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Memory retention of spatial knowledge in fire evacuation- and safety training

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Abstract

This study investigated the retention of spatial knowledge in buildings following route-learning training in a virtual reality environment. A total of 121 participants were tested up to three months later on putting waypoints of the route in the correct order and recalling directions at waypoints. Memory accuracy declined over time, consistent with classic memory theory. Route knowledge was retained more robustly than sequential order, highlighting the importance of contextual retrieval cues. Landmark presence, decision-point complexity, and route features modulated recall, demonstrating that both task and environmental characteristics influence spatial memory. A hierarchical Bayesian regression model quantified forgetting with median memory accuracy, capturing uncertainty across individual variability of participants and the environment in the experiment. Predicted accuracy decreased from approximately 91% initially to 77% after 12 weeks, and to approximately 72-75% after 6-12 months indicating that a substantial portion of spatial knowledge is retained over long intervals. By applying memory theory to analyse retention data, this study addresses a gap in the safety training field by providing a theory-driven approach to quantifying training effectiveness, enabling evidence-based design and assessment of safety and evacuation training in practice.

Keywords: fire safety, human behaviour, safety training, evacuation drill, spatial cognition, knowledge retention, forgetting, forgetting curve, brms, bayesian regression

Highlights

- Long-term memory retention in safety and evacuation training is underexplored.
- Spatial retention is tested up to three months in a controlled memory experiment.
- A hierarchical Bayesian regression model is used to predict memory accuracy.

1. Introduction

Building fires are a hazard to occupants and safe means for evacuation are of paramount importance during an incident. Although people's actions during a fire can be attempted to be guided in real time (e.g., signage or auditory instructions), adequate training and preparedness prior to a fire occurring are important to mitigate the impacts on occupant safety [1–4]. A variety of methods exist to train people for fire safety and evacuation [5,6]. There are pronounced increases in the use of virtual reality (VR), augmented reality (AR), and gamified training programs in the literature and in practice [5], but evacuation drills are still a common practice [6]. This may partly be attributed to drills usually being the only form of training being prescribed by regulations.

While fire safety and evacuation drills are often prescribed as a legal requirement, the contexts and applications for such requirements vary considerably across national legislation and often lack meaningful definition [2]. One issue is the separation of the goals of conducting training exercises for fire safety and evacuation, namely whether the activity intends to assess current evacuee performance or if it is aimed at improving future performance [2,6]. Out of these two, the effects of training on the future evacuee performance are still understood to a lower extent, although there is qualitative consensus on positive effects of training for emergency preparedness, assessment methods and metrics to capture training effectiveness vary greatly across studies [5].

Especially knowledge retention is less often investigated in (fire) safety or evacuation training, and is often limited to single delayed assessments at relatively short retention intervals [5,7]. Thus, longer term effects and potential benefits are still not yet that well understood over longer periods of time. Our memory, however, is central to our behaviour. This is exemplified in recent interviews on evacuation training and emergency behaviour in Menzemer et al. (2024), where multiple participants mentioned how memories influenced their response during emergencies, including the interpretation of alarm cues and the choice of protective actions [4].

The objective of this research is to investigate how memory and forgetting affect retention of knowledge from fire evacuation training. The study introduces theoretical approaches to memory (or conversely forgetting) and proposes their application to assess knowledge retention after training to quantify longer term training impact. The manuscript describes a memory experiment on spatial knowledge with retention intervals up to three months and investigates moderating variables on remembering the learned route. The contributions of this study are threefold. Firstly, it provides empirical evidence of the longer-term retention of (spatial) knowledge acquired in safety and evacuation training. Secondly, it informs training design practice regarding adequate training intervals and realistic knowledge thresholds. Lastly, it supplies empirical data to inform models of evacuation behaviour that account for memory-based rules [8,9].

2. Memory and forgetting

Memory theory is a helpful framework to better understand how knowledge is acquired from training, and how it is then stored and can be recalled later. Classic models distinguish between sensory, short-term (or working), and long-term memory [10–13]. Sensory memory lasts very briefly, typically seconds and less, and it processes and maintains raw information of environmental stimuli perceived through one's senses. Sensory information can then be encoded into short-term memory, where it can be consolidated into long-term memory. Information in short-term memory usually stays within the system for up to 60 seconds while undergoing organisation, manipulation and consolidation into long-term memory [10]. This process is strongly dependent on attention [14], and prone to disruption by interference [15,16]. Long-term memory may be further classified as explicit and implicit memory [17]. Explicit memory refers to consciously accessible knowledge, including the recall of specific information or experiences, while implicit memory could be described as more automated or unconscious remembering, like shifting gears while driving a car. For explicit memory, two forms of memory are distinguished, episodic and semantic memory [18]. Semantic memory entails general knowledge of concepts and facts, and episodic memory extends to personal experiences including the specific circumstances, context, and elicited emotions of a situation.

In this context, spatial memory, referring to information about the physical environment and the spatial relationships between oneself and objects within it, is of particular interest to understand how (emergency) wayfinding and navigation is affected by our ability to remember egress routes in a building. The question of how people learn and behave during navigation in physical spaces has a long tradition in psychology and eventually developed into its own subfield of "spatial cognition" with recent works in the neuroscience of its underlying processes [19]. Early research introduced the concept of cognitive maps, by showing that animals can form internal representations of their environment [20]. Siegel and White (1975) later proposed an influential model of spatial learning with progressive levels of spatial knowledge [21]. The first elements in that model consist of information on landmarks in an environment (landmark knowledge), followed by route knowledge on directions that connect landmarks with increasing detail on the relationship between them, before lastly acquiring survey knowledge, a map-like mental representation of a space independently from the personal position in it [21]. Modern research emphasizes that spatial memory and learning are complex and involve both egocentric (self-to-object) and allocentric (object-to-object) navigation strategies. Research also investigates representations and a multitude of spatial cues [22], and that memory may be more dynamic than progressively acquiring different stages of knowledge after another [23].

The successful recall of stored information generally depends on retrieval processes, which allow knowledge to be accessed. Successfully retrieving information depends on the interaction between how information was initially encoded and cues present during recall [24]. Even partial retrieval cues can lead to remembering as they can trigger processes, in which incomplete information activates reconstruction of the full memory trace ('pattern completion') [25]. Retrieval is influenced by heuristics and deliberate searching of memories, with fast, intuitive recall often complemented by slower, conscious reasoning [26,27].

However, the durability of spatial and general memory is subject to forgetting processes. Overall, forgetting commonly means the loss or reduction of the ability to retrieve stored information, and several mechanisms are thought to contribute: interference from competing information, trace decay reflecting the weakening of memory traces over time, and retrieval failure due to absence of effective cues [15,16,28]. Work by Ebbinghaus at the end of the 19th century established the basic forgetting curve showing rapid memory decay initially, followed by slower decay over time [29]. Following research showed that forgetting can take different forms (e.g. power-law, exponential, or linear memory decay) [15,30]. It is also indicated that memory loss can slow greatly over long periods, and some knowledge can remain stable for years [31]. More recently, Radvansky et al. (2022) proposed a framework that suggests that forgetting dynamics differ across stages of memory (from minutes to years), rather than following a single continuous function [30]. At the same time, some strategies can help to counter forgetting. In particular, distributed practice and repeated active retrieval are effective ways to strengthen retention and slow down forgetting [32,33]. This emphasises that forgetting can be actively mitigated through deliberate training interventions. Taken together, a better understanding of memory can provide valuable information to estimate how well knowledge acquired from training may be retained and can inform practical decisions about training modes and intervals.

Some studies have investigated how spatial knowledge decreases over time, offering insight into memory retention in applied contexts. This research indicates that spatial memory can persist over time, even after limited exposure. Ishikawa (2013) demonstrated that while route and landmark knowledge decay more rapidly, survey knowledge remains relatively stable over several months [34]. Kapaj et al. (2024) found that participants retained meaningful landmark and route knowledge two years after a single navigation episode in an outdoor environment, although a decay in landmark knowledge was observed [35]. Buttussi and Chittaro (2023) reported the retention of distance and direction information after a two-week interval following training in virtual reality and on a tablet screen [36]. These findings suggest that spatial memory can endure over time, especially when supported by engaging and rich learning experiences, and immersive training methods appear promising for enhancing retention. In the context of safety knowledge, Chittaro and Buttussi (2015) observed that immersive virtual reality (VR) training led to increased retention of safety procedures over a one-week interval compared to learning from a safety card [37], and Domgue K et al. (2025) observed increased accuracy in knowledge of operating fire extinguishers following training in virtual and augmented reality (AR) after 3-4 weeks compared to video-based training [38]. However, evidence from safety training effectiveness over time with longer or multiple retention intervals remains very scarce, as does research on knowledge on evacuation routes over time from training.

3. Methods

This research explores people's retention of spatial memory at different time intervals after being shown a route through a building in virtual reality. Prior to any recruitment and data collection, ethical approval for this study was obtained from the Swedish Ethical Review Authority (Etikprövningsmyndigheten; Application No. 2024-02160-01). Participants were informed that participation is voluntary, and they could at any time leave the experiment without being asked for a reason. The study and its data collection and analysis protocols were pre-registered on the 7th of March 2025 prior to any data collection.[1]

3.1. Research design

This study employed a mixed experimental design to investigate how people acquire and retain spatial knowledge from wayfinding training in buildings. The primary aim was to examine how well individuals remember a navigated route, with a focus on route knowledge as the dependent variable, operationalised as the ability to correctly recall or recognise route directions at decision points and to correctly arrange images from the route in the correct sequence (free reconstruction of order task).

The on-site wayfinding training was carried out in virtual reality (VR) with a head-mounted display and controllers. This approach was chosen for two reasons. First, to evaluate the efficacy of a proof-of-concept of deploying low-cost virtual wayfinding training in buildings that could be used analogously to teach egress routes in buildings. Second, to put a real-scale wayfinding task into a laboratory setting to facilitate larger sampling opportunities to study the memory of information acquired from such training over time. The building represented in the virtual environment is a multi-storey office building located in Denmark, and the virtual environment was created using 360° image and video footage of the actual building. Participants were first shown an immersive 360° video in VR that guided the viewer through the building. After a short break, they were asked to start from the same position and navigate along the same route through the building themselves. Figure 1 shows a floorplan drawing (not to scale) of the route that participants navigated on the building tour and in their wayfinding task. It starts at the main entrance of the building and finishes in a room on the third floor.

During the on-site session, participants completed a standardised psychometric test and a demographic survey. After the on-site session, participants were sent a retention test at different time intervals (retention intervals) to measure the spatial knowledge retained from the experiment. Retention intervals are manipulated between subjects with three groups tested after 2, 6, or 12 weeks, respectively. These intervals were chosen to ensure that they are all well within the period of Long-Lasting Memory [30], and to collect data as far into the future as reasonably possible within the time frame of the project period for this research endeavour with intermediate intervals.

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[1] The pre-registration report is available online at https://aspredicted.org/bn55-nkzc.pdf.

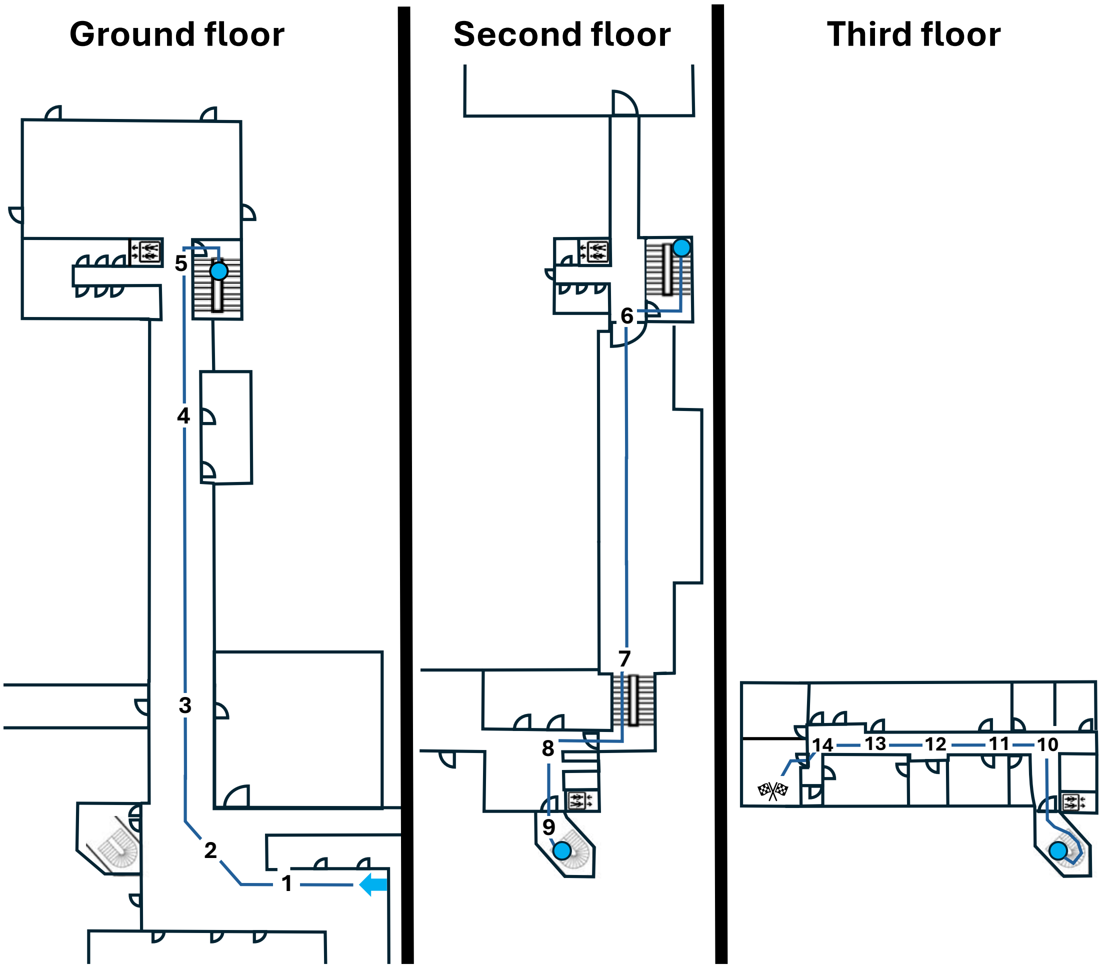

Figure 1 Qualitative drawing of the route in the virtual tour and wayfinding task. The staircase in the top right skips the first floor of the building. The numbers indicate the points where people's route choice was recorded.

The second variable manipulated in this experiment is previous familiarity with the environment. Table 1 provides an overview of the conditions for each experimental group in the study. Participants of Groups 1-3 will be recruited among the public with no prior knowledge of the building used in this study. To assess the influence of familiarity with the environment, a fourth group consisting of employees who work in the building represented in the virtual environment was tested at the 12-week interval. Originally the study protocol planned the retention test for Group 4 at the 6-week interval, but results from Groups 1-3 indicated relatively minor changes in memory over time and thus the protocol was adjusted to the 12-week interval. The design allows for controlled investigation of both the acquisition and decay of spatial memory over time.

Table 1 Experimental Design.

Group	Familiar with the building	Retention Interval
1	No	2 weeks
2	No	6 weeks
3	No	12 weeks
4	Yes	12 weeks

3.2. The virtual environment

The virtual environment in the experiment was a series of 360° pictures and videos of the building. The footage was captured with an Insta360 X3 camera and processed in proprietary software by the manufacturer (Insta360 Studio). The 360°-video footage was then used to create a 360°-video tour within the software Pano2VR (v7.1.8). The 360°-pictures were used in the same software environment to create a virtual tour by connecting each node with adjacent nodes using interactive markers in the environment (see Figure 2). Navigation between the nodes was possible through teleportation. This approach was favoured to promote easy, off-the-shelf solutions to developing a basic tool for training building routes. Background white noise and office sounds were added for increased immersion within the virtual environment. The application was compiled with NW.js (formerly node-webkit) to run locally as a standalone desktop app. The experiments were run on a desktop computer with an Intel Core i7-10700F CPU, 32 GB of RAM (3.2 GHz), and a dedicated NVIDIA GeForce RTX 3080 graphics card with 10 GB of GDDR6X VRAM. The hardware further included the HTC Vive Pro 2 head-mounted display with combined 5k resolution (2448 × 2448 pixels per eye) at 120 Hz and headphones. Participants could interact with the environment using an HTC Vive Pro Controller 2.0. The headset cable was suspended from above with flexible ceiling straps to allow free movement. Figure 2 exemplifies what participants would see during the experiment in the virtual environment.

Figure 2 Cropped screenshots from the virtual environment showing (left) walking up to waypoint 3, and (right) a participant choosing a direction at waypoint 3 during the experiment.

3.3. Sample characteristics

The on-site experiment with participants from the public was primarily conducted at the premises of Lund University. Participants were recruited from the area through advertising in local social media groups, via flyers and posters in and around the university. Participants needed to meet inclusion criteria to be considered eligible for the study, namely a minimum age of 18 years, the ability to give informed consent, and the ability to communicate in English. Criteria for exclusion from the study were cognitive impairments that would require permanent help from another person, physical impairments or the need of a hearing aid that would conflict with the usage of VR systems, being blind on one or both eyes, and certain medical conditions, like epilepsy, stress disorders, or a history of strong and recent concussion.

Volunteers to join the study were compensated with a voucher for a local supermarket equal to 150 SEK (approx. 13.40 €). Participants in Group 4, who worked in the building used in this study, were allowed to participate during working hours and were not further compensated.

A target sample size of n=22 per group was calculated in an a-priori power analysis for repeated and independent measures ($\alpha=0.05$; $1-\beta=0.8$) to detect large effect sizes which are based on reported experimental works on retention of spatial knowledge [34,36] and operational safety knowledge [38]. To account for participants not returning to the study for the retention test, recruitment aimed at target group sizes of 33 participants.

A total of 103 participants were recruited across Groups 1-3. Only 3 participants did not return to their retention test. Furthermore, one participant's data was excluded for not following instructions during the on-site session, one participant returned their retention test incomplete with the last task (free reconstruction of order) unanswered, and one participant was moved from Group 2 to Group 3 as they could not return the retention test at the originally assigned date. Among people familiar with the building in this study, 22 participants were recruited (Group 4). Some participants returned the retention test not on the exact day they were scheduled and contacted. Most people in each group returned the retention test at the assigned date and differences between the actual and nominal retention intervals did not exceed 5 days.

Table 2 gives an overview of the demographics of the participants that were included in the analysis for all experimental groups. The age span of all participants was between 20 and 40 years for Groups 1 to 3, and between 23 and 50 years for Group 4.

Table 2 Participant demographics for all groups in this study.

Group	**Number of Participants**			**Age**	**Spatial Orientation Test**	**VR Experience**		**Gaming Controller Experience**	
	Total	Female	Male	Mean ± SD	Mean Error ± SD	Yes	No	Yes	No
1	31	18	13	26.4 ± 4.0	21.0 ± 16.4	25	6	25	6
2	32	22	10	24.0 ± 2.7	16.9 ± 10.3	22	10	30	2
3	36	21	15	24.6 ± 3.8	17.9 ± 11.3	25	11	32	4
4	22	9	13	33.6 ± 6.0	18.8 ± 13.6	14	8	18	4

3.4. Data collection

Spatial abilities. The accuracy to imagine one's own perspective in relation to other objects and the relation between objects in space can vary between people. Since understanding these relationships forms an important ability to form spatial knowledge, it seemed relevant to ascertain a baseline for spatial abilities. The perspective-taking and spatial orientation test (SOT) [39] was administered during the on-site session in computerised form [40]. In a fixed array of objects, participants needed to imagine their position at one object, their facing direction towards a second object, and then point towards a third object. The pointing angle needs to be drawn into an adjacent egocentric diagram, meaning they needed to imagine their own position at the centre and draw the corresponding pointing angle. The score reports the mean angular error from a series of 12 tasks.

Route knowledge (way-finding task). Shortly after receiving the initial guided tour along the study route in virtual reality, participants were asked to find the same way through the building themselves starting from the same position. Participants could move through the building by navigating between fixed waypoints in a virtual environment comprising 360° images. They used a controller and point-and-click teleportation locomotion while physically standing up wearing virtual reality equipment (head-mounted display and headphones). Participants' navigation behaviour in the virtual environment was recorded via screen capture and monitored by the researcher in real time. Participants were advised to prioritise correct route decisions, and that their task completion time would be measured, but they were not further pressured. The time to complete the task was measured from the moment of confirming the instructions, thereby starting the wayfinding task, to the moment of reaching the final waypoint at the end of the route.

Route knowledge (retention test). Participants were asked to complete an online test. The survey's first part featured 14 images from along the route showing between 2 and 4 labelled arrows pointing in different directions. Participants should indicate the direction in which they remember going in the experiment. Figure 3 shows an example of one task from the test. Participants could leave an optional comment on what helped them find their way or influenced their response. Out of the 14 scenes, 2 images showed a stair landing, requiring participants to go upstairs (points 7 and 9 in Figure 1), 6 scenes required continuing straight ahead (points 1, 3, 4, 11, 12, and 13 in Figure 1), and the remaining 6 required a turn as the correct response (points 2, 5, 6, 8, 10, and 14 in Figure 1). The order of images in the test was randomised for each participant to address the impact of respondents' fatigue.

Figure 3 Example of a route knowledge retention test item in the study (Point 10 in Figure 1). Participants were asked to indicate the direction (here, A or B) they remember going in the experiment.

Sequential spatial knowledge. The last task of the survey was a free reconstruction of order task featuring 10 out of the 14 previously shown scenes in a random order. Participants were instructed to arrange the images in the order in which they had encountered them along the route in the experiment. The number of items was reduced to 10 to reduce the difficulty of the task and to ensure that participants could not easily infer the sequence from transitions between images.

Demographic data. To collect demographic information, a questionnaire was given to participants during the on-site experiment. The first part asked for people's age, biological sex, dominant hand, previous VR usage, previous experience navigating using gaming controllers, and employment status. The second part collected information on perceived task difficulty during the experiment and allowed for free-text comments on the experience and the experiment in general, on difficulties using the controls and navigation in the virtual task, and the realism and perceived disparity of the experience to reality. Participants in Group 4 were also asked to give a self-assessment of their general familiarity with the building.

Landmark presence. During the retention test, participants could optionally provide information on how they conceived their answers and if there was anything present at the scene that helped them in finding their way. The responses were analysed thematically and coded [41] for mentioning a landmark used for orientation. A landmark presence score has been calculated for each waypoint in the retention test as the ratio of participants mentioning using any landmark for orientation divided by the total number of participants providing a comment on the waypoint.

3.5. Experimental procedure

Upon arrival at the experimental site, all participants received a printed informed consent form with detailed information about the study's aim and procedure. The sections on risks of participation and exclusion criteria pertaining to health conditions that would constitute a contraindication for using virtual reality equipment, and the section on voluntary participation with the right to termination were specifically highlighted to every participant before proceeding.

After obtaining informed consent, the experiment commenced by administering the spatial orientation test (SOT). Next, the experimenter introduced participants to the VR system, explained how to wear the headset and operate the hand controllers, and answered any remaining questions. Participants were then fitted with the VR equipment and began the study with an immersive 360° video guiding them through a pre-defined route in the virtual representation of a real-world building (VR training tour). Instructions were to imagine being shown a room in the building which they must find their way later independently. The tour lasted for about 3.5 minutes slowing down at intersections along the route. After completing the guided tour, participants removed the VR equipment and took a brief break (approx. 1 to 5 minutes) before resuming the experiment. This was done to check on participants for any signs of motion sickness, and participants were offered a seat and water. During this break, participants were asked to complete the first part of the demographic survey.

After the break, participants were re-fitted with the VR headset and began a brief introductory scenario allowing them to practice basic point-and-click teleportation-based navigation within a neutral virtual environment. This control familiarisation lasted approximately 1 to 5 minutes. Once participants confirmed they were comfortable with the controls, the main wayfinding task was launched. In the wayfinding task, participants started at the same position as in the guided tour and were instructed to independently navigate the same route through the virtual building. The task ended either when the participant reached the final point of the route or after a maximum of 10 minutes.

Upon completing the VR task, participants completed the second part of the demographic survey. A short debriefing followed, during which the purpose of the study and data management protocol were explained. Participants could again ask questions, received their compensation, and were assigned a unique participant ID, which they would later use to complete the follow-up retention test. Participants were then assigned to one of three experimental groups. Group assignment was primarily random but allowed for manual adjustment to achieve balance across key demographic and cognitive characteristics. Participants were informed of their group's specific retention interval (2, 6, or 12 weeks) and the subsequent schedule for their follow-up test. Depending on their assigned group, participants were contacted after 2, 6, or 12 weeks to complete a retention test via an online questionnaire. Participants in Group 4 were scheduled to receive the same retention test at the 12-week interval.

4. Results

Free reconstruction of order

Figure 4 visualises the results from the free reconstruction of order task in the retention test in form serial position curves. For Groups 1-3, the data shows tendencies of primacy and recency effects where the position of items at the beginning and end of the memory task were remembered significantly better than items in the middle. This difference in memory performance between waypoints is compared statistically through separate Friedman tests that were conducted for each group (Group 1, $\chi^2(9) = 35.01$, $p = 5.93e{-05}$; Group 2, $\chi^2(9) = 73.93$, $p = 2.57e{-12}$; Group 3, $\chi^2(9) = 40.95$, $p = 5.11e{-06}$; and Group 4, $\chi^2(9) = 5.86$, $p = 7.54e{-01}$). These results indicate that recall performance varied significantly across serial positions within each group for Groups 1-3, whereas no significant effect was observed for Group 4.

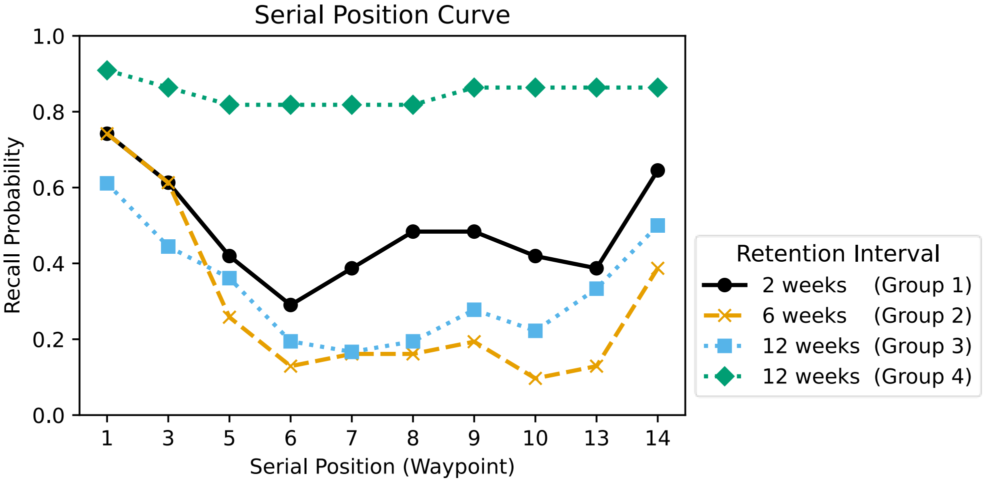

Figure 4 Results of the free reconstruction of order task (serial position curves) across all retention intervals. Unlike Groups 1-3, Group 4 was previously familiar with the environment.

Examining the data for Group 4, it was observed that 2 participants ordered the items in reverse (from end to start rather than start to end), but they likely still managed to infer the correct sequence of scenes and arrange them consistently. Subsequent examination of the data from the other groups yielded the suspicion that a few participants might have interpreted the task in a similar way, although this cannot be confirmed, and no participants in Groups 1-3 produced a fully correct but reversed order. The interpretation of the task likely varied systematically across all participants and groups, and thus it was decided not to modify the data.

To investigate the differences in memory between groups that are visible in Figure 4, pairwise statistical comparisons were conducted using Mann–Whitney U tests. Group 1 performed better than Group 2 ($p = 0.010$, Hedges' $g = 0.72$) and Group 3 ($p = 0.029$, Hedges' $g = 0.52$), whereas Group 2 and Group 3 were much closer to each other in performance ($p = 0.67$, Hedges' $g = -0.19$). Group 4, whose participants were familiar with the building in this experiment, performed substantially better than Group 3, who shared the same retention interval ($p = 0.000002$, Hedges' $g = 1.82$).

Route knowledge test

Because of the reasonable expectation that memory performance may vary across waypoints, the results from the route knowledge tests during the immediate on-site way-finding task and delayed retention test are first visualised and examined separately for each waypoint in the tasks. Figure 5 presents the results side by side in two plots for each group in the experiment.

For Groups 1-3, it is visible that all groups perform at similar levels of memory accuracy in the immediate wayfinding task during the experiment. Furthermore, Groups 1-3 generally show strong variation in their memory accuracy across the 14 waypoints in this task. This variation is much smaller for Group 4, which remains consistently near ceiling-level performance. Figure 6 presents a scatter plot of the participant data pooled over all waypoints in the memory tasks, together with the means for each group (or retention interval) and 95% confidence intervals. This qualitatively illustrates a pooled forgetting curve across the 12-week period.

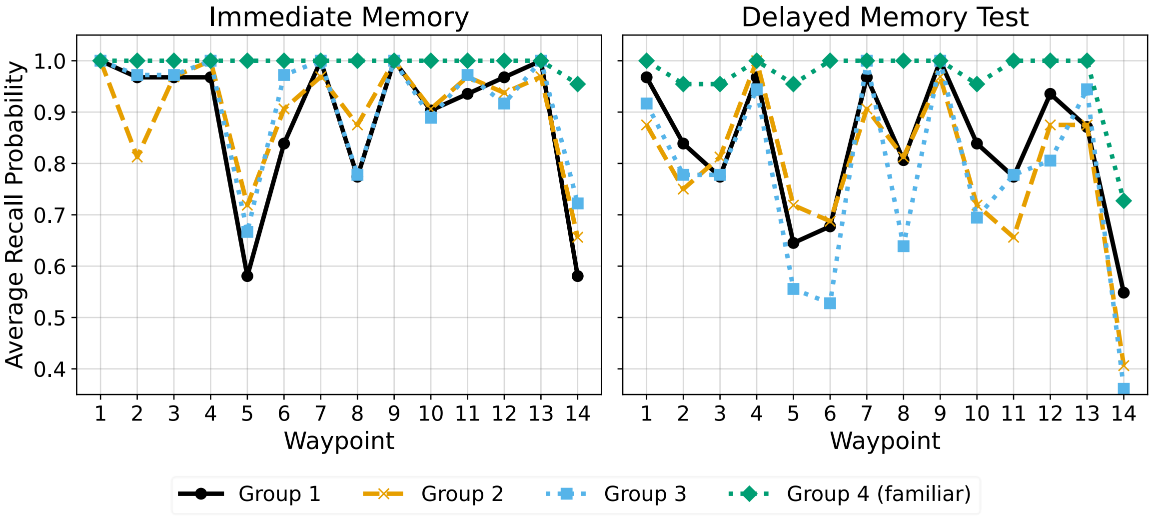

Figure 5 Average recall probability of correct directions for each of the waypoints tested in the task (left) during the experiment following the 360-video tour and (right) in delayed retention tests.

To investigate the apparent effect of waypoints quantitatively alongside other potentially relevant factors, a Bayesian multilevel logistic regression with a logit link was fit to the accuracy data. The model tested the effects of test time (immediate vs delayed), group (nominal retention interval), and waypoint characteristics, namely landmark presence, waypoint complexity (number of possible choices), and waypoint type (straight, turn, or stairs). Additional predictors included spatial orientation abilities, experience with gaming controllers and virtual reality, age, and sex, with random intercepts specified for participants to account for individual variability. The model was fit using the R package brms [42] to accommodate the hierarchical structure of the data, with repeated measures nested within participants, and binary outcome. Including participant-level random effects allows accounting for individual differences in overall performance.

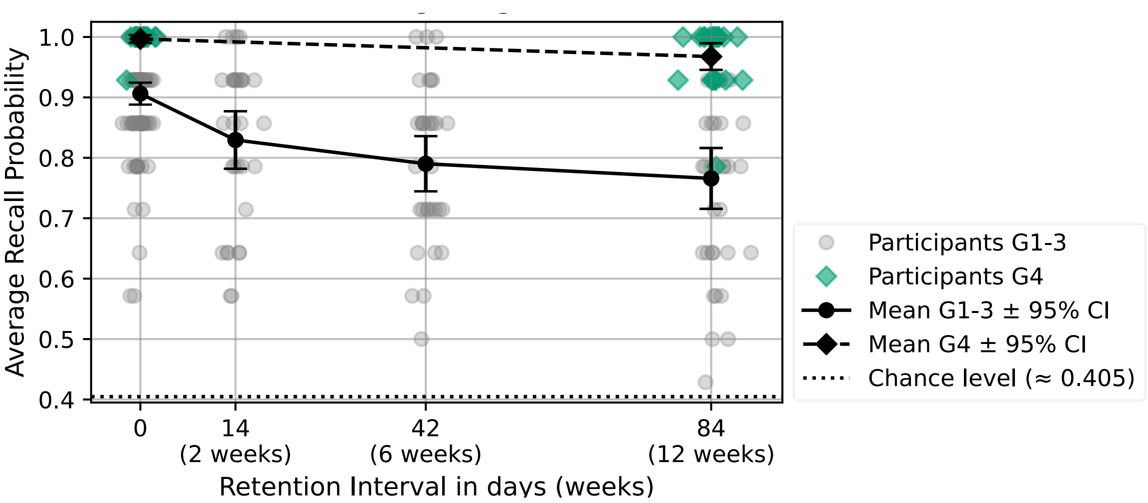

Figure 6 Averaged memory performance in correctly estimating route directions with 95% Confidence intervals (CI). Unlike Groups 1-3 (G1-3), Group 4 (G4) was previously familiar with the environment.

The posterior estimates indicated a decrease in memory accuracy over time (delayed test, β = −0.64, 95% CI [−1.08, −0.20]). Waypoints with a higher landmark presence score were recalled more accurately (β = 0.77, 95% CI [0.26, 1.30]), whereas more complex waypoints reduced accuracy (β = −0.50, 95% CI [−0.69, −0.32]). Stair-type waypoints showed higher accuracy (β = 1.96, 95% CI [1.12, 2.94]), whereas turn-type waypoints were recalled less accurately (β = −1.38, 95% CI [−1.70, −1.06]). For the interaction between test time (immediate vs. delayed) and group, results suggested a decline in Group 2 at the delayed test (β = −0.50, 95% CI [−1.09, 0.11]), although the 95% credible interval included zero, while Group 3 showed a decline in delayed accuracy compared to Group 1 (β = −0.89, 95% CI [−1.49, −0.31]). No meaningful effects were observed for spatial orientation, age, sex, or prior experience with computer gaming or VR. The participant-level random intercept standard deviation was 0.81 (95% CI [0.62, 1.03]), indicating moderate variability across participants. A comprehensive overview of the posterior estimates is provided on the OSF repository for this project [43], including diagnostics of the model, which indicate good model convergence (all $\hat{R}$=1.00).

Forgetting over time

To characterize memory decay, a Bayesian multilevel model was fitted to the binary accuracy data using the R package brms, considering a power-law formulation (see Eq. 1) which is the classic formulation in forgetting literature [15,30]. The model was fitted with random intercepts for participants and waypoints to account for repeated measures and item-level variability. These models estimated individual- and waypoint-level deviations in initial accuracy and forgetting rate.

$$M(t) = c + (a - c) * (1 + t)^{-b} \tag{1}$$

where *a* is initial accuracy, *b* the decay exponent, and *c* the asymptotic accuracy.

Weakly informative priors were chosen to reflect plausible ranges for memory performance, *a* was centred near ceiling, *c* towards chance level, and the decay parameter *b* was left largely uninformative to allow the data to determine the forgetting rate. Posterior predictions indicated a decline in memory accuracy over increasing retention intervals. For the power-law model, initial accuracy was high (*a* = 0.88, 95% CI [0.69, 0.98]), with a decay exponent (*b* = 0.17, 95% CI [0.10, 0.26]) and an asymptotic accuracy level (c = 0.28, 95% CI [0.01, 0.84]), capturing the characteristic slowing of forgetting over longer delays. Between-participant variability was substantial for initial accuracy (sd_a ≈ 0.98), moderate for asymptotic accuracy (sd_c ≈ 0.71) and decay parameters (sd_b ≈ 0.07), while waypoint-level variability was higher for initial accuracy (sd_a ≈ 3.44) and moderate for asymptotic accuracy (sd_c ≈ 1.26).

Figure 7 illustrates a forgetting curve across the observed delay intervals, derived from sample-level predictions of the fitted power-law model. The red regression line represents the model's posterior median predictions of memory accuracy over time, while the shaded ribbon indicates the 95% credible interval. The scatter presents individual participants' average recall performance at each measured delay, with black error bars showing the population-level means and 95% confidence intervals, similar to Figure 6. The model predicts a gradual decline in memory accuracy from baseline toward lower levels over the first three months. Performance would eventually stabilise over long delays. Together, the regression line and uncertainty bands capture the expected median forgetting trajectory. For plotting purposes, the number of posterior draws and delay resolution were reduced. The full regression model is available on the OSF repository associated with this project [43].

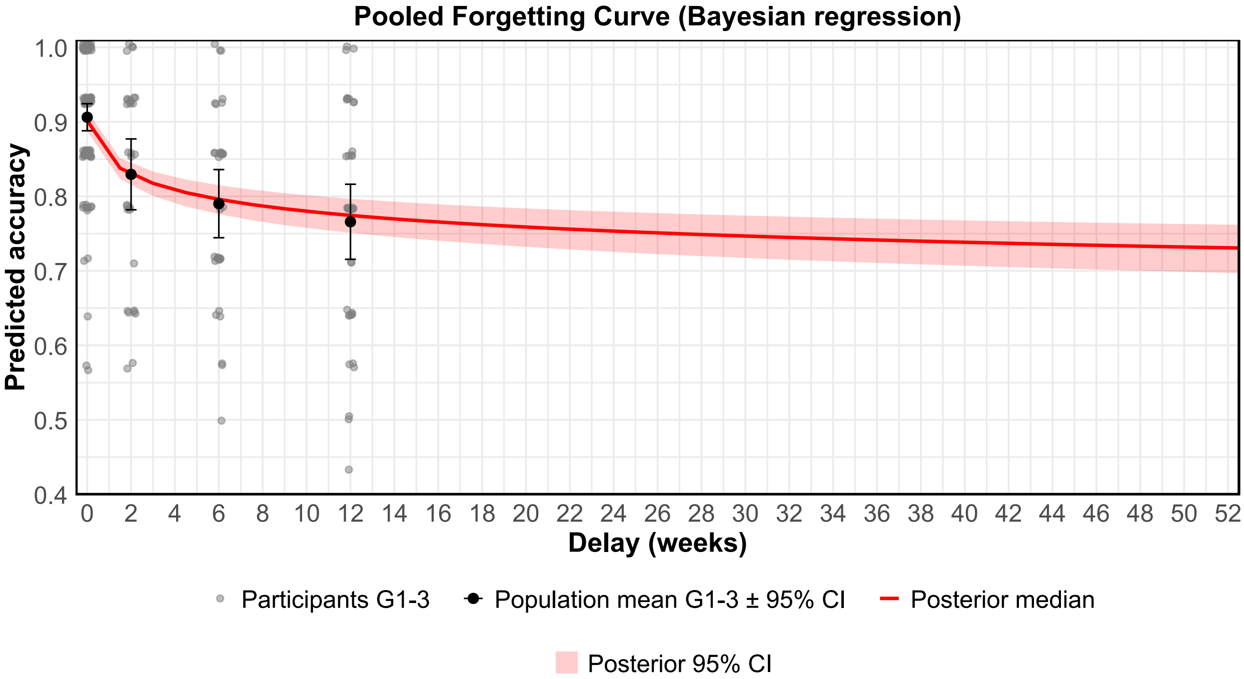

Figure 7 Memory performance over time as observed in this experiment in Groups 1-3 (G1-3) and posterior median with 95 % credible interval (CI) from a Bayesian multilevel regression.

5. Discussion

This study investigated how spatial knowledge from wayfinding training is retained over time. It used a virtual reality route-learning task with retention intervals up to three months, analogously to teaching egress routes for fire evacuation training. Overall, memory performance showed a clear decline over time, consistent with classic forgetting dynamics [15,29,30], following the form of a power-law decay function with more rapid forgetting initially and slower forgetting over time. The decline in recall accuracy slowed notably over longer intervals, indicating that a portion of spatial knowledge remains relatively stable even after several months. A notable difference in performance level between the two memory tasks employed in this study (free reconstruction of order and route knowledge) is visible with participants showing lower accuracy in ordering items correctly from start to finish compared with recall directions at waypoints. In the first instance, the lower accuracy in the free reconstruction of order task likely reflects higher cognitive demands compared with the route knowledge task. This highlights the relative difficulty of remembering relationships between scenes in sequence, which is more vulnerable to primacy and recency effects, interference among middle items, and error propagation when one element is misplaced. By contrast, route knowledge stayed relatively stable and relies on cued recall of directions at specific waypoints, where visual and landmark cues act as strong retrieval anchors. The distinction suggests that different processes are engaged: remembering "what to do at a scene" benefits from contextual and landmark-based cues, whereas reconstructing "how scenes are related" can be more fragile. The weaker performance in the free reconstruction task may reflect an underdeveloped form of survey knowledge, which decays quickly when only formed from a single exposure. Group 4 consistently showed high memory accuracy with a small decline over 12 weeks, emphasising that actual familiarity with the building can strongly influence route retention. This suggests that in a group evacuation, having even a single trained or familiar person may play a key role in guiding others, highlighting the practical importance of focusing wayfinding training on individuals unfamiliar with a building, while already familiar personnel could be trained on complementary tasks such as emergency response or organisational responsibilities. This aligns with findings by Ishikawa (2013) that once established, survey knowledge remains relatively stable over longer periods [34], and with Kapaj et al. (2024), who demonstrated that meaningful route and landmark knowledge can be retained for longer periods of time after a single exposure [35].

Memory performance was strongly influenced by specific characteristics (e.g. landmarks) of the environment and individuals in this study. However, most buildings contain comparable features that can function as anchors for navigation. The Bayesian regression model implemented in this study allowed quantification of memory decay with explicit uncertainty estimates, providing median expected accuracy and 95% credible intervals across participants and waypoints. For our dataset, predicted accuracy started around 0.91 at the initial interval and declined to roughly 0.77 after 12 weeks and 0.75 after 6 months (26 weeks). While these values illustrate the general pattern of forgetting and memory retention, indicating that a substantial portion of spatial knowledge is retained, they are specific to the task, sample, and characteristics of this study, and thus should be interpreted with care and as indicative rather than absolute thresholds. Waypoints with higher landmark presence scores were recalled more accurately, while more complex decision points reduced performance, both of which could be anticipated from landmarks acting as anchors and recall cues for effective retrieval of associated actions. Stair-type waypoints were recalled more reliably than other waypoint types, which is likely a result of participants using route feature knowledge as the route through the building always led upstairs, similarly to how routes in most evacuation scenarios typically always lead downstairs. Turns were recalled less accurately than going straight, which could potentially be influenced by the locomotion technique, where teleportation creates an abrupt change in scenery and viewpoint when turning. This could be disorienting or disrupt memory for the transition itself due to the lack of continuous visual flow, whereas going straight was easier because the scene before and after teleportation was more predictable and continuous in terms of spatial layout and because of a lack of continuous self-updating of spatial position [44]. While teleportation in virtual reality showed improved memory accuracy over less immersive solutions [36], a continuous locomotion technique may further improve that performance.

Beyond the immediate findings, there are broader implications of this work for applied fire safety and evacuation training contexts. First, the use of VR in this study likely provides a conservative estimate of retention compared with real-life navigation and fire evacuation scenarios. VR may reduce sensory cues compared to reality, potentially limiting encoding quality. This can pertain, for example, to different levels of depth perception, locomotion techniques, olfactory, auditory, or haptic feedback in VR than in reality, and the overall realism and fidelity of the virtual environment. The reduced field of view of VR headsets compared to reality does not affect spatial learning [45]. Second, participant engagement and attention during training can significantly influence memory outcomes. Experimental participation may not perfectly reflect real-world motivation and attention of people during safety training and encoding under lower engagement may accentuate forgetting. In this context, engaging and more immersive training methods are proven to increase training effectiveness in various contexts [5,7,46]. However, in carefully and engagingly designed real-life training, memory performance could be expected to be better, likely making our current findings a cautious baseline for longer term retention. Third, this study provides insights into the influence of familiarity and environmental variables on retention. Landmark presence, decision-point complexity, and route features (e.g., stairs vs. turns) all modulated memory performance, demonstrating that both task and environmental characteristics shape the acquisition and retention of spatial knowledge. These findings can guide the design of egress routes and inform training programmes towards repeated practice [32], reinforcement of salient cues, and structured exposure to complex tasks to maximise retention.

Finally, a key contribution of this work is its application of memory theory to training contexts. The study provides a framework for assessing long-term retention of training effects and effectiveness in a comparable, theory-driven approach. This framework allows for systematic evaluation of training effectiveness across different retention intervals and participant groups, providing both a predictive tool for future memory performance and an evidence-based approach for optimizing training design. In applied contexts of safety training, this approach can further investigate the influence of repeated practice, retrieval under varied conditions (e.g. realistic emergency conditions), and active engagement to quantify effectiveness of knowledge over time. All of which are not part of this study and are acknowledged as important to take such research results into future evidence-based practice.

Moreover, the study employed a rather homogeneous sample of participants, which is likely reflected in the absence of meaningful effects of age and previous experience in gaming or VR, although spatial abilities and sex were less homogenous among the sample of participants and are known to affect spatial learning [22,47,48]. While this reduces variability, it limits generalization to more diverse populations, particularly older adults or individuals with functional limitations [49] or different navigational experiences, since participants were healthy younger adults.

Contextual factors were not manipulated in this study. For example, signage, social influences, and stress were not included, all of which likely affect encoding and retrieval. Stress, in particular, can narrow attentional focus and enhance memory for central cues while impairing memory for peripheral details, as described in cue-utilization theory [50,51]. Such effects are highly relevant in practical emergency contexts. Participants experienced only a single exposure to a single route, limiting opportunities for interference effects that might arise if multiple routes were taught. The route in the experiment was, in fact, rather inefficient in connecting starting point and finish, as alternative routes are much shorter. The fact that Group 4 showed such high accuracy in remembering this route precisely implies that repeated exposure and developing robust survey knowledge of the environment can overcome potential interference. The virtual reality environment, while providing controlled exposure, may have yielded weaker memory traces compared with real-world navigation due to differences in visual and proprioceptive input. Finally, the derivation of the landmark presence factor relied on voluntary participant responses, which may have captured only the most salient features and missed less obvious cues as most participants did not provide optional comments.

Future research should build on the current findings to inform safety training procedures and the assessment of training effectiveness. Integrating broader theoretical frameworks from cognition, learning, and memory into training design could improve the acquisition and long-term retention of knowledge critical for emergency situations, like knowledge of egress routes. Furthermore, model-based predictions provide a framework for evidence-based decision-making in training design. This approach can optimise practice schedules, highlight areas that require additional exposure, and ensure that critical knowledge is sufficiently retained. Expanding studies to more diverse age groups and abilities would enhance generalisability, while neuroscientific methods could investigate underlying cognitive mechanisms of (spatial) learning. Systematic investigation of memory retention under varied conditions and over longer periods would enable more accurate predictions of forgetting curves and guide the timing of repeated training. Finally, exploring social influence and collectively retrievable memories (i.e. how many people in a population need to be trained and how is that information shared in an emergency) [52,53], memory thresholds (i.e. what level of memory accuracy is sufficiently ‘safe’), and optimal reinforcement strategies (i.e. how often should which kind of training be administered) could inform practical designs for repeated practice, ensuring critical (route) knowledge remains accessible when needed most.

6. Conclusions

This study examined the retention of spatial knowledge acquired through wayfinding training in a virtual reality environment, with retention intervals extending up to three months. Overall, results demonstrated the expected decline in memory performance over time, consistent with classic forgetting dynamics, yet a portion of spatial knowledge remained relatively stable even after several months. Notably, route knowledge supported by landmark and visual cues proved more resilient than the recall of relationships between sequential scenes, which is more cognitively demanding and prone to interference. A predictive memory curve based on hierarchical Bayesian regression further allowed for extrapolation of performance beyond the observed three-month interval, providing a tool for anticipating future memory performance.

A key contribution of this work is the provision of empirical retention data over a substantially longer period than most existing studies in safety training literature, which typically report on intervals of up to a few weeks. This extended observation window allows for a more nuanced understanding of forgetting curves and knowledge retention.

Beyond describing forgetting dynamics, this study demonstrates the value of applying memory theory directly to training contexts. By quantifying long-term retention in a theory-driven and comparable manner, the framework presented here can inform practical training design, support predictions of future performance, and provide a benchmark for evaluating the effectiveness of wayfinding and other emergency training programs.

Declaration of competing interest

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.

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Data Availability

The registration report, code, and data in anonymised form that support the findings of this study will be openly available in the OSF repository associated with this project after publication: https://doi.org/10.17605/OSF.IO/N6JBD

CRediT authorship contribution statement

Leo Willem Menzemer: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. Steve Gwynne: Conceptualization, Writing – review & editing, Supervision. Enrico Ronchi: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

References

[1] G. Proulx, Occupant behaviour and evacuation, in: Proceedings of the 9th International Fire Protection Symposium, Munich, 2001: pp. 219–232.

[2] S.M.V. Gwynne, E.D. Kuligowski, K.E. Boyce, D. Nilsson, A.P. Robbins, R. Lovreglio, J.R. Thomas, A. Roy-Poirier, Enhancing egress drills: Preparation and assessment of evacuee performance, Fire and Materials 43 (2017) 613–631. https://doi.org/10.1002/fam.2448.

[3] G. Proulx, I.M.A. Reid, Occupant Behavior and Evacuation during the Chicago Cook County Administration Building Fire, Journal of Fire Protection Engineering 16 (2006) 283–309. https://doi.org/10.1177/1042391506065951.

[4] L.W. Menzemer, M.M. Vad Karsten, S. Gwynne, J. Frederiksen, E. Ronchi, Fire evacuation training: Perceptions and attitudes of the general public, Safety Science 174 (2024) 106471. https://doi.org/10.1016/j.ssci.2024.106471.

[5] L.W. Menzemer, E. Ronchi, M.M. Vad Karsten, S. Gwynne, J. Frederiksen, A scoping review and bibliometric analysis of methods for fire evacuation training in buildings, Fire Safety Journal 136 (2023). https://doi.org/10.1016/j.firesaf.2023.103742.

[6] S.M.V. Gwynne, M. Amos, M. Kinateder, N. Benichou, K. Boyce, C.N. van Der Wal, E. Ronchi, The future of evacuation drills: Assessing and enhancing evacuee performance, Safety Science 129 (2020). https://doi.org/10.1016/j.ssci.2020.104767.

[7] D. Scorgie, Z. Feng, D. Paes, F. Parisi, T.W. Yiu, R. Lovreglio, Virtual reality for safety training: A systematic literature review and meta-analysis, Safety Science 171 (2024) 106372. https://doi.org/10.1016/j.ssci.2023.106372.

[8] Y. Xia, S.C. Wong, C.-W. Shu, Dynamic continuum pedestrian flow model with memory effect, Phys. Rev. E 79 (2009) 066113. https://doi.org/10.1103/PhysRevE.79.066113.

[9] S. Xue, B. Jia, R. Jiang, J. Shan, Pedestrian evacuation in view and hearing limited condition: The impact of communication and memory, Physics Letters A 380 (2016) 3029–3035. https://doi.org/10.1016/j.physleta.2016.07.030.

[10] R.C. Atkinson, R.M. Shiffrin, Human Memory: A Proposed System and its Control Processes, in: Psychology of Learning and Motivation, Elsevier, 1968: pp. 89–195. https://doi.org/10.1016/S0079-7421(08)60422-3.

[11] A.D. Baddeley, G. Hitch, Working Memory, in: Psychology of Learning and Motivation, Elsevier, 1974: pp. 47–89. https://doi.org/10.1016/S0079-7421(08)60452-1.

[12] A. Baddeley, The episodic buffer: a new component of working memory?, Trends in Cognitive Sciences 4 (2000) 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2.

[13] A. Baddeley, M.W. Eysenck, M.C. Anderson, Memory, 4th ed., Routledge, London, 2025. https://doi.org/10.4324/9781003453536.

[14] M.J. Kane, A.R.A. Conway, D.Z. Hambrick, R.W. Engle, Variation in Working Memory Capacity as Variation in Executive Attention and Control, in: A. Conway, C. Jarrold, M. Kane, A. Miyake, J. Towse (Eds.), Variation in Working Memory, 1st ed., Oxford University PressNew York, 2008: pp. 21–48. https://doi.org/10.1093/acprof:oso/9780195168648.003.0002.

[15] J.T. Wixted, The Psychology and Neuroscience of Forgetting, Annu. Rev. Psychol. 55 (2004) 235–269. https://doi.org/10.1146/annurev.psych.55.090902.141555.

[16] G. Keppel, B.J. Underwood, Proactive inhibition in short-term retention of single items, Journal of Verbal Learning and Verbal Behavior 1 (1962) 153–161. https://doi.org/10.1016/S0022-5371(62)80023-1.

[17] L.R. Squire, Declarative and Nondeclarative Memory: Multiple Brain Systems Supporting Learning and Memory, Journal of Cognitive Neuroscience 4 (1992) 232–243. https://doi.org/10.1162/jocn.1992.4.3.232.

[18] E. Tulving, Episodic and Semantic Memory, in: Organization of Memory, Academic Press, Cambridge, MA, 1972: pp. 381–403.

[19] M. Denis, J.M. Loomis, Perspectives on human spatial cognition: memory, navigation, and environmental learning, Psychological Research 71 (2007) 235–239. https://doi.org/10.1007/s00426-006-0079-x.

[20] E.C. Tolman, Cognitive maps in rats and men., Psychological Review 55 (1948) 189–208. https://doi.org/10.1037/h0061626.

[21] A.W. Siegel, S.H. White, The Development of Spatial Representations of Large-Scale Environments, in: Advances in Child Development and Behavior, Elsevier, 1975: pp. 9–55. https://doi.org/10.1016/S0065-2407(08)60007-5.

[22] T. Wolbers, M. Hegarty, What determines our navigational abilities?, Trends in Cognitive Sciences 14 (2010) 138–146. https://doi.org/10.1016/j.tics.2010.01.001.

[23] D.R. Montello, A New Framework for Understanding the Acquisition of Spatial Knowledge in Large-Scale Environments, in: M.J. Egenhofer, R.G. Golledge (Eds.), Spatial And Temporal Reasoning In Geographic Information Systems, Oxford University PressNew York, NY, 1998: pp. 143–154. https://doi.org/10.1093/oso/9780195103427.003.0011.

[24] E. Tulving, Elements of episodic memory, Clarendon, Oxford, 1983.

[25] E.T. Rolls, The mechanisms for pattern completion and pattern separation in the hippocampus, Front. Syst. Neurosci. 7 (2013). https://doi.org/10.3389/fnsys.2013.00074.

[26] A. Tversky, D. Kahneman, Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty., Science 185 (1974) 1124–1131. https://doi.org/10.1126/science.185.4157.1124.

[27] D. Kahneman, Thinking, fast and slow, Farrar, Straus and Giroux, New York, 2011.

[28] M.C. Anderson, R.A. Bjork, E.L. Bjork, Remembering can cause forgetting: Retrieval dynamics in long-term memory., Journal of Experimental Psychology: Learning, Memory, and Cognition 20 (1994) 1063–1087. https://doi.org/10.1037/0278-7393.20.5.1063.

[29] H. Ebbinghaus, Memory - A Contribution to Experimental Psychology, Teachers College, Columbia University, New York City, USA, 1913.

[30] G.A. Radvansky, A.C. Doolen, K.A. Pettijohn, M. Ritchey, A new look at memory retention and forgetting., Journal of Experimental Psychology: Learning, Memory, and Cognition 48 (2022) 1698–1723. https://doi.org/10.1037/xlm0001110.

[31] H.P. Bahrick, Semantic memory content in permastore: Fifty years of memory for Spanish learned in school., Journal of Experimental Psychology: General 113 (1984) 1–29. https://doi.org/10.1037/0096-3445.113.1.1.

[32] H. Pashler, D. Rohrer, N.J. Cepeda, S.K. Carpenter, Enhancing learning and retarding forgetting: Choices and consequences, Psychonomic Bulletin & Review 14 (2007) 187–193. https://doi.org/10.3758/BF03194050.

[33] H.L. Roediger, A.C. Butler, The critical role of retrieval practice in long-term retention, Trends in Cognitive Sciences 15 (2011) 20–27. https://doi.org/10.1016/j.tics.2010.09.003.

[34] T. Ishikawa, Retention of memory for large-scale spaces, Memory 21 (2013) 807–817. https://doi.org/10.1080/09658211.2012.758289.

[35] A. Kapaj, C. Hilton, S.I. Fabrikant, Long-Term Landmark and Route Memory Retention Acquired in a Real-World Map-Aided Navigation Task, LIPIcs, Volume 315, COSIT 2024 315 (2024) 13:1-13:9. https://doi.org/10.4230/LIPICS.COSIT.2024.13.

[36] F. Buttussi, L. Chittaro, Acquisition and retention of spatial knowledge through virtual reality experiences: Effects of VR setup and locomotion technique, International Journal of Human-Computer Studies 177 (2023) 103067. https://doi.org/10.1016/j.ijhcs.2023.103067.

[37] L. Chittaro, F. Buttussi, Assessing Knowledge Retention of an Immersive Serious Game vs. a Traditional Education Method in Aviation Safety, IEEE Transactions on Visualization and Computer Graphics 21 (2015) 529–538. https://doi.org/10.1109/TVCG.2015.2391853.

[38] L.I. Domgue K, D. Paes, Z. Feng, S. Mander, S. Datoussaid, T. Descamps, A. Rahouti, R. Lovreglio, Video see-through augmented reality fire safety training: A comparison with virtual reality and video training, Safety Science 184 (2025) 106714. https://doi.org/10.1016/j.ssci.2024.106714.

[39] M. Kozhevnikov, M. Hegarty, A dissociation between object manipulation spatial ability and spatial orientation ability, Memory & Cognition 29 (2001) 745–756. https://doi.org/10.3758/BF03200477.

[40] A. Friedman, B. Kohler, P. Gunalp, A.P. Boone, M. Hegarty, A computerized spatial orientation test, Behav Res 52 (2020) 799–812. https://doi.org/10.3758/s13428-019-01277-3.

[41] V. Braun, V. Clarke, Using thematic analysis in psychology, Qualitative Research in Psychology 3 (2006) 77–101. https://doi.org/10.1191/1478088706qp063oa.

[42] P.-C. Bürkner, brms : An *R* Package for Bayesian Multilevel Models Using *Stan*, J. Stat. Soft. 80 (2017). https://doi.org/10.18637/jss.v080.i01.

[43] L.W. Menzemer, Memory retention of spatial knowledge in fire evacuation- and safety training, (2025). https://doi.org/10.17605/OSF.IO/N6JBD.

[44] L.A. Cherep, A.F. Lim, J.W. Kelly, D. Acharya, A. Velasco, E. Bustamante, A.G. Ostrander, S.B. Gilbert, Spatial cognitive implications of teleporting through virtual environments., Journal of Experimental Psychology: Applied 26 (2020) 480–492. https://doi.org/10.1037/xap0000263.

[45] N.R. Caluya, A. Plopski, C. Sandor, Y. Fujimoto, M. Kanbara, H. Kato, Does overlay field of view in head-mounted displays affect spatial memorization?, Computers & Graphics 102 (2022) 554–565. https://doi.org/10.1016/j.cag.2021.09.004.

[46] M.J. Burke, S.A. Sarpy, K. Smith-Crowe, S. Chan-Serafin, R.O. Salvador, G. Islam, Relative Effectiveness of Worker Safety and Health Training Methods, Am J Public Health 96 (2006) 315–324. https://doi.org/10.2105/AJPH.2004.059840.

[47] E. Coluccia, G. Louse, Gender differences in spatial orientation: A review, Journal of Environmental Psychology 24 (2004) 329–340. https://doi.org/10.1016/j.jenvp.2004.08.006.

[48] A. Kapaj, C. Hilton, S. Lanini-Maggi, S.I. Fabrikant, The influence of landmark visualization style on task performance, visual attention, and spatial learning in a real-world navigation task, Spatial Cognition & Computation 24 (2024) 227–267. https://doi.org/10.1080/13875868.2024.2328099.

[49] O. Bukvic, G. Carlsson, G. Gefenaite, B. Slaug, S.M. Schmidt, E. Ronchi, A review on the role of functional limitations on evacuation performance using the International Classification of Functioning, Disability and Health, Fire Technol 57 (2021) 507–528. https://doi.org/10.1007/s10694-020-01034-5.

[50] J.A. Easterbrook, The effect of emotion on cue utilization and the organization of behavior., Psychological Review 66 (1959) 183–201. https://doi.org/10.1037/h0047707.

[51] S.-Å. Christianson, Emotional stress and eyewitness memory: A critical review., Psychological Bulletin 112 (1992) 284–309. https://doi.org/10.1037/0033-2909.112.2.284.

[52] M. Kinateder, M. Müller, M. Jost, A. Mühlberger, P. Pauli, Social influence in a virtual tunnel fire – Influence of conflicting information on evacuation behavior, Applied Ergonomics 45 (2014) 1649–1659. https://doi.org/10.1016/j.apergo.2014.05.014.

[53] M. Kinateder, E. Ronchi, D. Gromer, M. Müller, M. Jost, M. Nehfischer, A. Mühlberger, P. Pauli, Social influence on route choice in a virtual reality tunnel fire, Transportation Research Part F: Traffic Psychology and Behaviour 26 (2014) 116–125. https://doi.org/10.1016/j.trf.2014.06.003.