



Spatial knowledge and firefighters' wayfinding performance: A virtual reality search and rescue experiment

Yangming Shi^a, John Kang^b, Pengxiang Xia^a, Oshin Tyagi^b, Ranjana K. Mehta^b, Jing Du^{c,*}

^a Department of Civil & Coastal Engineering, University of Florida, Weil Hall 454A, Gainesville, FL 32611, United States

^b Department of Industrial & Systems Engineering, Texas A&M University, ETB 4024, College Station, TX 77843, United States

^c Department of Civil & Coastal Engineering, University of Florida, Weil Hall 460F, Gainesville, FL 32611, United States

ARTICLE INFO

Keywords:

Firefighter
Spatial knowledge
Wayfinding
Virtual reality

ABSTRACT

Firefighters often need to digest complex spatial information within a short period of time for search and rescue. Previous wayfinding literature has documented evidence about how the general population in normal situations leverage different forms of spatial information, including landmarks, routes and survey (maps), to develop spatial knowledge and guide wayfinding. However, little is known about how the arbitrarily given spatial information affects firefighter wayfinding behavior and performance when the time is limited and there is no privilege for them to develop complete spatial knowledge in an evolving manner. To narrow the knowledge gap, we conducted a wayfinding experiment with firefighters ($n = 40$) using Virtual Reality (VR). In the experiment, firefighters were required to find three victims in a simulated office maze. Each firefighter randomly experienced four experimental conditions in this study including control condition, landmark condition, route condition, and survey (map) condition. For each experimental condition, firefighters had 3 min to memorize the different layouts of the virtual office mazes using one of three spatial information including landmarks, routes, and survey (map), and then went to the virtual office maze to find the victims. The number of victims found, time, and navigation patterns were used to evaluate firefighters' wayfinding performance. The results indicated that the route and survey spatial information was more efficient in facilitating firefighter to memorize the layout, leading to a better wayfinding performance. We also found that although the survey information provided more complete information about the layout, it also burdened firefighters in a way that they had to plan the path with limited time. Since survey information may induce different path planning strategies, survey information did not result in a better performance than the route information as suggested by previous studies. This research helps explain the relationship between different forms of spatial information and the wayfinding performance of firefighters. The findings will help professionals design better training protocols and technologies for firefighters.

1. Introduction

Firefighters are emergency responders who specialize in extinguishing the fire, rescuing people from dangerous situations, and performing medical assistance. They are often involved in intensive physical activities while making difficult decisions under dynamically changing conditions (Pendleton et al., 1989), which makes firefighting one of the most dangerous professions in the United States (US) (Bryant and Harvey, 1996; Nydegger et al., 2011). In 2018, 64 firefighters lost their lives and 58,250 firefighters were reported to be injured in the line of duty (Campbell and Molis, 2019; FEMA, 2018). Disorientation is one

of the major causes of firefighter injuries and fatalities according to Federal Emergency Management Agency (FEMA) (FEMA, 2018). Firefighters are usually required to develop spatial understanding of unfamiliar environments (e.g., a building) in a short period of time, with imperfect or little information at hand. Time pressure and incomplete information together lead to an insufficient development of the spatial knowledge that is critical to firefighters' search and rescue operations (Morganti et al., 2007). There is a critical need to better understand how firefighters develop spatial understanding and spatial memory in the line of duty.

According to Siegel and White's Landmark-Route-Survey (LRS)

* Corresponding author.

E-mail addresses: shiyangming@ufl.edu (Y. Shi), jjkang612@tamu.edu (J. Kang), xia.p@ufl.edu (P. Xia), oshin_tyagi@tamu.edu (O. Tyagi), rmehta@tamu.edu (R.K. Mehta), eric.du@essie.ufl.edu (J. Du).

<https://doi.org/10.1016/j.ssci.2021.105231>

Received 30 November 2020; Received in revised form 1 February 2021; Accepted 19 February 2021

Available online 16 March 2021

0925-7535/© 2021 Elsevier Ltd. All rights reserved.

model (Siegel and White, 1975), a person's spatial knowledge of the unfamiliar building environment is developed based on the acquisition of spatial information in three main forms including landmarks (i.e., distinctive objects), routes (i.e., sequences of landmarks or locations), and survey (i.e., cognitive maps). In a normal situation, humans rely on a systematic and comprehensive strategy to leverage all three forms of spatial information to develop spatial knowledge and memory. According to the LRS model, most people demonstrate a learning process of switching from a simple symbolic memory anchor (e.g., landmarks) to a more advanced cognitive mapping (e.g., survey knowledge), and this spatial learning process usually takes a significant amount of time. In most cases, spatial knowledge acquisition can be more complex - people may rely on a combination of all three forms of spatial information all together in some manner, drawing the boundary of spatial knowledge acquisition strategies less clear (Moeser, 1988). This process of spatial knowledge acquisition in normal conditions usually happens in an evolving and natural way, without the need for intervention (Siegel and White, 1975). However, in most cases firefighters do not have the time needed for leveraging all the three forms of spatial information or the privilege of engaging in a natural way of spatial learning. Instead, firefighters are often given whatever information that is available in the line of duty, and thus they often acquire only limited spatial knowledge. For decision makers and front-line firefighters, it remains an under-explored and critical question as to what forms of spatial information are more apt to the need for a more effective spatial memory development. There is still a pressing need to understand the impact of an arbitrarily given form of spatial information on firefighter's wayfinding performance. Indeed, this is a particularly unique challenge to firefighters as they don't have the freedom to choose the instructions they receive and thus, the lessons learned from the classic LRS model may not apply to the situations faced by the firefighters.

This study aims to investigate how different spatial information per the LRS model affects firefighters' wayfinding performance in emergency search and rescue. Owing to the difficulty of reproducing emergency scenarios in the real world, we developed a Virtual Reality (VR) system to simulate the emergency wayfinding scenarios in an office maze. The task was designed to let firefighters find three trapped victims with each provided wayfinding information in a fixed time period in the virtual environment. The remainder of this paper introduces the point of departure of this study, the research method and the experiment, and the findings and recommendations.

2. Related studies

2.1. Spatial knowledge development

Acquiring spatial knowledge from the surrounding environment is a critical process of creating spatial memory (Werner et al., 1997). According to Siegel and White (1975)'s study, the spatial knowledge can be hierarchically categorized into three main forms, which are landmark knowledge, route knowledge, and survey knowledge. The landmarks are defined as unique and distinctive objects at fixed locations in the environment (Werner et al., 1997). Landmark knowledge pertains to identifying and memorizing landmarks based on their shapes, sizes, colors, and contextual information (Elvins, 1997). People can incidentally recognize the landmarks and unconsciously build their landmark knowledge through the navigation in the environment (van Asselen et al., 2006). The process of acquiring landmark knowledge usually does not need much mental efforts. Siegel and White (1975) found that even very young children were able to identify and make use of landmarks in spatial understanding. Route knowledge is a more advanced strategy for spatial knowledge acquisition. Route knowledge is encoded as the knowledge of memorizing the sequences of landmarks or locations from one location to the other location (Siegel and White, 1975). People can gain route knowledge either from a map or from a navigation experience (Taylor et al., 1999). The process of developing route knowledge

requires a higher mental effort, and thus practices are helpful for the acquisition of route knowledge such as navigating in the environment (Lindberg and Gärling, 1983). Lastly, survey knowledge is the process to mentally abstract the configurational information as a map-like representation of the environment (Werner et al., 1997). It is the last and the most mentally demanding spatial knowledge acquisition method. People can gain survey knowledge either from a map study or from real-world exposure to the environment (Elvins, 1997). van Asselen et al. (2006) found that route knowledge and survey knowledge coexisted in the process of spatial memory development. They further found that the spatial information representation methods of the environment could significantly affect the process of spatial knowledge acquisition. Subjects who learnt from a map outperformed others in developing the survey knowledge. On the other hand, subjects who learnt by navigating in the environment performed better than others in developing the route knowledge (Taylor et al., 1999; van Asselen et al., 2006).

It has been found that people usually rely on one or several spatial information combinations in navigation. The selection of spatial information, according to the LRS framework, represents a personal spatial knowledge acquisition strategy that plays a critical role in daily life. Cognitive science literature has found a substantial relationship between spatial knowledge acquisition strategies and spatial memory development effectiveness in navigation tasks (Devlin, 1976; Golledge et al., 1985; Ishikawa and Montello, 2006; Jansen et al., 2009; Richardson et al., 1999; Thorndyke and Hayes-Roth, 1982; Verghote et al., 2019). However, little attention has been given to elucidate situations when the choices of spatial information are limited. In addition, in normal situations, the spatial knowledge acquisition involves a process of building upon the previously anchored information and hence is shown as a sequential process. For example, a person may rely on landmarks for spatial orientation at the very beginning, then slightly switch to connected evidence of route knowledge, which ultimately lead to the cognitive mapping of the environment, or survey knowledge. This process is broken into pieces for firefighters as they either do not have the time to develop a comprehensive spatial knowledge, or do not have access to the complete information. A deeper understanding of the spatial knowledge acquisition and its impacts on wayfinding task for firefighters is needed. This study will help narrow the knowledge gap with a controlled VR-based experiment.

2.2. VR for wayfinding and fire safety studies

VR has been widely used to investigate human navigation and wayfinding behaviors (Bosco et al., 2008; Lin et al., 2020b; Zhu et al., 2020). VR can provide a high-fidelity virtual environment to evoke participants' mental and behavioral responses to the simulated emergencies with a high ecological validity (Lin et al., 2019, 2020a; Meng and Zhang, 2014). For example, Lin et al. (2019) explored the influence of repeated exposures and mental stress on human wayfinding performance using VR. They found that the simulated hazardous environments of a fire emergency in VR could trigger a similar negative impact on wayfinding performance. In another study, Lin et al. (2020b) used VR to investigate the influence of crowd flows on human evacuation behavior during a building fire emergency. They created a virtual metro station and Non-player characters (NPC) to simulate crowd evacuation in a fire emergency. Their finding confirms the effectiveness of VR-based experiments for studying human evacuation behavior, even with the complex social influence. Bliss et al. (1997) compared the benefits of using 2D blueprints and VR models in an indoor navigation task. They found that firefighters trained with VR models outperformed those without training in both navigation speed and accuracy. Rare scenarios in real world can be simulated in VR to enrich scientific investigation. For example, Lin et al. (2020b) simulated the uneven splits of crowd flow in VR, and found that the patterns of crowd flow motivated experiment participants to follow the majority of the crowd during evacuation. Because of the flexibility of VR experiment, they repeated

the experiment in different locations including the US, UK and China, providing further cross-cultural evidence. Feng et al. (2020) successfully applied VR to study the earthquake drill. They developed an immersive earthquake emergency scenario in a hospital and used Verbal Protocol Analysis (VPA) to investigate individual's decision-making process. They found that participants tended to be influenced by other people and wanted to accompany with others during an evacuation. Lovreglio et al. (2018) also used VR serious games to explore how building occupants behaved during earthquake evacuations and to train building occupants to cope with earthquake evacuations emergencies. They pointed out several key design components such as building types, damage to the building, interaction between non-player characters (NPC) and human participants for developing effective virtual training scenarios for the users.

VR has also been used to investigate human behavior in fire-related incidents and for fire safety training. For instance, Lovreglio et al. (2020) compared the effectiveness of fire extinguisher training between the use of VR and of traditional video training. They found that VR trainees scored better than video trainees in terms of knowledge acquisition. At the same time, the participants in the VR group had maintained the same level of self-efficacy for long-term retention compared to the participants in the video training group. Ronchi et al. (2016) conducted a VR experiment with 96 participants to explore the design of flashing lights at emergency exit portals for road tunnel emergency evacuation. They found that green or white flashing lights led to a better performance compared to blue lights. In addition, they also found that the flashing rate of 1 and 4 Hz were more effective than a flashing rate of 0.25 Hz, and a light emitting diode light source encouraged a better performance than the single and double strobe light. VR has also been used for investigating exit choice behavior in fire incidents. For example, Song and Lovreglio (2020) used VR to study individual-specific taste preferences for exit choice behavior. They implemented Hierarchical Bayes estimation approach, which allows the estimation of individual-specific parameters. They found that there were two distinct groups of people for exit choice behavior: "followers" and "non-followers". Individuals' age, nationality, and education have great impact on exit choice behavior during the fire evacuation. In summary, the previous studies reveal that the VR-based experiment is an effective approach to investigate individual's evacuation and wayfinding behavior in the indoor environment.

3. Points of departure

According to the LRS model, the process of spatial knowledge acquisition in normal conditions usually happens in an evolving and natural way, without the need for intervention (Siegel and White, 1975). However, the major issue of firefighters' search and rescue operations in real-world practice is the insufficient development of the spatial knowledge of unfamiliar environments (e.g., a building) in a short period of time, with imperfect or little information at hand (Morganti et al., 2007). For decision makers and front-line firefighters, it remains an under-explored and critical question as to what forms of spatial information are more apt to the need for a more effective spatial memory development. There is still a pressing need to understand the impact of an arbitrarily given form of spatial information on firefighter's wayfinding performance. Therefore, the central question to be answered is:

Based on the LRS model, what spatial information format (landmarks, routes and survey) leads to the best wayfinding performance in target searching?

Owing to the difficulty of reproducing emergency scenarios in the real world, we developed a Virtual Reality (VR) system to simulate the emergency wayfinding scenarios in an office maze. The experimental task was designed to find three victims in the virtual office within given time (3 min). Depending on what spatial information was provided to

the firefighters prior to the wayfinding task, four spatial knowledge conditions were tested in this experiment including the control condition, landmark condition, route condition, and survey condition. Each firefighter randomly experienced each spatial information condition. To avoid the influence of the previous spatial knowledge trials on their wayfinding performance, we used an incomplete randomized block design. The findings will help professionals design better training protocols and technologies for firefighters.

4. Methodology

4.1. VR system with trajectory tracking function

We developed a VR system with the navigation trajectory analysis function as the testbed for human-subject experiment based on our previously validated VR systems (Du et al., 2017; Du et al., 2018; Shi et al., 2019; Shi et al., 2016). To provide a high fidelity virtual environment, the HTC VIVE Head Mounted Display (HMD) integrated with the Tobii Pro eye tracker (Tobii, 2019b) was used in this study. The locomotion method used in this study was ArmSwinger technique (Keller, 2016). The user could swing their left and right arms holding the HTC VIVE controllers to navigate in the virtual environment. We created a separate virtual training scenario for firefighters to learn the locomotion technique in the virtual environment. To achieve the trajectory tracking and playback functions in the virtual environment, we developed several C# scripts based on the Tobii Pro Software Development Kit (SDK) (Tobii, 2019a) and the application programming interface (API) in Unity. In the virtual environment, the system could collect firefighters' navigation trajectory data, hand movement data, and head movement data at the frequency of 90 Hz. After each experiment trial, the VR system automatically generated a CSV file with raw data. Fig. 1 (a) shows the first-person view of the participating firefighters in the virtual environment with our VR system. To better control the

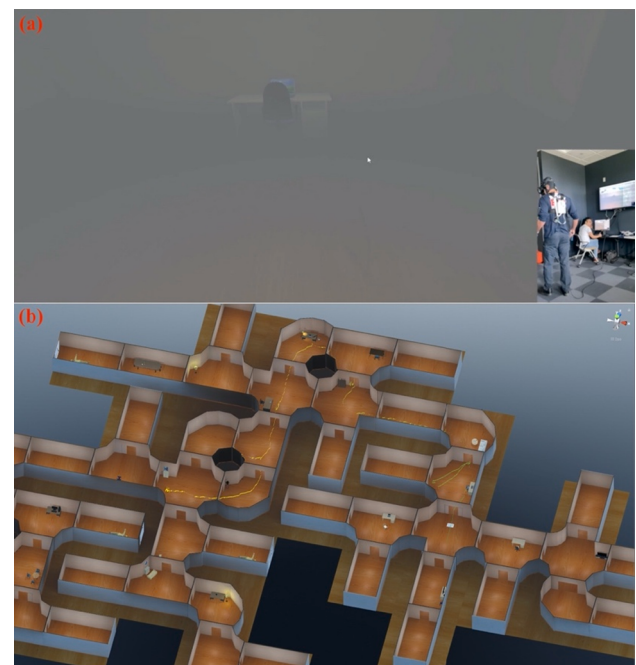


Fig. 1. The proposed VR system. (a) The first-person view of the firefighter in the virtual environment (with limited visibility). The visibility level was set to a level that it would not affect the view of major landmarks when the test subject approaches them. In the virtual environment, the user could easily see the landmarks in each room; (b) the perspective view of the firefighter's walking trajectory (yellow lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

environmental variables in this experiment, the smoke level and the visibility of the smoke were set to be constant (smoke was not propagated in the virtual environment) for each experimental condition (control, landmark, route, and survey conditions). The visibility level of the smoke in the landmark condition was set to be the baseline as same as other conditions. In addition, the visibility level was set to a level that it would not affect the view of major landmarks when the test subject approaches them. In the virtual environment, the user could easily see the landmarks in each room as illustrated in Fig. 1 (a). Fig. 1 (b) shows the playback of the firefighter's navigation trajectory (yellow lines) in the virtual environment.

4.2. Virtual office maze design

In order to test the impacts of spatial information on firefighters' wayfinding performance, a repeated measures approach was undertaken, where participants performed all the different experiment tasks. In order to rule out learning effects due to the repeated measures design, the layout of the space in each trial was different. We developed a workflow to randomly generate different virtual office maze layouts with the same level of difficulty (total travel distance and number of turns) using the SDK in Unity 3D and external libraries (Unity, 2019; Vazgriz, 2019) as illustrated in Fig. 2: First of all, we created several building components as the pre-defined prefabs in the building generation pool including different types of rooms, start room, end room, and different types of corridors. The system randomly picked each building components without overlaying in each generation as shown in Fig. 2 (a). Second, the workflow used the Bowyer-Watson algorithm (Rebay, 1993) to perform Delaunay Triangulation for all the picked building components. The purpose was to fully connect all the picked building components without intersecting lines as shown in Fig. 2 (b). Third, the workflow constructed a minimum spanning tree for the fully connected building components using A Prim Algorithm as shown in Fig. 2 (c).

Fourth, this pipeline applied a 15% possibility to connect the leaf for the minimum spanning tree, and then the A* algorithm was applied to find the shortest path from the start room to the end room as shown in Fig. 2 (d). Fifth, the system fully connected all the building components with the corridor components as shown in Fig. 2 (e). At last, all the building components were generated and rendered in the Unity 3D as shown in Fig. 2 (f). Before each virtual office environment generation, the authors validated the shortest distance from the start room to the end room to ensure each office maze model maintains the same level of difficulty as illustrated in Fig. 3. Fig. 3 also shows the four office mazes in this experiment. We also added several simulated environmental cues including simulated smoke gradually occluding the vision, virtual smoke propagation, sudden structural collapse sound, and fire burning sound in the distance to make the virtual wayfinding experience as realistic as possible for the participating firefighters.

4.3. Experimental task

The experimental task was designed to find three victims in the virtual office within given time (3 min). Depending on what spatial information was provided to the firefighters prior to the wayfinding task, four spatial knowledge conditions were tested in this experiment including the control condition, landmark condition, route condition, and survey condition. In the control condition, no information about the virtual environment was provided to the firefighters. In the landmark condition, the firefighters were given important landmarks as illustrated in Fig. 4 (a) to help them find the three victims. For the route condition, firefighters were provided with the sequences (turning left, right, or moving forward) as illustrated in Fig. 4 (b). The firefighters were told that one sequence was designed for only one room. For the survey condition, firefighters were given a map of the building as illustrated in Fig. 4 (c). The positions of the start point, and three victims were marked clearly on the map. All firefighters were given 3 min to memorize the

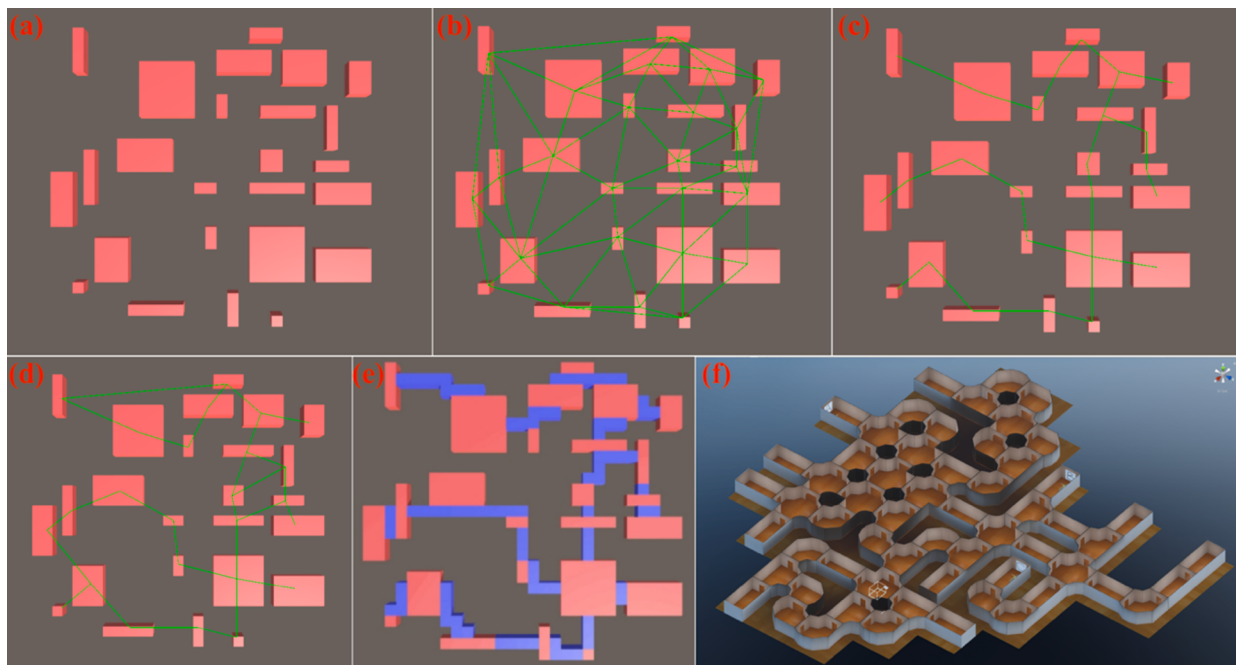


Fig. 2. The workflow of generating different building layouts. (a) The system randomly generates several building components (red blocks) from pre-defined building generation pool; (b) the system uses the Bowyer-Watson algorithm to perform Delaunay Triangulation for all the picked building components. The green lines link each building components; (c) the system constructs a minimum spanning tree for the fully connected building components using A Prim Algorithm. The remaining green lines show the minimum spanning tree; (d) this system connects the leaf for the minimum spanning tree with a 15% possibility, and then the A* algorithm is applied to find the shortest path from the start room to the end room; (e) the system fully connects all the building components with the corridor components (blue blocks); (f) all the building components are generated and rendered in the Unity 3D. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

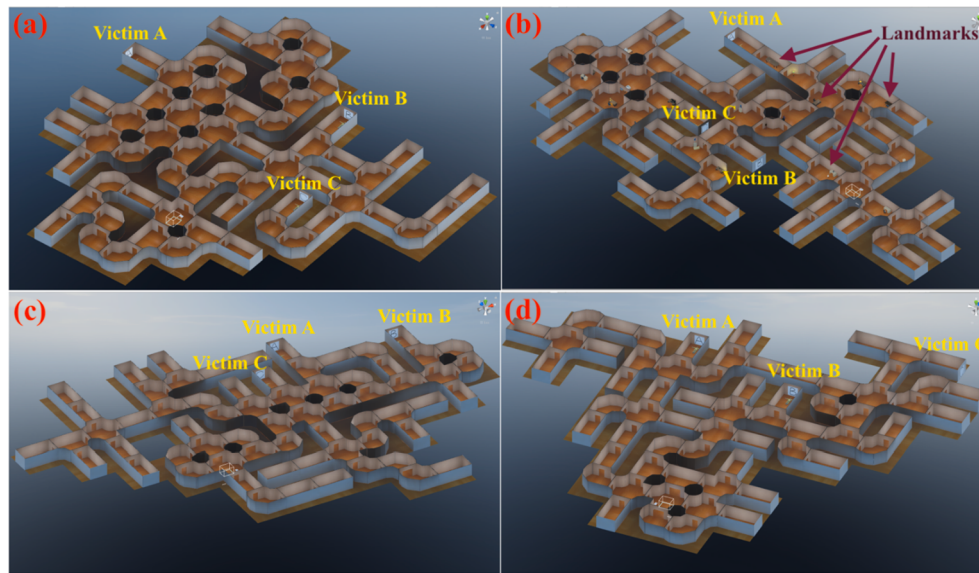


Fig. 3. The virtual office mazes. (a) Control condition; (b) landmark condition (the red arrows indicated the landmarks in the maze); (c) route condition; (d) survey condition. All the three victims (A, B, and C) were located in different positions in the office maze for each condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

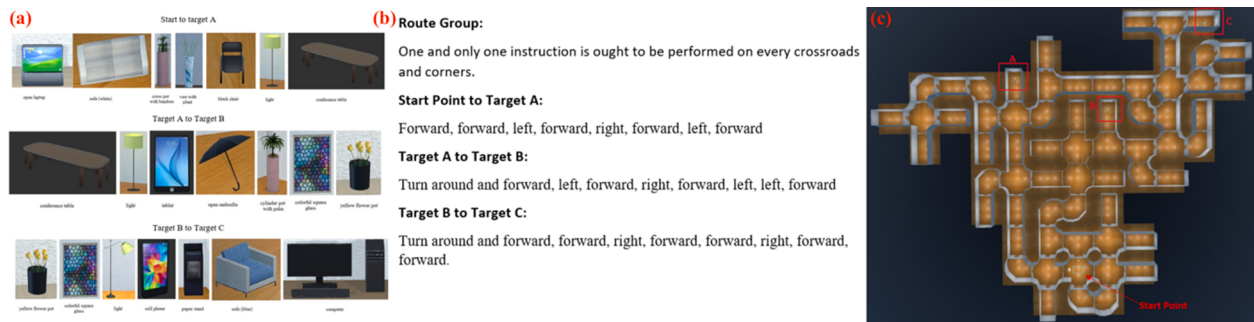


Fig. 4. The spatial information provided to firefighters. (a) Landmark condition; (b) route condition; (c) survey condition. The words of “Forward” in Start point to Target A, “Turn around and forward” in Target A to Target B, and “Turn around and forward” in Target B to Target C are instruction words for the firefighters to know that they need to turn around after they found the victims.

spatial knowledge information provided for each condition. We applied the within participation design where all firefighters participated in all four conditions. To avoid the influence of the previous spatial knowledge trials on their wayfinding performance, we used an incomplete randomized block design as illustrated in Fig. 5. Firefighters were randomly assigned to one of the three condition blocks (order) as between-subject factor, which are landmark-route-survey, survey-landmark-route, and route-survey-landmark. The spatial knowledge virtual conditions are same across different blocks. The firefighters were also instructed that their task performance would be documented towards their training credits. The purpose of this experimental design was to motivate firefighters to find the victims as many as possible.

4.4. Experiment procedure

The experiment consisted of five sessions: (1) preparation session, (2) device calibration and VR training session, (3) review session, (4) wayfinding session, and (5) questionnaire and interview session. The preparation session (15–20 min) was designed to allow firefighters to familiarize with the procedure and potential benefits or risks of the experiment. Firefighters’ demographical information including age, gender, Body Mass Index (BMI), work experience, and previous game and VR experience were collected in this session. At the same time, firefighters’ baseline spatial ability was also collected using the paper-

based cube test provided by the Educational Testing Service (ETS) (Dadi et al., 2014). The device calibration and VR training session (10–20 min) were designed for firefighters to familiarize themselves with the VR system and body tracking system. We created a training virtual scenario and all the firefighters were also given instructions about how to use the two controllers to navigate in the virtual office building. The review session (3 min) was used for firefighters to review and memorize the spatial information for searching the missing victims. The firefighters were informed to sit quite in a chair and memorize as much information as possible in the review session. After the review session, firefighters were immediately asked to perform the wayfinding task in the virtual environment with a 3-minute time limit. At the end of each condition, firefighters were asked to report their cognitive load using the NASA-TLX questionnaire. At the end of the whole experiment, we collected firefighters’ comments and feedbacks about the VR system. All experiments were done at the same location with the same devices.

4.5. Data collection

4.5.1. Wayfinding task performance

We evaluated firefighters’ wayfinding task performance using two metrics: the number of victims found and the time of finding the victims (seconds). The number of victims found directly represents how well the firefighters memorized the spatial information and finished the

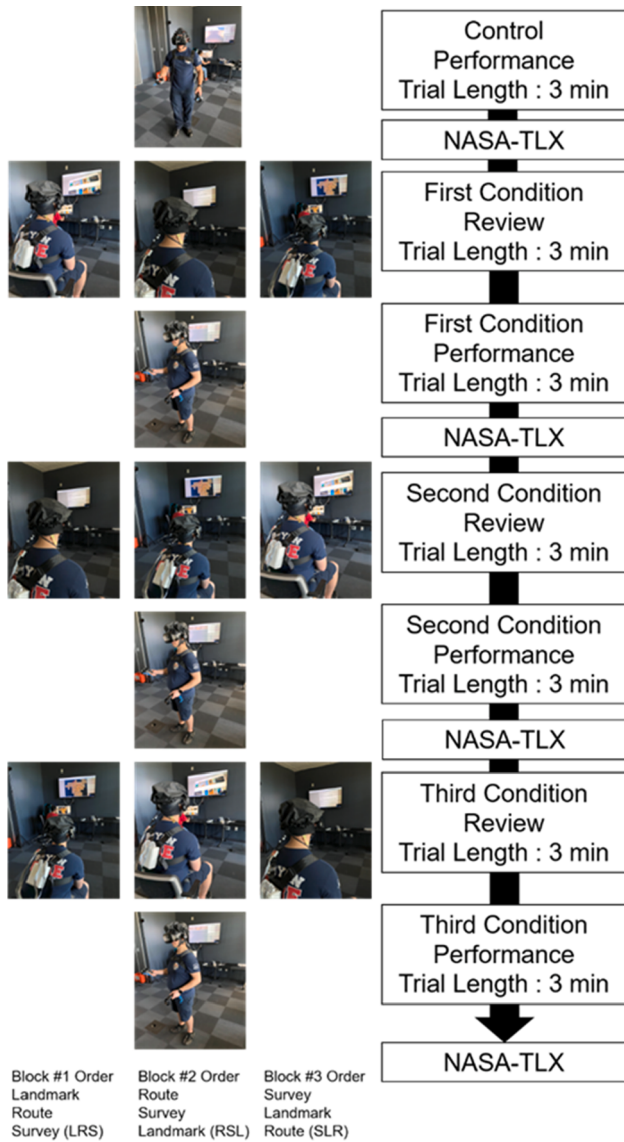


Fig. 5. The incomplete randomized block design and experiment procedure. The firefighters were randomly assigned to one of the three blocks. Block order #1; landmark – route – survey; Block order #2; route – survey – landmark; Block order #3; survey – landmark – route.

wayfinding task. The number of victims found is ranged from 0 to 3. On the other hand, the time of finding the victims was defined as the time that firefighters found each victim in the virtual environment. The time of finding the victims represents how efficiently the firefighters finished the task. To better evaluate firefighters' wayfinding performance, we developed a task performance indicator called the *wayfinding score* based on the number of victims found and the time of finding the victims as shown in Eq. (1). Wayfinding score is also ranged from 0 to 3 and participant who performed better means a higher score. This indicator represents how effectively and efficiently the firefighters finished the wayfinding task. The higher value of the wayfinding score indicated that firefighter found more victims with less time.

$$\text{Wayfinding Score} = \frac{T_{\text{total}} - T_1}{T_{\text{total}}} + \frac{T_{\text{total}} - T_2}{T_{\text{total}}} + \frac{T_{\text{total}} - T_3}{T_{\text{total}}} \quad (1)$$

where T_{total} is the fixed 3 min of finding the victims in each experiment condition. T_1 , T_2 , and T_3 are the time of finding the 1st, 2nd and 3rd victims in the virtual environment respectively. If the firefighter did not find any of the victims, the values of T_1 , T_2 , or T_3 would be set to T_{total} .

4.5.2. Navigation trajectory

We were also interested in assessing the navigation trajectories under different spatial information conditions, as they show how firefighters planned out their navigations leading to the search for the victims. The darkness of the lines indicates the density of the overlapped trajectories. To better quantify aggregated walking trajectory, we also evaluated firefighters' total travel distance for each experimental condition.

To better understand how spatial information forms affected each firefighter's path planning, we used an indicator called *Percentage Above Optimal (PAO)* as demonstrated in Eq. (2).

$$PAO = \frac{d_{\text{walked}} - d_{\text{shortest}}}{d_{\text{shortest}}} \times 100 \quad (2)$$

where d_{walked} is the actual travel distance of firefighter in the virtual environment for each experiment condition. d_{shortest} is the optimized walking trajectory for each condition. Fig. 6 shows the optimized walking trajectory for each condition. According to Buecher et al. (2009)'s study, PAO standardizes individual's traveled distance over the optimized distance. This indicator provides a quantitative measure of the efficiency of path planning pertaining to the closeness to the shortest possible path. PAO has been used in previous studies to benchmark wayfinding performance (Buecher et al., 2009; Ruddle et al., 1997; Wiener et al., 2004).

Previous literature has suggested that as the latest and the most advanced spatial knowledge, survey information (cognitive map) is usually more effective in guiding wayfinding (Blacker et al., 2017; De Goede and Postma, 2015). However, in our experiment we did not find a substantial advantage of providing the map to the firefighters. As a result, we further analyzed the survey condition in order to gain a deeper insight into the behavioral splits given the survey information.

5. Results

5.1. Participants

We recruited 40 male firefighters from the Bryan Fire Department in College Station, Texas. Among all, eight firefighters were unable to finish the experiment task due to the VR sickness during the experiment and their incomplete data was removed. Firefighters' ages ranged from 23 to 41 with a mean (M) age of 30.74 and the standard deviation (SD) of 4.19. Firefighters' work experiences ranged from 8 months to 17 years (M = 6.9, SD = 3.99). Firefighters' average Body Mass Index (BMI) was 29.43 with a SD of 4.16. The study was approved by the Institutional Review Board (IRB) of the University of Florida and Texas A&M University.

5.2. Wayfinding task performance

Our experiment follows a mixed experiment design with between-subject factor (block) and within-subject factor (condition). In addition, our data met the normality assumption of Analysis of variance (ANOVA). As a result, we used a two-way mixed ANOVA to compare the differences in wayfinding with a significant (α) of 0.05. According to our experiment results, none of the firefighters could find all three victims with the given time. We used the ggpubr package (Kassambara, 2020) in the R to illustrate the experiment results. For the number of victims found, the two-way mixed ANOVA found a significant difference in within-subject factor (condition) of wayfinding score ($F(3, 87) = 20.241$, $p < 0.001$, $\eta^2 = 0.342$) as illustrated in Fig. 7. There was no between-subject effect (block) ($p = 0.818 > 0.05$) and interaction effect (block * condition) ($p = 0.364 > 0.05$). Based on the post-hoc paired t -test (Bonferroni corrected), we found significant differences between the control condition and the route condition ($p < 0.001$), between the control condition and the survey condition ($p < 0.001$), between the landmark condition and the route condition ($p < 0.001$), and between

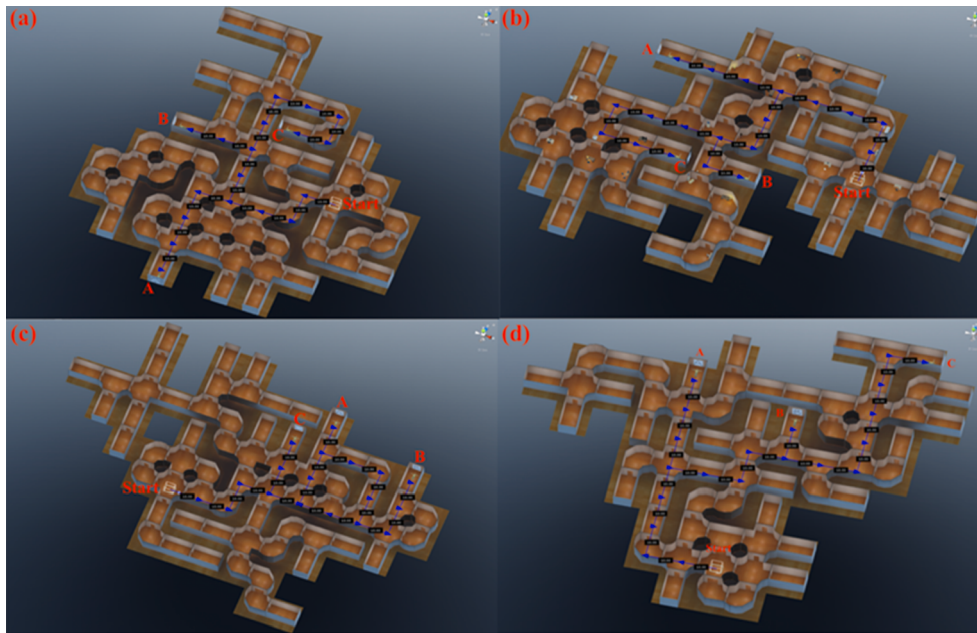


Fig. 6. The optimized walking trajectory for each condition. (a) Control group; (b) landmark group; (c) route group; (d) survey group.

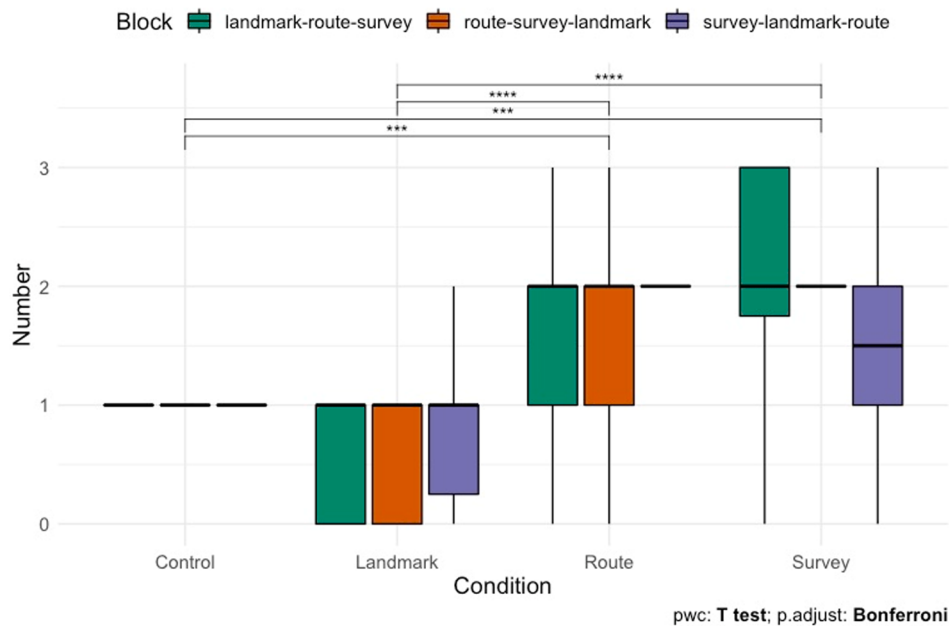


Fig. 7. The result of the number of victims found in the experiment.

the landmark condition and the survey condition ($p < 0.001$). There were no significant differences in the wayfinding score between the control condition and the landmark condition, or between the route condition and the survey condition.

For the wayfinding score, the two-way mixed ANOVA found a significant difference in within-subject factor (condition) of wayfinding score ($F(3, 87) = 33.819$, $p < 0.001$, $\eta^2 = 0.452$) as illustrated in Fig. 8. There was no between-subject effect (block) ($p = 0.987 > 0.05$) and interaction effect (block * condition) ($p = 0.187 > 0.05$). Based on the post-hoc paired t -test (Bonferroni corrected), we found significant differences between the control condition and the route condition ($p < 0.001$), between the control condition and the survey condition ($p < 0.001$), between the landmark condition and the route condition ($p < 0.001$), and between the landmark condition and the survey condition

($p < 0.001$). There were no significant differences in the wayfinding score between the control condition and the landmark condition, or between the route condition and the survey condition. The results of the wayfinding score indicated that firefighters performed better (in terms of finding the victims) in route and survey conditions than in control and landmark conditions. Meanwhile, the order of the forms of spatial information provided to the firefighters did not affect their wayfinding performance.

5.3. Results of navigation trajectory

5.3.1. Aggregated walking trajectory

We were also interested in assessing the navigation trajectories under different spatial information conditions, as they show how firefighters

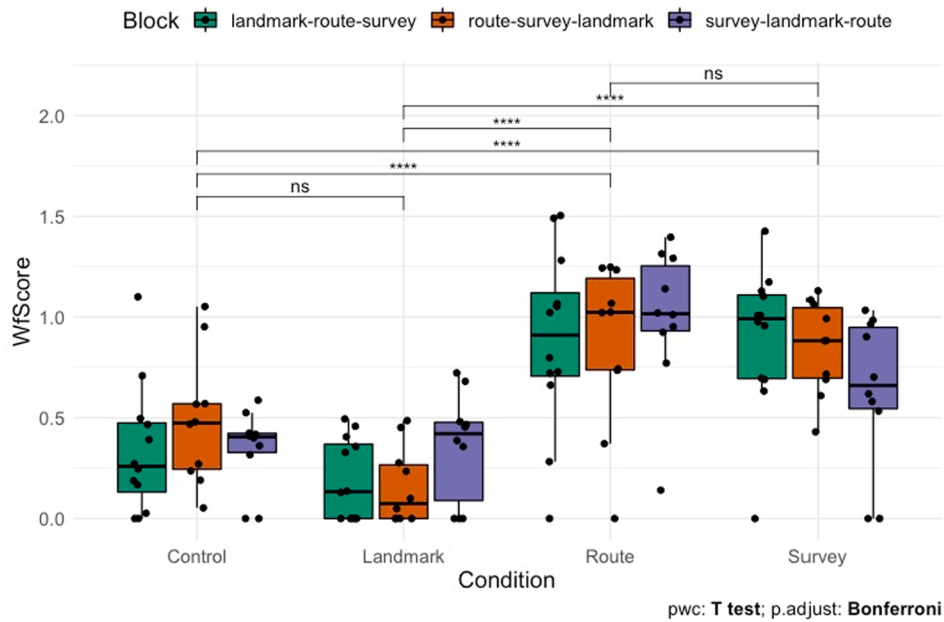


Fig. 8. The result of the wayfinding score. NS means no significant difference.

planned out their navigations leading to the search for the victims. Fig. 9 illustrates the aggregated navigation trajectories of all firefighters for each condition. The darkness of the lines indicates the density of the overlapped trajectories. We found that the control condition had lighter aggregated trajectories but larger coverage areas than other conditions. Based on the interview feedback from the firefighters, since there was no spatial information provided for the firefighters under the control condition, all firefighters had to use “right-hand search” or “left-hand search” strategies per their previous trainings. The “right-hand search” and “left-hand search” strategies are common methods for firefighters to search an unfamiliar building environment according to their training protocol. These search methods require firefighters to frequently raise their right or left arm and rub the hands along the surface of the wall, searching for doors, hallways, or a change of direction in the room walls

(Davis and Gallagher, 2014). Fig. 7 (a) clearly show that some firefighters used “right-hand search” method while others used “left-hand search” method in the control condition, showing a split of search paths in the space. To be noted, the left-hand-search or right-hand-search is primarily a safety-based approach for firefighters, rather than an optimal search technique.

One of the ways to quantify the effectiveness of aggregated walking trajectory under each condition is calculating the total travel distance. For each firefighter's total travel distance, the two-way mixed ANOVA found a significantly difference in within-subject factor (condition) of total travel distance ($F(3, 87) = 4.489, p = 0.006 < 0.05, \eta^2 = 0.064$) and there was also an interaction effect (block * condition) ($F(6, 87) = 3.362, p = 0.005 < 0.05, \eta^2 = 0.093$) as illustrated in Fig. 10. There was no between-subject effect (block) ($p = 0.082 > 0.05$). Based on the post-

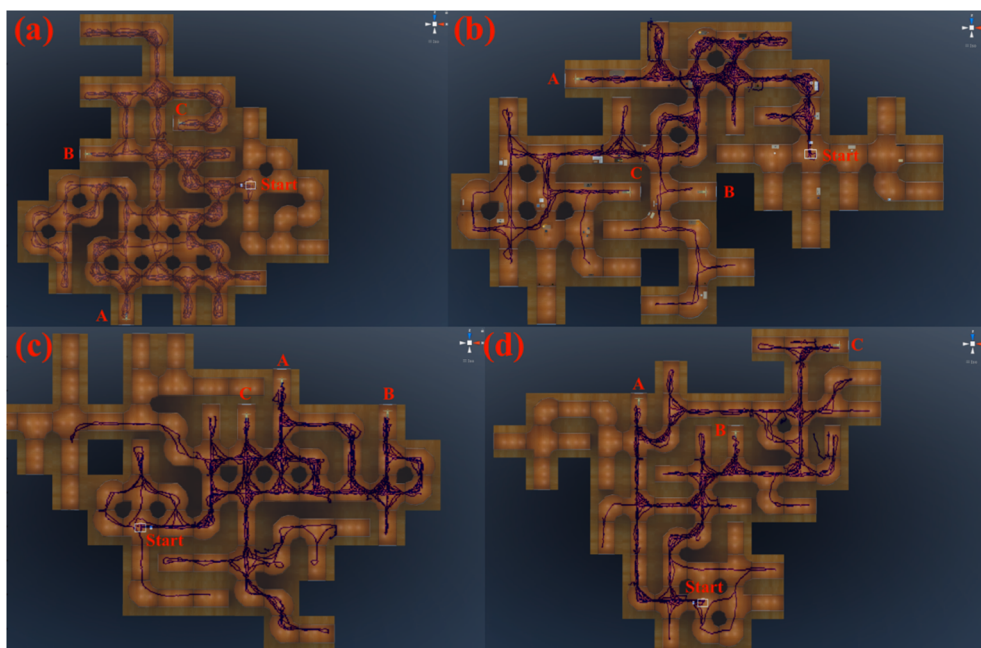


Fig. 9. The result of walking trajectories in the virtual environment. (a) Control group; (b) landmark group; (c) route group; (d) survey group.

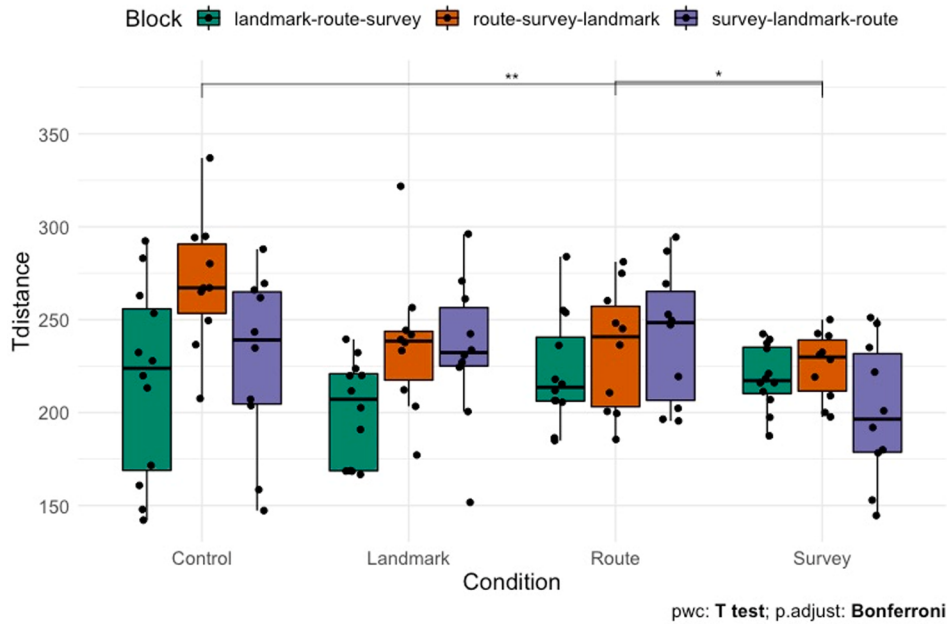


Fig. 10. The result of total travel distance.

hoc paired *t*-test, we found significant differences in each firefighter's total travel distance between the control condition and the survey condition ($p = 0.008 < 0.05$) and between the route condition and the survey condition ($p = 0.047 < 0.05$). The results suggest that the forms of spatial information affected the effectiveness of the paths selected by the firefighters and conditions that led to better wayfinding task performance (i.e., finding more victims) correlated with shorter travel distances. In addition, we found that the traditional search methods were clearly less efficient than the conditions with provided spatial information in terms of both the navigation trajectory and wayfinding task performance.

5.3.2. Percentage Above Optimal (PAO)

The two-way mixed ANOVA found a significant difference in within-subject factor (condition) of PAO ($F(3, 87) = 4.222, p = 0.008 <$

$0.05, \eta^2 = 0.095$) as illustrated in Fig. 9. There was no between-subject effect (block) ($p = 0.487 > 0.05$) or interaction effect (block * condition) ($p = 0.388 > 0.05$). Based on the post-hoc paired *t*-test, we found significant differences in PAO between the landmark condition and the survey condition ($p = 0.003 < 0.05$). The result of PAO revealed that the order of providing spatial information did not affect firefighter's PAO. The results of PAO also indicated that firefighters were having a hard time of identifying the optimal path in the landmark condition compared to other conditions.

5.4. Different path planning strategies for survey condition

Based on the results of PAO and observation, we clustered the planned paths in survey condition. We found that there were three path planning strategies across all the firefighters in the survey condition as

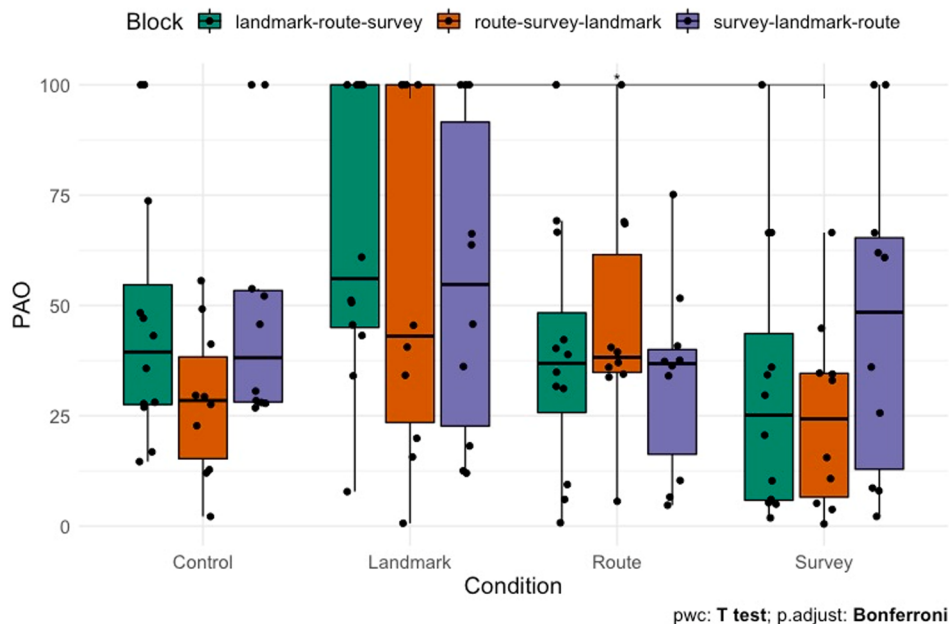


Fig. 11. The result of percentage above optimal (PAO).

illustrated in Fig. 13: type #1 as demonstrated in Fig. 13 (a), type #2 as demonstrated in Fig. 13 (b), and type #3 as demonstrated in Fig. 13 (c). The type #1 path planning strategy led to a path very close the optimal path (the shortest path) for this building environment. In contrast, the type #2 path planning strategy would lead to a lot of unnecessary travels to find the victims, which ultimately lead to a longer distance to find three victims. The other path planning strategies were grouped into the type #3 path planning strategy. The clustering result shows that 13 out of 32 firefighters (40.63%) used type #1 path planning strategy and the average number of victims found was 2.38; 12 out of 32 firefighters (37.5%) were using type #2 strategy and with the average number of victims found of 1.83; and 7 out of 32 firefighters (21.87%) fell into the type #3 path planning strategy with the average number of victims found of 0.86. It clearly indicates that there was an obvious behavioral split in the survey condition, in terms of how firefighters planned their search and selected the path.

We also quantified the impact of the path planning strategies on the wayfinding task performance. Since the wayfinding scores for each path planning strategy type were not normally distributed based on a Shapiro-Wilk test of normality, we used a non-parametric Kruskal-Wallis test ($\alpha = 0.05$) for this analysis. We found a significant difference ($\chi^2(2) = 14.8$, $p < 0.001$) in wayfinding score across the three path planning types as illustrated in Fig. 11. A post-hoc nonparametric comparison of Wilcoxon test (Bonferroni corrected) found significant differences between type #1 path planning type and type #2 path planning type ($p = 0.021 < 0.05$), and between type #1 path planning type and type #4 path planning type ($p = 0.003 < 0.05$). We did not find any significant difference between type #2 path planning type and type #3 path planning type ($p = 0.075 > 0.05$). This result indicated that type #2 and type #3 path planning type could greatly reduce firefighters' wayfinding performance in the survey condition. Because the time given to the firefighters to digest the spatial information and plan out their search path was limited (3 min), survey information burdened their mental processes in addition to the regular benefits. Certain firefighters could not identify the optimal path for their task even though the complete spatial information was provided. In contrast, the route information, although less complete in reflecting the overall spatial configuration of the space, eased the process of path planning. The reality faced by firefighters complicated the impact of providing a more complete survey information.

5.5. Results of the NASA-TLX questionnaire

Finally, we evaluated firefighters' cognitive load using the NASA-TLX questionnaire after they finished the wayfinding task for each condition. The purpose is to examine if there is any correlation between any of the wayfinding performance and the perceived difficulty of the task. The two-way mixed ANOVA found a significant difference in within-subject factor (condition) of NASA-TLX score ($F(3, 87) = 21.947$, $p < 0.001$, $\eta^2 = 0.114$) as illustrated in Fig. 12. There was no between-subject effect (block) ($p = 0.23 > 0.05$) and interaction effect (block * condition) ($p = 0.702 > 0.05$). Based on the post-hoc paired t -test, we

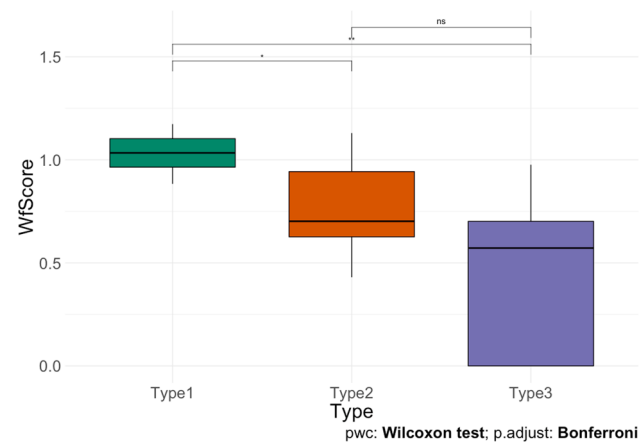


Fig. 13. The result of wayfinding score related to path planning strategies.

found significant differences in NASA-TLX score between the control condition and the landmark condition ($p < 0.001$), between the control condition and the route condition ($p < 0.001$), and between landmark condition and survey condition ($p < 0.001$), between the landmark condition and the route condition ($p = 0.009 < 0.05$), and between route condition and survey condition ($p < 0.001$). There were no significant differences in the NASA-TLX score between the control condition and the survey condition ($p = 0.726 > 0.05$). The result indicated that the order of spatial information did not affect firefighters' subjective cognitive load. The result also indicated that firefighters had higher cognitive load in landmark condition than other conditions, corresponding to the worse performance in all aspects (see Fig. 14).

6. Discussion

The experimental results reveal several important implications regarding how different spatial information forms (based on the LRS model) affect firefighters' path planning behavior and wayfinding performance. First, given the same amount of time for memorizing the layout of an unfamiliar building environment, the route and survey information could help firefighter better memorize the layout than other methods. This result echoes the findings of previous wayfinding literature (Taylor et al., 1999; van Asselen et al., 2006). The result of the NASA-TLX questionnaire also reveal that firefighters had a higher cognitive load with landmark information than other conditions. This result conflicts with most studies using the LRS model. According to the LRS model, landmark knowledge is the fundamental process for forming spatial knowledge (Siegel and White, 1975). People can incidentally recognize the landmarks and unconsciously build their landmark knowledge (van Asselen et al., 2006). As a result, it is usually believed that the process of acquiring landmark knowledge does not need much mental efforts. To be noticed, firefighters' cognitive load was assessed after they finished the wayfinding task. The cognitive load measured

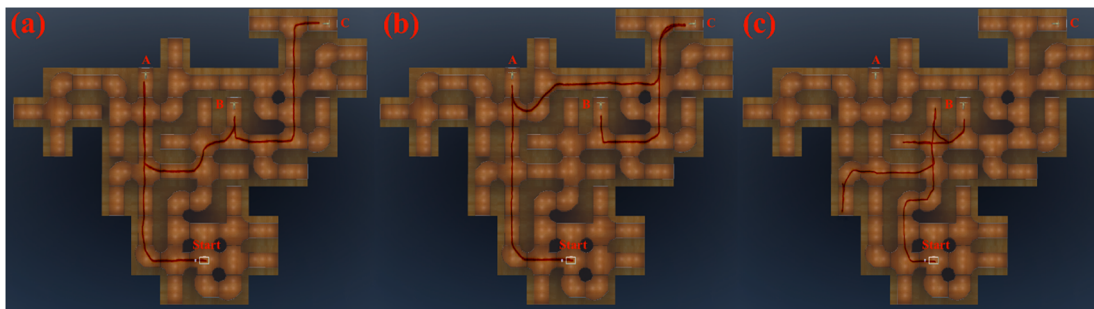


Fig. 12. Three types of path planning strategies. (a) Type #1; (b) type #2; (c) type #3.

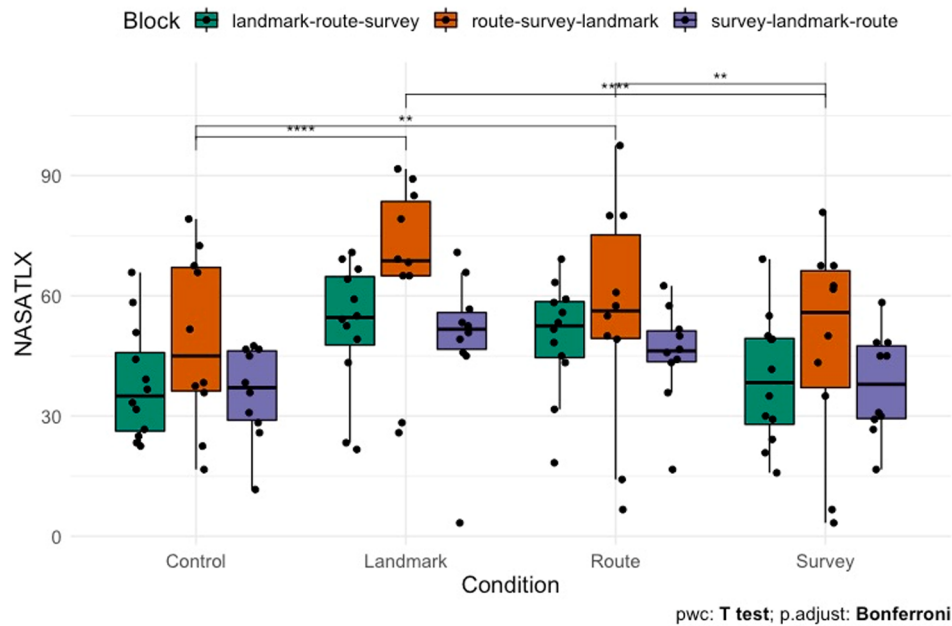


Fig. 14. The result of the NASA-TLX Score.

reflected their overall evaluation of the perceived difficulty of the tasks including memorizing information and using it in the search task. According to Wicken's model of human information processing (Wickens, 2008; Wickens and Flach, 1988) and our previous study (Shi et al., 2020), the cognitive load may show complete different patterns in the memory development (information encoding) and memory retrieval (information retrieval) phases. The higher cognitive load reported for the landmark condition may be affected by how efficiently the memorized landmark information could be retrieved and used in the search task. A further investigation is needed.

Second, we did not find any significant difference between the route condition and the survey condition. This result echoes the findings of several previous wayfinding studies (Latini-Corazzini et al., 2010; van Asselen et al., 2006) that route knowledge and survey knowledge coexist in the process of spatial memory development. Previous literature explains it as a "mixed strategy" that is likely to be involved when both types of encoding (route and survey) at the same time (Latini-Corazzini et al., 2010). However, our explanation is different. First, we changed the layout of the building for the route and survey conditions, and the spatial information was provided to the firefighters separately. As a result, it was impossible for the firefighters to leverage the mixed use of both the route and survey knowledge. Instead, we found that there were three path planning strategies in the survey condition among all the firefighters. With limited time (3 min) to memorize the survey spatial information and plan out the path for the search task, 59.37% of the firefighters used a less optimal path planning strategies (type #2 and type #3) that had significantly worsened their wayfinding performance. For those who could selected a close-to-optimal path, their performance with survey information was better than that with the route information. The reason that survey information did not differentiate performance was likely because of the behavioral splits due to the lack of time for path planning with excessive spatial information. When the optimal path is hard to identify in the building environment, the route information seems to be more effective and efficient for the firefighters than the survey information (map).

7. Conclusions

Firefighters always need to make difficult decisions and process a significant amount of spatial information in the line of duty, such as

search and rescue. Nonetheless, firefighters can only access limited spatial information in most cases, and often under extremely limited time. The classic LRS model that explains how people develop spatial knowledge in an evolving way is not applicable to explaining how firefighters use limited information in a rapid path planning and way-finding. There is still an apparent knowledge gap regarding how different forms of spatial information affect firefighters' wayfinding performance. The motivation of this study is to find out which types of spatial information are more effective for firefighters to memorize the unfamiliarized building environments in a limited time. With that said, the scope is more on the planning of route based on the given information than on the safety concerns in search and rescue navigation. To narrow the knowledge gap, we conducted a wayfinding experiment with 40 firefighters. The participating firefighters were asked to find three missing victims using one of three spatial information, including landmarks, routes and survey (map) for each trail. For the control condition, they were provided with no information at all and they had to rely on their established search strategies (such as the right-hand search method) to finish the task. The number of victims found and search time were used to evaluate firefighters' wayfinding task performance. We also evaluated the travel distance, PAOs and analyzed individual differences in path planning. The results indicate that the route and survey information could help firefighter better memorize the layout of the building than other spatial information given the limited time. They also represented shorter total travel distances in the task. As for perceived cognitive load, the landmark information caused a higher cognitive load than other conditions. However, we did not find a significant better performance with the survey information as suggested by the previous literature. We found that firefighters tended to behave differently in identifying the optimal path with the survey information (map), partially because of the limited time to process the survey information and make good decisions. Therefore, although survey information is usually considered superior to other information as it provides a more complete view of the space, it may not suit for the situations faced by firefighters as it further burdens them in path planning. Compared to the traditional search and rescue training that firefighters can easily memorize the layout of the physical maze after several training trials, our proposed VR training system can generate a big number of building mazes for firefighters' search and rescue training. Our VR search and rescue training system can be added to firefighters' existing training

curriculum more as “mental training” that allow firefighters to experience the feeling of disorientation in an unfamiliarized building environment and train firefighters to use their existing training knowledge to find victims and get out of the maze in limited time. The findings will help professionals design better training protocols and technologies for firefighters.

Several research limitations still need to be addressed in the future. First, this study was conducted in a well-controlled laboratory environment. In the real-world scenario, firefighters' wayfinding tasks are more unpredictable due to the complexity of the environment. Although we simulated the hazardous environments in VR, such as the low visibility and fire, more evidence is still needed to compare the findings with data collected from real missions. Second, there was a gender bias in this study (40 males, 0 female). According to previous literature (Cherney et al., 2008; Lawton and Kallai, 2002; Lin et al., 2012), the gender difference is known as a factor to influence individual's wayfinding performance. Chen et al. (2009) also found that males exhibited better wayfinding performance than females. Previous literature also has found gender differences strongly affect strategies used in path planning and the spatial knowledge development (Coluccia and Louse, 2004; Lawton, 2010; Lawton and Kallai, 2002). We admit that gender bias to be one of the limitations in this study. We will investigate the effects of diverse subjects including discipline, background, age, and gender in our future studies. At the same time, we only recruited firefighters in our study. This is because we wanted to focus on examining the impacts of spatial information on the professionally trained group of people, i.e., firefighters. It may be interesting to collect an additional convenience sample of non-firefighters, such as students, as control group to compare the differences between firefighters and non-firefighter groups in our future study. At last, in our future research, more physiological data such as Electrocardiogram (ECG) data, eye-tracking data, and functional near-infrared spectroscopy (fNIRS) data will be analyzed to explain the neurophysiological basis of path planning and wayfinding performance.

Acknowledgments

The authors would like to acknowledge Abedallah Al Kader, Sarah HopkoS, Rohiith Karthikeyan, and Yibo Zhu Ph.D. Students from the Department of Industrial & Systems Engineering at Texas A&M University, and Maria Elena Celedon undergraduate student from Pontificia Universidad Catolica de Chile for facilitating the experiment. Finally, the authors would like to thank all the firefighters for their valuable time to participate in the experiment. This material is supported by the National Science Foundation (NSF) under Grant 1937878, as well as the National Institute of Standards and Technology (NIST) under Grant 60NANB18D152. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not reflect the views of the NSF and NIST.

References

- Blacker, Kara, Weisberg, Steven, Newcombe, Nora, Courtney, Susan, 2017. Keeping track of where we are: spatial working memory in navigation. *Vis. Cognit.* 25, 691–702.
- Bliss, J.P., Tidwell, P.D., Guest, M.A., 1997. The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence: Teleoper. Virtual Environ.* 6, 73–86.
- Bosco, A., Picucci, L., Caffo, A.O., Lancioni, G.E., Gyselinck, V., 2008. Assessing human reorientation ability inside virtual reality environments: the effects of retention interval and landmark characteristics. *Cogn. Process.* 9, 299–309.
- Bryant, R.A., Harvey, A.G., 1996. Posttraumatic stress reactions in volunteer firefighters. *J. Trauma. Stress* 9, 51–62.
- Buecher, S.J., Holscher, C., Wiener, J., 2009. Search strategies and their success in a virtual maze. In: *Proceedings of the annual meeting of the cognitive science society*. Campbell, R., Molis, J., 2019. United States Firefighter Injuries in 2018.
- Chen, C.-H., Chang, W.-C., Chang, W.-T., 2009. Gender differences in relation to wayfinding strategies, navigational support design, and wayfinding task difficulty. *J. Environ. Psychol.* 29, 220–226.
- Cherney, I.D., Brabec, C.M., Runco, D.V., 2008. Mapping out spatial ability: sex differences in way-finding navigation. *Percept. Mot. Skills* 107, 747–760.
- Coluccia, E., Louse, G., 2004. Gender differences in spatial orientation: a review. *J. Environ. Psychol.* 24, 329–340.
- Dadi, G.B., Goodrum, P.M., Taylor, T.R., Carswell, C.M., 2014. Cognitive workload demands using 2D and 3D spatial engineering information formats. *J. Constr. Eng. Manage.* 140, 04014001.
- Davis, J., Gallagher, S., 2014. Physiological demand on firefighters crawling during a search exercise. *Int. J. Ind. Ergon.* 44, 821–826.
- De Goede, Maartje, Postma, Albert, 2015. Learning your way in a city: experience and gender differences in configurational knowledge of one's environment. *Front. Psychol.* 6, 402.
- Devlin, A.S., 1976. The “small town” cognitive map: adjusting to a new environment. *Environ. Know.: Theor. Res. Methods*.
- Du, J., Shi, Y., Zou, Z., Zhao, D., 2017. CoVR: cloud-based multiuser virtual reality headset system for project communication of remote users. *J. Constr. Eng. Manage.* 144, 04017109.
- Du, J., Zou, Z., Shi, Y., Zhao, D., 2018. Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Autom. Constr.* 85, 51–64.
- Elvins, T.T., 1997. VisFiles: virtually lost in virtual worlds—wayfinding without a cognitive map. *ACM SIGGRAPH Comput. Graph.* 31, 15–17.
- FEMA, 2018. Firefighter Fatalities in the United States in 2018.
- Feng, Z., González, V.A., Trotter, M., Spearpoint, M., Thomas, J., Ellis, D., Lovreglio, R., 2020. How people make decisions during earthquakes and post-earthquake evacuation: Using Verbal Protocol Analysis in Immersive Virtual Reality. *Saf. Sci.* 129, 104837.
- Golledge, R.G., Smith, T.R., Pellegrino, J.W., Doherty, S., Marshall, S.P., 1985. A conceptual model and empirical analysis of children's acquisition of spatial knowledge. *J. Environ. Psychol.* 5, 125–152.
- Ishikawa, T., Montello, D.R., 2006. Spatial knowledge acquisition from direct experience in the environment: individual differences in the development of metric knowledge and the integration of separately learned places. *Cogn. Psychol.* 52, 93–129.
- Jansen, P., Schmelter, A., Heil, M., 2009. Spatial knowledge acquisition in younger and elderly adults. *Exp. Psychol.*
- Kassambara, A., 2020. ggpubr: 'ggplot2' Based Publication Ready Plots.
- Keller, J., 2016. ArmSwinger VR Locomotion System.
- Latini-Corazzini, L., Nesa, M.P., Ceccaldi, M., Guedj, E., Thinus-Blanc, C., Cauda, F., Dagata, F., Péruch, P., 2010. Route and survey processing of topographical memory during navigation. *Psychol. Res.* 74, 545–559.
- Lawton, C.A., 2010. Gender, spatial abilities, and wayfinding. *Handbook of gender research in psychology*. Springer, pp. 317–341.
- Lawton, C.A., Kallai, J., 2002. Gender differences in wayfinding strategies and anxiety about wayfinding: a cross-cultural comparison. *Sex Roles* 47, 389–401.
- Lin, C.-T., Huang, T.-Y., Lin, W.-J., Chang, S.-Y., Lin, Y.-H., Ko, L.-W., Hung, D.L., Chang, E.C., 2012. Gender differences in wayfinding in virtual environments with global or local landmarks. *J. Environ. Psychol.* 32, 89–96.
- Lin, J., Cao, L., Li, N., 2019. Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology. *Adv. Eng. Inf.* 39, 53–61.
- Lin, J., Cao, L., Li, N., 2020a. How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations: a VR-based experimental study. *Autom. Constr.* 113, 103136.
- Lin, J., Zhu, R., Li, N., Becerik-Gerber, B., 2020b. Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study. *Adv. Eng. Inf.* 43, 101040.
- Lindberg, E., Gärling, T., 1983. Acquisition of different types of locational information in cognitive maps: automatic or effortful processing? *Psychol. Res.* 45, 19–38.
- Lovreglio, R., Duan, X., Rahouti, A., Phipps, R., Nilsson, D., 2020. Comparing the effectiveness of fire extinguisher virtual reality and video training. *Virtual Reality* 1–13.
- Lovreglio, R., Gonzalez, V., Feng, Z., Amor, R., Spearpoint, M., Thomas, J., Trotter, M., Sacks, R., 2018. Prototyping virtual reality serious games for building earthquake preparedness: the Auckland City Hospital case study. *Adv. Eng. Inf.* 38, 670–682.
- Meng, F., Zhang, W., 2014. Way-finding during a fire emergency: an experimental study in a virtual environment. *Ergonomics* 57, 816–827.
- Moeser, S.D., 1988. Cognitive mapping in a complex building. *Environ. Behav.* 20, 21–49.
- Morganti, F., Gaggioli, A., Strambi, L., Rusconi, M.L., Riva, G., 2007. A virtual reality extended neuropsychological assessment for topographical disorientation: a feasibility study. *J. NeuroEng. Rehabil.* 4, 1–5.
- Nydegger, R., Nydegger, L., Basile, F., 2011. Post-traumatic stress disorder and coping among career professional firefighters. *Am. J. Health Sci. (AJHS)* 2, 11–20.
- Pendleton, M., Stotland, E., Spiers, P., Kirsch, E., 1989. Stress and strain among police, firefighters, and government workers: a comparative analysis. *Criminal Justice Behav.* 16, 196–210.
- Rebay, S., 1993. Efficient unstructured mesh generation by means of Delaunay triangulation and Bowyer-Watson algorithm. *J. Comput. Phys.* 106, 125–138.
- Richardson, A.E., Montello, D.R., Hegarty, M., 1999. Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory Cognit.* 27, 741–750.
- Ronchi, E., Nilsson, D., Kojić, S., Eriksson, J., Lovreglio, R., Modig, H., Walter, A.L., 2016. A virtual reality experiment on flashing lights at emergency exit portals for road tunnel evacuation. *Fire Technol.* 52, 623–647.
- Ruddle, R.A., Payne, S.J., Jones, D.M., 1997. Navigating buildings in “desk-top” virtual environments: experimental investigations using extended navigational experience. *J. Exp. Psychol.: Appl.* 3, 143.

- Shi, Y., Du, J., Ahn, C.R., Ragan, E., 2019. Impact assessment of reinforced learning methods on construction workers' fall risk behavior using virtual reality. *Autom. Constr.* 104, 197–214.
- Shi, Y., Du, J., Lavy, S., Zhao, D., 2016. A multiuser shared virtual environment for facility management. *Procedia Eng.* 145, 120–127.
- Shi, Y., Du, J., Worthy, D.A., 2020. The impact of engineering information formats on learning and execution of construction operations: a virtual reality pipe maintenance experiment. *Autom. Constr.* 119, 103367.
- Siegel, A.W., White, S.H., 1975. The development of spatial representations of large-scale environments, *Advances in child development and behavior*. Elsevier, pp. 9–55.
- Song, X.B., Lovreglio, R., 2020. Investigating personalized exit choice behavior in fire accidents using the hierarchical Bayes estimator of the random coefficient logit model. *Anal. Methods Acc. Res.* 29, 100140.
- Taylor, H.A., Naylor, S.J., Chechile, N.A., 1999. Goal-specific influences on the representation of spatial perspective. *Memory Cogn.* 27, 309–319.
- Thorndyke, P.W., Hayes-Roth, B., 1982. Differences in spatial knowledge acquired from maps and navigation. *Cogn. Psychol.* 14, 560–589.
- Tobii, 2019a. Tobii Pro SDK.
- Tobii, 2019b. Tobii Pro VR Integration.
- Unity, 2019. Maze Generator.
- van Asselen, M., Fritschy, E., Postma, A., 2006. The influence of intentional and incidental learning on acquiring spatial knowledge during navigation. *Psychol. Res.* 70, 151–156.
- Vazgriz, 2019. *Procedurally Generated Dungeons*.
- Verghote, A., Al-Haddad, S., Goodrum, P., Van Emelen, S., 2019. The effects of information format and spatial cognition on individual wayfinding performance. *Buildings* 9, 29.
- Werner, S., Krieg-Brückner, B., Mallot, H.A., Schweizer, K., Freksa, C., 1997. Spatial cognition: The role of landmark, route, and survey knowledge in human and robot navigation, *Informatik'97 Informatik als Innovationsmotor*. Springer, pp. 41–50.
- Wickens, C.D., 2008. Multiple resources and mental workload. *Hum. Factors* 50, 449–455.
- Wickens, C.D., Flach, J.M., 1988. *Information processing, Human factors in aviation*. Elsevier, pp. 111–155.
- Wiener, J.M., Schnee, A., Mallot, H.A., 2004. Use and interaction of navigation strategies in regionalized environments. *J. Environ. Psychol.* 24, 475–493.
- Zhu, R., Lin, J., Becerik-Gerber, B., Li, N., 2020. Influence of architectural visual access on emergency wayfinding: a cross-cultural study in China, United Kingdom and United States. *Fire Saf. J.* 102963.