of intersections across environments and examine eye movements at critical intersections to examine the influence of route planning on later memory (Zhu et al., 2022). Relatedly, we did not equate the routes travelled in the passive, guided, and active conditions during the encoding phase. That is, we did not use a recording of the "active" route to generate the "guided" and "passive" routes Our analysis of path complexity revealed that the path explored during the active encoding condition was significantly more complex than that of the passive condition. No other significant differences emerged. However, because we did not find a significant correlation between overall path complexity and route memory performance for any of the conditions we do not believe this undermines our findings. Finally, future research could directly measure individual differences pertaining to motivation and preference on a moment-by-moment basis for greater precision. In the current study we did not find any significant correlations between motivation and preference scores and route overlap in any one of the three navigation conditions. However, we believe that measuring changes in states of motivation using thought probes could provide useful information about one's state of boredom and engagement during exploration (Yakobi & Danckert, 2021).

6. Conclusion

Our findings suggest that integrated self-generated motor activity at encoding is critical to benefit route memory. Given this, relying on an external GPS device for route guidance may not dampen our memory for those particular routes, as long as the motor system is engaged during initial encoding. These findings have implications for the way in which GPS navigational aids are currently viewed by the public and by the scientific community. Specifically, the results of the current study emphasize the need to precisely define and measure distinct measures of spatial navigation (i.e., route memory, survey knowledge, landmark recognition), and to determine the way in which GPS uniquely influences each measure.

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