

集中和分散的视觉引导系统支持火灾疏散

Fire evacuation supported by centralized and decentralized visual guidance systems

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它们总是指示相同的逃生路线而不受危险的位置影响。

ABSTRACT

In the event of fires and other hazards, visual guidance systems that support evacuation are critical for the safety of individuals. Current visual guidances for evacuations are typically non-adaptive signs in that they always indicate the same exit route independently of the hazard's location. Adaptive signage systems can facilitate wayfinding during evacuations by optimizing the route towards the exit based on the current emergency situation. In this paper, we demonstrate that participants that evacuate a virtual museum using adaptive signs are quicker, use shorter routes, suffer less damage caused by the fire, and report less distress compared to participants using non-adaptive signs. Furthermore, we develop both centralized and decentralized computational frameworks that are capable of calculating the optimal route towards the exit by considering the locations of the fire and automatically adapting the directions indicated by signs. The decentralized system can easily recover from the event of a sign malfunction because the optimal evacuation route is computed locally and communicated by individual signs. Although this approach requires more time to compute than the centralized system, the results of the simulations show that both frameworks need less than two seconds to converge, which is substantially faster than the theoretical worst case. Finally, we use an agent-based model to validate various fire evacuation scenarios with and without adaptive signs by demonstrating a large difference in the survival rate of agents between the two conditions.

1. Introduction

Fire is an exceedingly dangerous but common hazard in private and public spaces. Worldwide, it is estimated that 7,000,000 to 8,000,000 fire incidents occur annually, which lead to 70,000 to 80,000 fire deaths and 500,000 to 800,000 fire injuries (Brushlinsky et al., 2015). Although most of these fire incidents are on residential properties, nonresidential building fires still account for over 100,000 cases per year in the US, causing \$2.6 billion in property damage (National Fire Data Center, 2020). Whereas it is usually easier to evacuate from familiar properties (Proulx, 2002), it can be more difficult to navigate through unfamiliar public environments when signs provide incorrect or incomplete spatial information (Lovelace et al., 1999). Research has

found that design flaws could undermine the effectiveness of evacuation guidance and thus threaten the safety of users (Brickey, 1985; Kobes et al., 2010; Li et al., 2018; Hulida et al., 2019; Nilsson et al., 2009). Indeed, it has been demonstrated that the conventional exit sign without animation or enhanced illumination is not fully visible in unfamiliar environments (Xie, 2011) or helpful for evacuees when poorly designed (Grosshandler et al., 2005). Despite these findings, little progress has been made in human–building interaction technologies such as intelligent evacuation systems.

Animation, adaptation, and decentralization can be used to improve existing signage systems. Animations on signs can attract evacuees' attention and indicate a particular direction (Galea et al., 2014). The

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direction indicated by a sign or signage system can also adapt to the location of the hazard by indicating the safest route (Chu, 2011). While these systems are often centralized, which makes them easier to design and maintain, decentralized systems may be more robust to malfunctions affecting one part of the system (de Farias et al., 2014). To our knowledge, previous research has not designed and implemented an adaptive and decentralized system for controlling evacuation signage.

In this paper, we combine a Virtual Reality (VR) experiment with agent simulations to test the efficiency and effectiveness of a decentralized and adaptive signage system (see Fig. 1) that guides people/agents towards the safest and most efficient route during a simulated fire evacuation. To anticipate, in the VR experiment, we found that such a system can improve evacuation efficiency, decrease damage caused by the fire, and reduce participants' level of stress. The agent simulations also demonstrate that adaptive systems can substantially increase the survival rate of agents during a fire evacuation. We also compared the performance of centralized and decentralized signage systems for computing and communicating the optimal evacuation route. Although the decentralized system propagated signage information slightly slower than the centralized system (by approximately one second), the decentralized system is more resilient to system malfunctions. These findings may contribute to the development of intelligent systems for human-building interaction and crowd management in public spaces.

This paper systematically describes our work of implementing and examining the decentralized adaptive signage system. The paper is organized in the following manner. In Section 2, we review the related work on the topic of a fire evacuation. In Section 3, we test the effectiveness of the adaptive signage using a VR Experiment. In Section 4, we implement the computational framework for automatically generating the adaptive signs and routes in both centralized and decentralized systems. In Section 5, we further validate the computational framework with agent-based simulations. In Sections 6 and 7, we present the general discussion and conclusion of the study.

2. Related work

Previous research has identified three key factors for successful fire evacuations: evacuation efficiency (Proulx, 1995), information that supports wayfinding (Fridolf et al., 2013), and the emotional stability of the evacuees (Proulx, 1993). One of the main causes of casualties during fires is exposure to toxic fumes. Indeed, there are two times more fatalities caused by smoke inhalation than fatalities caused by burns (Flynn, 2010). To avoid the danger of smoke, a fast and efficient evacuation is vital. Since the stress of facing dangerous fire situations could affect the cognitive processes and decision making abilities of evacuees, it is important to ensure that they evacuate as quickly and calmly as possible (Proulx, 1993). Here, an adaptive signage system may be designed to solve such issues by highlighting the direction of the optimal route considering both path distance and safety.

2.1. Intelligent fire evacuation systems

To overcome the shortcomings of traditional exit signage, numerous researchers have attempted to devise a more intelligent system based on sensor and network technologies (Chung et al., 2017; Barnes et al., 2007; Tabirca et al., 2009; Zeng et al., 2010; Chen et al., 2012; Ran et al., 2014; Xie et al., 2020; Topol and Slater, 1985; Chalmet et al., 1982; Wagner et al., 1997; Lee and Kim, 2018; Zhang et al., 2018; Bai et al., 2010; Dhalmahapatra et al., 2021; Galea et al., 2018; Xie et al., 2012; Fujii et al., 2021; Zhang et al., 2021b; Kinatader et al., 2014a) to collect information regarding the locations of fires (Khadivi and Hasler, 2009) and individual evacuees (Yan et al., 2019; Kubota et al., 2021) and to deliver route guidance information (Chung et al., 2017; Zhang et al., 2017). For example, Hsu and colleagues (Hsu et al., 2014) implemented a digital panel to provide route guidance during an evacuation. Other researchers have used sensors to detect the locations

of fires and indicate a safe route using blinking signs (Yenumula et al., 2015). In addition, the traditional exit sign icon (i.e., a running person) may be oriented and located towards the direction of the optimal exit route in order to guide evacuations (Kim et al., 2016). Here, various designs for indicating incorrect or inefficient directions have also been tested. Signs with a red "X" symbol were found to be the most dissuasive (Olander et al., 2017), and ground installations tend to be more effective than overhead suspensions for guiding evacuees (Ran et al., 2014). Finally, some researchers have introduced novel computational methods to optimize the locations of signs (Zhang et al., 2017; Dubey et al., 2017).

2.2. Decentralized system for smart buildings

Intelligent systems concepts such as Intelligent Evacuation Guidance System for Large Building was proposed to adjust evacuation plans based on road conditions and population density (Wu et al., 2016). Researchers have also used Internet-of-Things and data exchange technologies to provide optimal evacuation paths (Yu et al., 2018). However, such intelligent systems are usually built using a centralized processing and communication entity, which undermines the systems' abilities to handle loss or damage of their components (Rao et al., 1993). Current fire alarm systems face the challenge of hardware failure and software failure (Xu et al., 2012), especially if the central controlling entity of the system (Liu et al., 2010) is located in only one physical position. Many centralized systems are made more reliable by having a fault alarm, auto-switching between the main and backup power supplies, and self-test functions (Liu et al., 2010). However, centralized systems are also often vulnerable to cable erosion, communication failures, and operator error (PAś and KlimczAK, 2019; Shu-Guang, 2011).

A decentralized system can avoid situations in which a failed central entity causes a system to collapse by distributing the resource or introducing independent management (Colson et al., 2011). Towards this end, de Farias and colleagues (de Farias et al., 2014) created a decentralized control and decision-making system for smart buildings in which wireless sensor and actuator network nodes share the sensed data and make cooperative decisions. Similarly, Sarkar and colleagues (Sarkar et al., 2014) proposed a distributed layered architecture for Internet of Things applications. While various frameworks have been proposed to facilitate the establishment of such distributed systems (Truong and Abowd, 2002; Stojmenovic, 2014; Lilis, 2017), none of these decentralized systems were designed for wayfinding or evacuation situations.

2.3. Virtual reality for fire evacuation research

Fire evacuations can be difficult and unethical to investigate with real participants because of their dangerous nature. Here, VR (Kinatader et al., 2015; Zhang et al., 2019; Leder et al., 2019; Shi et al., 2021; Feng et al., 2020; Ronchi et al., 2016; Arias et al., 2019; Lovreglio et al., 2021), field experiment (Xue et al., 2021; Ma et al., 2012; Hu et al., 2020; Jin et al., 2019), and agent-based simulations (Rozo et al., 2019; Zheng et al., 2009; Bernardini et al., 2020; Wahlqvist et al., 2021; Xue et al., 2020; Luo et al., 2020; Kuang et al., 2014; Zhu et al., 2011; Ding et al., 2017) may offer safe and cost-effective alternatives in controlled environments (Kinatader et al., 2014b; Gwynne et al., 1999; Schadschneider et al., 2009; Kinatader et al., 2018). In addition, VR experiments allow researchers to gain insight regarding the level of stress experienced during an evacuation (Shaw et al., 2019; Cao et al., 2021). Stress and mass panic could severely reduce the efficiency of the evacuation (Li et al., 2014), causing arching and clogging at the exit (Helbing et al., 2000). At the same time, agent-based simulations allow for the testing of large numbers of different evacuation scenarios in a short amount of time. The combination of VR experiments and



Fig. 1. Evacuation sign design. The four arrow designs were applied and animated with scrolling motion in both the non-adaptive and adaptive sign conditions. The blinking red “X” only appeared in the adaptive sign group.

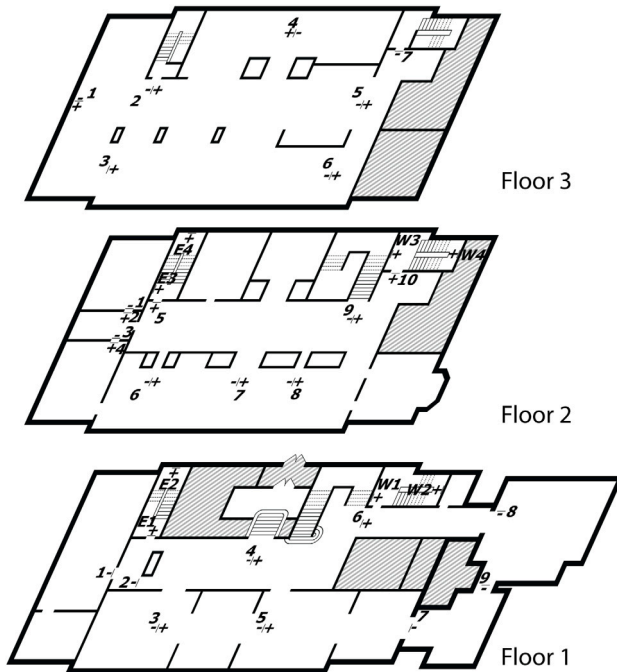


Fig. 2. Museum floor plan. Each number corresponds to one evacuation sign. Depending on the placement location, each sign has either one or two sides (+/-) and the stairwell signs are indicated with East (E) or West (W). Three floors are connected via two side stairwells and a main stairway between the first and second floor. The main entrance and only exit are located on the first floor next to the main stairway. Gray areas were not accessible by participants during the experiment.

agent simulations can be used to connect individual behaviors to the state of a larger crowd.

To test our decentralized and adaptive signage system, we established a workflow that included a lab experiment with human participants and agent-based modeling to validate the computational framework. First, we designed a prototype of the adaptive signage system and examined its utility using a desktop VR experiment. With validated evidence of the adaptive signage from the experiment, we then implemented an automatic computational framework for the adaptive signage system, using graph-based algorithms and either centralized or decentralized computational structures. Lastly, we used an agent-based model to verify the effectiveness of the entire system.

3. Adaptive signage validation with VR experiment

In this experiment, we tested the utility of an adaptive signage system compared to traditional exit signs for fire evacuation from a virtual museum. We expected participants using adaptive signage to evacuate more efficiently, more safely, and with lower stress levels. This experiment was approved by the ethics committee of the university.

3.1. Participants

Participants were recruited via the university experiment registration system. In total, 94 participants (average age of 23 years and

a range of 18 to 33 years; 46 women) participated in the study. Nine participants were excluded from the experiment due to simulator sickness or software failures. In addition, two participants were excluded from the behavioral data analysis due to incomplete database recording. Because of motion artifacts, an additional three participants were excluded from the heart rate variability (HRV) analysis, and three participants were excluded from the electrodermal activity (EDA) analysis. All participants were compensated 30 CHF regardless of how well they performed.

3.2. Materials

3.2.1. Virtual museum

For this study, we adapted a 3D model of the Cooper Hewitt Smithsonian Design Museum in New York (used with permission) (Museum, 2014). This 3D model was chosen because it was sufficiently complex and realistically detailed. Specifically, the model contains three floors that are connected by one main stairway between the first and second floor and two side stairwells that traverse all three floors (see Fig. 2). The virtual museum was altered using the Unity game engine (<https://unity.com>) by placing physical barriers to block specific areas and by adding art installations (e.g., paintings and sculptures). Materials for these installations were obtained online and from the Unity Asset Store.

3.2.2. Software and hardware

We used the *Experiment in Virtual Environments (EVE) framework* (Grübel et al., 2017; Weibel et al., 2018) to implement and control the VR experiment. The experiment was conducted using a high-performance gaming computer (Dell Alienware Area 51 Base; i7-5820K processor at 3.8 GHz overclocked; dual NVIDIA GeForce GTX 1080 video cards; 32 GB of SDRAM; Windows 10 operating system) with a 55" ultra-high-definition television (Samsung UE55JU6470, 3840X2160 pixels). Participants navigated with a mouse and keyboard control interface, and the virtual museum was presented on a desktop display. Previous research suggests that this type of setup is sufficient for eliciting realistic wayfinding behavior (Zhao et al., 2018, 2020; Thrash et al., 2015).

In addition to the behavior data collected during the experiment, we also collected electrodermal activity (EDA) and heart rate data in order to measure participants' physiological responses (Collet et al., 1997; Wiederhold et al., 2002; Weibel et al., 2018). These data were collected using a Powerlab 8/35 recording device with FE116 GSR Amp and FE132 Bio Amp signal amplifiers and LabChart 8.14 software (<https://www.adinstruments.com/>). For EDA, two electrodes were placed on participants' right shoulders so that they could operate the mouse and keyboard with both hands. Two heart rate electrodes were placed on the second intercostal space below the middle of the right and left clavicles. In addition, another electrode was attached below the ninth left rib.

3.2.3. Sign systems

Five types of signs were designed by combining the traditional running person symbol (Kim et al., 2016) with animated arrows (see Fig. 1). For both adaptive and non-adaptive sign groups, the arrow signs were animated with a scrolling motion (Galea et al., 2014). In the non-adaptive sign group, the signs always directed participants along the shortest path towards the exit of the building without considering paths blocked by fire. In the adaptive sign group, the signs indicated

safe directions towards the exit based on the distribution of fire in the building. A red blinking “X” (Olander et al., 2017) indicated that the route was blocked and that participants should turn around and seek an alternative path. Left and right arrows indicated that the participant should turn left or right, respectively. In the stairwells, the up arrow indicated that participants should move upstairs, and the down arrow indicated that participants should move downstairs. Outside of the stairwells, the down arrow indicated that the participant should keep moving in the same direction. For the VR experiment only, all sign directions, sign locations, and fire locations were manually placed for both groups. Signs were placed where a navigation decision was needed.

3.2.4. Fire mechanism

Fire in the virtual environment consisted of visual flames, smoke effects (see Fig. 3c), and physical barriers to prevent passage. Fire locations were designed to block particular routes that would have been safe in normal circumstances. Given the restrictions of only one entrance/exit and the two stairway structures of the 3D model, we designed the fire locations to limit the number of possible evacuation routes. For each trial, we placed the fires to block one or several transitions between the stairs and the floors, while ensuring that there exists at least one possible egress route. The fire blocks were designed to be large enough so that the participants could not traverse the blocked area. All of these fire locations are listed in the supplementary materials. The harmful effects of smoke and burns depended on the time spent in the building and collisions with the fire during the entire evacuation. Towards this end, we defined a health score that ranged from 0 to 1. The participants had five minutes to escape, representing the harmful effects of toxic fumes to approximate real-life survival expectancy (Marsar, 2010). As a simple starting point for this experiment, we defined a function by which the score decreased linearly (ranging from 0 to 1) starting from the beginning of the evacuation. In addition, if participants were within approximately 0.5 meters from the physical obstacle representing the fire, their health decreased rapidly at the rate of 5% per second and a red screen flashed as a warning message. Otherwise, this health score was not visible to participants during the experiment. The size of the area of the fire remained constant during the experiment in order to guarantee consistency across trials and participants in terms of the usefulness of the information delivered by the exit signage.

3.3. Procedure

Before the experiment, participants read and signed an information sheet and consent form. The experimenter then helped the participant to attach the physiological electrodes for measuring the heart rate and electrodermal activity and provided them with a mouse and keyboard. The experiment began with a demographics questionnaire, a video game experience questionnaire, and the first part of the Short Stress State Questionnaire (SSSQ) (Helton, 2004). Next, participants were trained to navigate with a mouse and keyboard through the virtual environment by completing a tutorial in a multi-floor virtual hotel (see Fig. 3a). During training, participants were asked to move through the environment and collect gems placed at different locations and elevations. Such designs were applied based on previous research that was successful in helping participants learn the controls and virtual environment (Grübel et al., 2017; Hackman et al., 2019). After training, participants watched a seven-minute nature video in order to obtain a baseline of physiological activity.

Participants then navigated through the virtual museum on three different trials. Each trial consisted of a learning route and an evacuation route. To become familiar with the environment and the navigation task, participants were asked to follow a learning route by collecting a series of gems. The location of each successive gem was

indicated by a moving arrow in the middle of the participant's viewpoint (see Fig. 3b). Each learning route ensured that participants moved through all three floors of the virtual museum, albeit in different orders for different trials. At the end of each learning route, the evacuation route was immediately triggered. During the evacuation route, participants were instructed to locate the main entrance, where they started their first learning route in the first trial. For every trial, the end of the learning route and beginning of the evacuation route was on a different floor. After each trial, participants were asked to rate their level of stress during the evacuation on a scale from 1 to 9. After the third trial, participants completed the second part of the SSSQ.

3.4. Design and analyses

We created six learning routes with different floor visiting orders. The order of learning routes across trials was constrained for each participant so that the first trial always started on the first floor, each of the three trials started on a different floor, and each of the three trials ended on a different floor. These constraints resulted in four different orders of learning routes that were the same for adaptive and non-adaptive sign groups. We also devised six evacuation routes with different fire distributions that were also the same for adaptive and non-adaptive sign groups. Thus, the only difference between adaptive and non-adaptive sign groups of participants was the direction indicated by the signage system.

Participants were randomly assigned to one of the four possible trial orders and one of the two sign groups (between-subjects). The two sign types were the only independent variable. The dependent variables consisted of responses to the stress level questionnaires, video game questionnaire, health score, evacuation path length, evacuation time, damage (percentage of health score resulting from direct fire harm), and physiological responses (EDA and HRV) (Helton, 2004; Critchley and Nagai, 2013; Kim et al., 2018). These dependent measures were compared between adaptive and non-adaptive sign groups using two-tailed, independent-samples *t*-tests.

For physiological responses, we exported both EDA and electrocardiogram data from LabChart, imported the EDA data into LedaLab (<http://www.ledalab.de>), and imported the electrocardiogram data into Kubios (<https://www.kubios.com>). All physiological data were visually inspected for artifacts. In LedaLab, we downsampled the EDA data from 1000 Hz to 10 Hz and extracted the number of non-specific skin conductance responses (nSCR) using Continuous Decomposition Analysis with a minimum amplitude threshold of 0.01 μ S (Benedek and Kaernbach, 2010). In Kubios, we first applied low threshold (0.45 s) and smoothness prior filters ($\lambda = 500$, cut-off frequency = 0.035 Hz) to the electrocardiogram data. In order to calculate HRV as a measure of stress or worry (Log(HF)), we then selected and natural log-transformed the absolute values of power in the high-frequency range between 0.15 Hz to 0.4 Hz (Berntson et al., 1997; Rawenwaaij-Arts et al., 1993). We subtracted EDA and HRV during the baseline nature video from EDA and HRV during the evacuation routes in order to derive a measures of reactivity towards the evacuation scenario.

3.5. Results

In the adaptive sign group, participants successfully evacuated from the building in 111 of 126 (88%) trials. In comparison, participants from the non-adaptive sign group escaped in only 83 of 123 (67%) trials. A two-proportion Z-test confirmed that these survival rates are significantly different ($Z = 3.921$, $p < .001$, $d = 0.817$). The following results represent all of trials, including those in which the participants were not able to evacuate from the building until the time out (5 mins). We found a significant difference between the adaptive and non-adaptive sign groups in terms of SSSQ Distress ($t(83) = -2.743$, $se = 0.580$, $p = .008$, $d = -0.607$), health score ($t(83) = 4.503$, $se = 0.038$, $p < .001$, $d = 0.991$), damage ($t(83) = -3.689$, $se = 0.019$, $p < 0.001$,

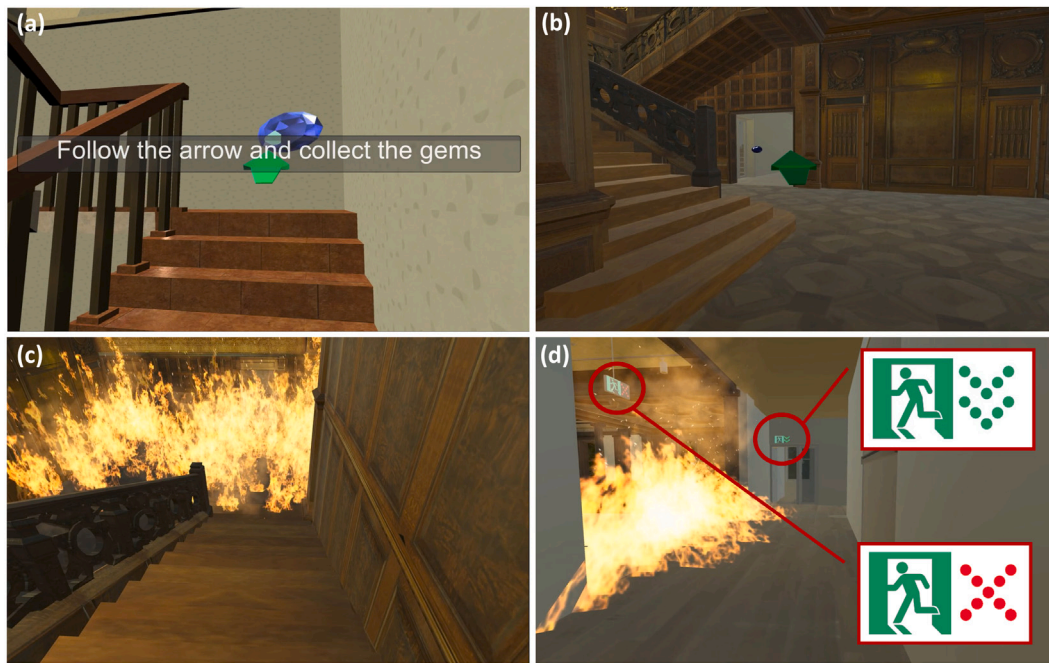


Fig. 3. (a) Training tutorial. The instructions were for participants to collect the gems by walking towards them one by one using the mouse and keyboard. (b) Learning route with a floating green arrow that guided participants towards the gems. (c) Virtual environment with fire illustration. (d) An evacuation route from the adaptive sign group. The red “X” indicates to participants not to enter the area, and the down arrow indicates to participants to pass through the doorway on the right.

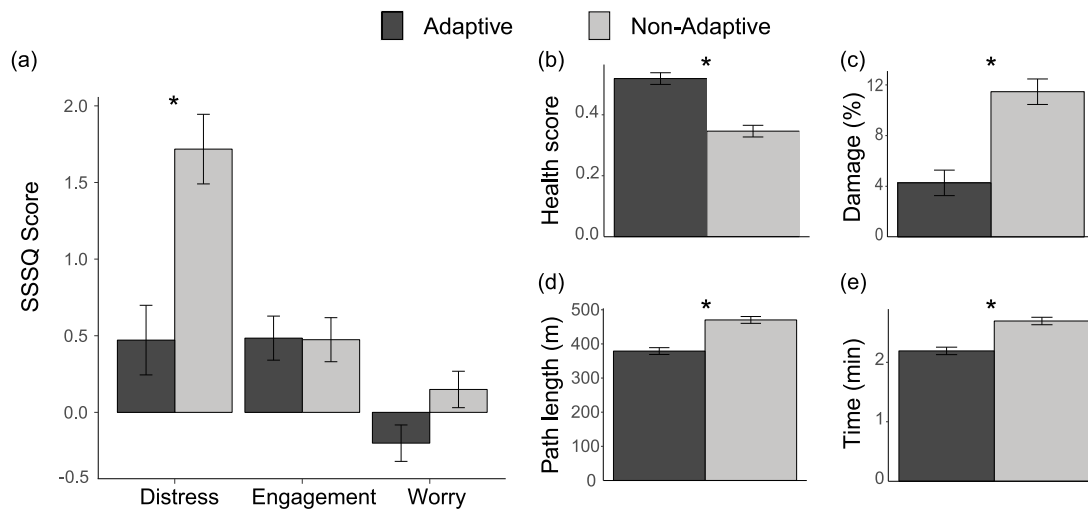


Fig. 4. Results of the VR evacuation experiment. (a) SSSQ scores, (b) health score, (c) damage caused by the fire, (d) path length, and (e) evacuation time. The error bars represent the standard error of the difference between the two groups. Asterisks denote significant differences between adaptive and non-adaptive sign groups.

$d = -0.812$), path length ($t(83) = -4.571$, $se = 19.968$, $p < .001$, $d = -1.006$), and time ($t(83) = -4.008$, $se = 0.130$, $p < .001$, $d = -0.881$) (see Fig. 4). These results demonstrate that participants in adaptive sign group experienced less distress, obtained a higher health score, suffered less damage, and exited the building with shorter path lengths in less time. We did not find significant differences in terms of SSSQ Engagement ($t(83) = 0.037$, $se = 0.287$, $p = .972$, $d = 0.008$), SSSQ Worry ($t(83) = -1.474$, $se = 0.238$, $p = .145$, $d = -0.325$), and self-reported stress level immediately after each trial ($t(83) = -1.233$, $se = 0.344$, $p = .221$, $d = -0.271$). There was also no significant difference between the sign groups in terms of video game experience ($t(83) = 0.885$, $se = 0.126$, $p = .129$, $d = 0.334$). For the physiological measures, we did not find significant differences between the adaptive and non-adaptive sign groups in terms of nSCR ($t(82) = -0.596$, $se = 0.032$, $p = 0.553$, $d = -0.131$) or in terms of Log(HF) ($t(82) = -1.232$, $se = 0.180$,

$p = .221$, $d = -0.273$). However, there were significant differences between the baseline and the evacuation routes in terms of nSCR ($t(82) = -2.183$, $se = 0.027$, $p = .031$, $d = -0.341$) and Log(HF) ($t(82) = 3.970$, $se = 0.173$, $p < .001$, $d = 0.623$).

3.6. Discussion

Overall, the results of the VR experiment supported our hypothesis that adaptive signs can be more effective and efficient during an evacuation in terms of survival rate, self-reported distress, health score, fire damage, path length, and time to evacuate. Contrary to our expectations, we did not find significant differences between the two sign conditions in terms of physiological arousal (i.e., EDA and HRV). This may indicate that the evacuation task was stressful in general, as supported by the significant physiological differences between the

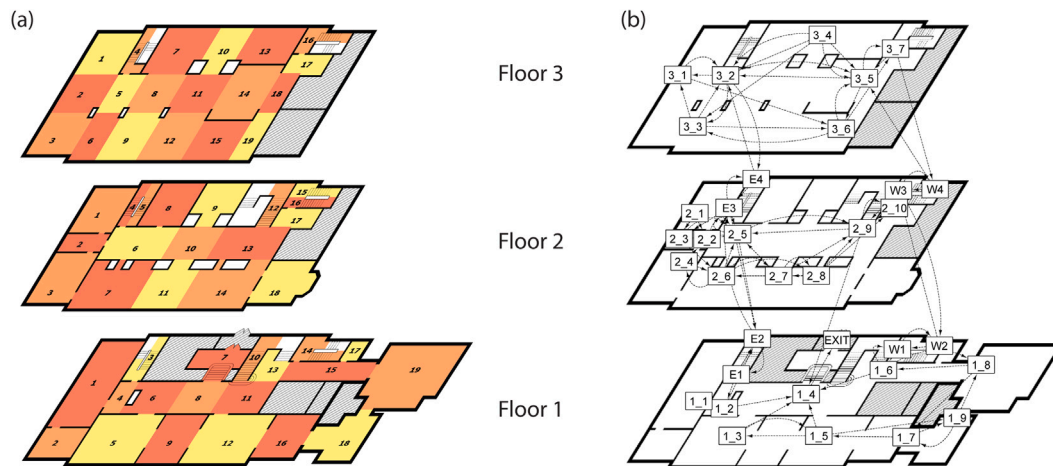


Fig. 5. (a) Illustration of sensor areas for each floor of the building. Different colors represent the coverage areas of different sensors. (b) Connection graph of all exit signs in the museum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

baseline and evacuation phases. We also found no significant differences in self-reported stress level immediately after each trial. Although this short question allowed us to measure self-reported stress after each trial, this measure may not have been sufficiently sensitive (consistent with Kobes et al., 2010).

Together, these findings demonstrate that this adaptive signage prototype may be developed further to produce a viable system. For the VR experiment, we manually determined the directions indicated by the signs so that the difference between the adaptive and non-adaptive settings was meaningful. However, in real-world applications, the emergency of the fire accidents did not allow the manager to operate the system manually. To extend the engineering viability of the proposed concept, these signs would need to adapt to the locations of the fire automatically. To achieve this, we completed a computational framework for automatically directing evacuees during a fire. The following section describes in detail our attempts of implementing such a system in both centralized and decentralized manners.

4. Computational framework for adaptive signs

In this section, we present a computational framework that uses either a centralized or decentralized approach to automate the control of sign direction. The main difference between the centralized and decentralized versions of the system is that the optimal path is automatically and explicitly computed in the centralized system but emerges from the relay of information among different nodes in the decentralized system. This computational framework was implemented within the Unity game engine. We define four requirements for such a framework, including universality, adaptability, autonomy, and robustness. Universality refers to the principle that it should be possible to apply the sign system to any existing building based on the blueprint or 3D model. Adaptability refers to the ability of the framework to quickly respond to detected fire locations by automatically changing the directions of the evacuation signs accordingly. The system should be autonomous so that it is resilient and reliable in the absence of a building supervisor. The system should also be robust so that it is prepared to respond to unpredictable events (e.g., the malfunction of a sensor or sign).

这个计算框架是在Unity游戏引擎中实现的。

4.1. Room segmentation

To achieve the above goals, we developed a virtual sensor system to simulate the detection of fire incidents across the virtual museum. In our sensor system, each sensor monitors a specific area of the building. The area covered by each sensor was manually defined. In a real

application, the building manager would have assigned the location and density of these sensors during installation of the system. Fig. 5a illustrates the coverage area of our virtual sensor system. The sensor of each area represents a virtual entity that can judge that this area is no longer suitable for an evacuation route. Such a judgment can be triggered by a variety of potential effects, such as the thermal heat temperature rise, level of smoke or toxic air, disconnection from the network, malfunction, or being attacked by a malicious third party. The sensors properties (i.e., location, function) are bundled with the signage in that area. Different aspects of the characteristics (e.g., temperature, toxic air, pathway barrier) of the area can be combined and used to determine the safety of the area. The location of the implemented sensors can be further extended vertically for rooms with a high ceiling in order to avoid incorrect judgment of a safe route in case that the smoke only accumulated near the ceiling. In order to generate a safe route, the system only requires that each area provide a flag of being safe or not, which can be signaled by passing a certain temperature, the presence of smoke, a blockage of a key area or pathway, or a barrier created by a failed automatic door. The system can be tested with only one of these parameters as a safe route indicator, but a final judgment of the route's safety can be based on a combination of several different parameters.

4.2. Sign network graph

To calculate the evacuation paths, a sign network graph was generated based on the topological connections of the fire sensors and their corresponding areas. A directed graph $G(V, E)$ is defined, where the set of nodes V represents all the evacuation signs, and the set of edges E represents navigational routes between two nodes (see Fig. 5b). Each edge is weighted to represent cost, defined as the length of the walking distance in this case. Due to the complex structure of the building, each node may have multiple edges which connect multiple nodes. Each edge corresponds to one of the five possible sign types, depending on the relative positions of the two nodes. Without any fire, the directions of the edges in the graph naturally converge to the optimal evacuation route leading to the exit node on Floor 1. Each node of the graph has access to all the sensors of its neighboring areas. Once a fire breaks out, the graph recalculates sign directions based on the distribution of the fire. For signs that contains two sides (+/-), the indicated directions are altered based on the relative position between two nodes. If one edge of the node is considered unsafe (i.e., passing through the fire area), this edge is removed from the graph and the system regenerates the optimal route without this edge. A signage topology of the first floor is illustrated in Fig. 8. More details can be found in the supplementary materials.

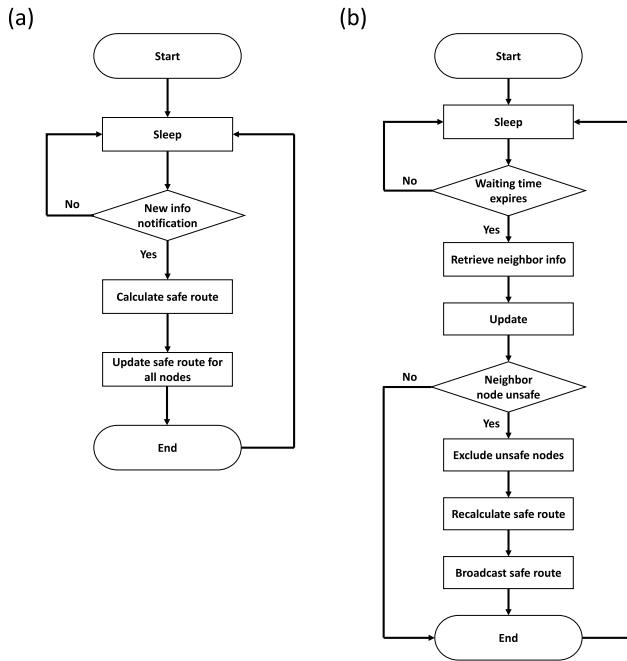


Fig. 6. Illustrations of the computation procedure of (a) centralized system, and (b) decentralized system.

4.3. Centralized and decentralized systems

In case of fire, the network system needs to be robust and resilient to withstand unexpected damage. To study the trade-off between security and efficiency, we implemented and compared two kinds of structures for the sign system.

4.3.1. Centralized system

The centralized approach includes a central entity which has access to the information from every sensor and can communicate directly to every sign in the building (see Fig. 7a). Here, each of the signs displays routing information without having any computational ability. Computations in the central entity have the major responsibility of enabling the signs. In order to achieve this task, the central entity needs to gather information about the hazard and react to the corresponding situation. Once a fire sensor is triggered, the central entity gathers all the information from the sensors regarding the current locations of different fires in the building and updates the graph accordingly. When a hazard occurs, the sensors immediately notify the corresponding entity with a command that checks whether outgoing edges are safe or not. If the locations of the fires remain unchanged, the central entity sleeps for a predefined amount of time (120 ms) until new fire information arrives. Disconnection between any sensor and the central entity is treated as a fire situation in the corresponding area. After collecting the fire information in the previous step, the central entity calculates the optimal evacuation route based on the new graph, while considering the disconnected edges between the nodes. After the optimal route is generated, the central entity assigns different directions to each sign so that all the signs display the shortest and safest route to the exit. The whole calculation finishes until further new danger information is updated to the central entity. The computation procedure is illustrated in Fig. 6. Detailed pseudo code of the system is provided in the supplementary materials.

4.3.2. Decentralized system

For the centralized system, the communication between the central entity and the fire sensors is not always guaranteed because it could be

affected by the fire, causing a vital link on the evacuation route to be compromised. In order to overcome such disadvantages, we propose a decentralized system in which the signs are independent of each other and no central entity is required. The decentralized system differs from the centralized system in that there exists no central entity which controls the communication among all of the sensors and signs and computes the optimal path (see Fig. 7b). Here, each sign is equipped with its own computational power that can be used to store the network graph and calculate the new optimal route based on up-to-date information. During a fire, each sign individually updates its path based on information collected from the sensors and communicates the updated path to its neighbors. Each node in the decentralized system constantly queries the fire situation from its corresponding sensors and detects its neighbors' statuses. When danger appears, the node can function in a similar way as the centralized system to update the optimal evacuation route and transfer this updated information to the neighbor nodes. However, the danger can also be that the neighbor node is damaged or compromised. In such cases, the node cannot update information with its neighbor nodes for a period of time (here, defined as 1300 ms). Once this happens, this node is considered by the neighboring nodes as unsafe, and the optimal route is recalculated. This information is then passed on to other nodes one by one through the entire network with a message sending function. The communication over these edges occurs in exactly the opposite direction of the graph (i.e., the node receives messages over the outgoing edges and sends messages over the incoming edges). This is due to the fact that the nodes closest to an exit are informed first about the existence of a path, after which they propagate this information backward through the graph until it reaches all the rerouted nodes. With this design, the decentralized nodes can function as a distributed network of an intelligent entity. The computation procedure is illustrated in Fig. 6. Detailed pseudo code of the system is provided in the supplementary materials.

Compared to a decentralized system, the centralized approach can be easier to implement and cheaper to install in the real world since the only required communication is from the sensors to the central entity and from the central entity to the signs. However, a potential danger of the centralized system is that, if the central entity is damaged or malfunctioning, communication throughout the sign system breaks down. In contrast, the decentralized system should be more robust to system failure because the information communicated among the signs is redundant and distributed. However, decentralized systems may be more difficult to implement and more expensive.

4.4. Results

The performance of the centralized and decentralized systems were compared in terms of the generated optimal routes and computational time for the same fire distributions. Computational time was defined as the time elapsed between the initial event (e.g., detection of a fire, failure of a node) and the last event that occurred in any sign direction. Computational time for both systems included the amount of time required for communication to the sensors. While computational time for the centralized system was based on computations in the central entity, computational time for the decentralized system included the time required for the individual entities to converge on an optimal route. Because both systems generated the same optimal routes, we focus here on computational time. All of the measurements were conducted on a PC running Windows 8.1 with an Intel Core i7-5500U CPU at 2.4 GHz, 15.9 GB RAM, and a NVIDIA GeForce GTX 850M graphics card. For these simulations, we used Unity 2018.2.18f1 Personal (64 bit). In order to compare the performance of centralized and decentralized systems statistically, we conducted these simulations in 100 different fire scenarios. For each fire scenario, we pseudorandomly generated the fire with the constraints that between one and eight fire locations were placed on each floor. A two-tailed, paired-samples t-test revealed that computational time for the centralized system ($mean = 0.001$ s, $max =$

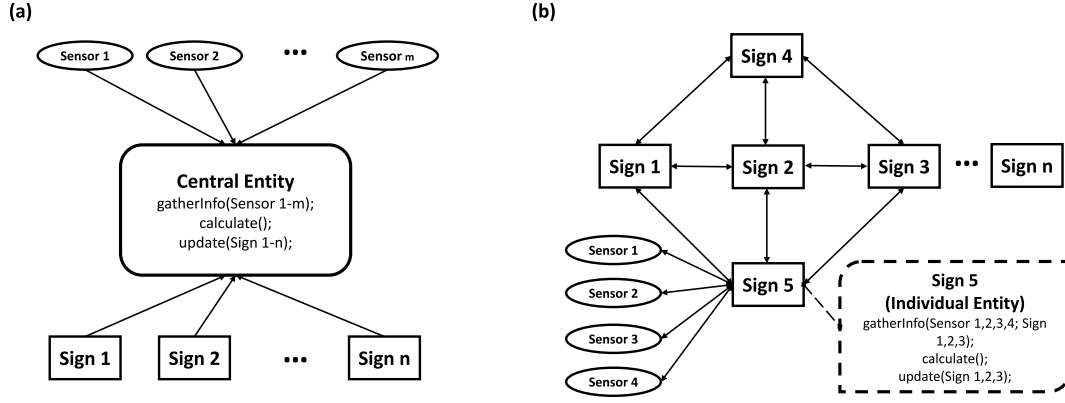


Fig. 7. Visualization of the centralized and decentralized sign system. (a) Centralized system. The Central Entity is in charge of gathering sensor information and then calculating the optimal route and corresponding sign directions. The Central Entity then regularly broadcasts the sign directions to all the signs. (b) Decentralized system. The decentralized system functions without a Central Entity. Each sign gathers information from its corresponding sensors and then constantly sends and receives information from its connected neighbor signs.

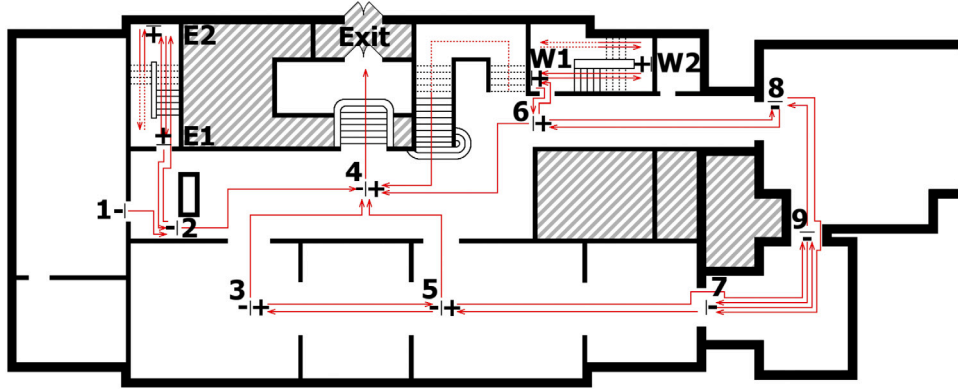


Fig. 8. Connection visualization of signage topology of the first floor of the building. E1/2 represents the signs within the East stairwell and W1/2 represents the signs within the West stairwell. The plus and minus symbols represent the two sides of each sign. Such a design allows the system to differentiate the direction indicated by the signs with two sides.

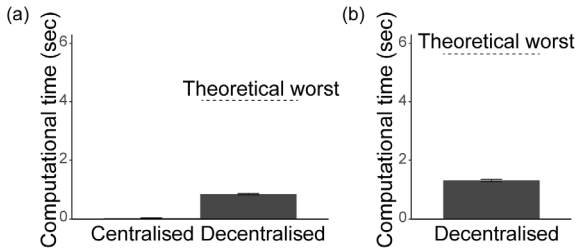


Fig. 9. (a) Mean computational time for functioning centralized and decentralized systems after a fire event. (b) Mean computational time for the decentralized system after a node malfunction.

0.003 s, $SD = 0.001$) was significantly lower than computational time for the decentralized system ($mean = 0.838$ s, $max = 1.788$ s, $SD = 0.439$), $t(99) = -19.087$, $se = 0.044$, $p < .001$, $d = 2.69$ (see Fig. 9a). Despite this significant difference, the maximum computational time for either system was below two seconds.

We next compared the performance of the decentralized system to the theoretical worst case given the detection of a fire. The theoretical worst case of computational time for the detection of a fire was $n * wait_time$. Here, $wait_time$ (120 ms) represented the maximum time between two update functions, and n was the number of nodes (34 in this case) in the graph. We included an additional $(n - 1) * wait_time$ because this process could have continued until the fire information

propagated through all nodes in the graph. The theoretical worst-case computational time for fire detection was 4.1 s. A two-tailed, one-sample t-test revealed that the mean computational time for 100 simulations of the decentralized system was significantly lower than this theoretical worst case, $t(99) = -74.353$, $se = 0.044$, $p < .001$, $d = 7.431$ (see Fig. 9a).

Another event that could activate the decentralized system is the failure of one or more nodes. Here, we simulated the failure of between one and five randomly selected nodes for the same fire locations as in the previous simulations. These node failure simulations were repeated 100 times ($mean = 1.306$ s, $max = 2.823$ s, $SD = 0.739$). The theoretical worst case (5.3 s) for this scenario was computed as $invalidation_time + (n - 1) * wait_time$, $invalidation_time (= 1.3s)$. Here, $invalidation_time$ (1.3 s) is the maximum time required for the neighbor nodes to treat the current node as invalid, and n excludes the deactivated nodes because they were not used in the active graph. A two-tailed, one-sample t-test revealed that the 100 simulations of node failure in the decentralized system resulted in significantly lower computational time than the theoretical worst case, $t(99) = -54.064$, $se = 0.074$, $p < .001$, $d = 5.405$ (see Fig. 9b).

4.5. Discussion

Together, our simulation results demonstrate the advantages and disadvantages of the decentralized adaptive signage system. Compared to the centralized system, the decentralized system was inherently slower because of the communication between individual entities.

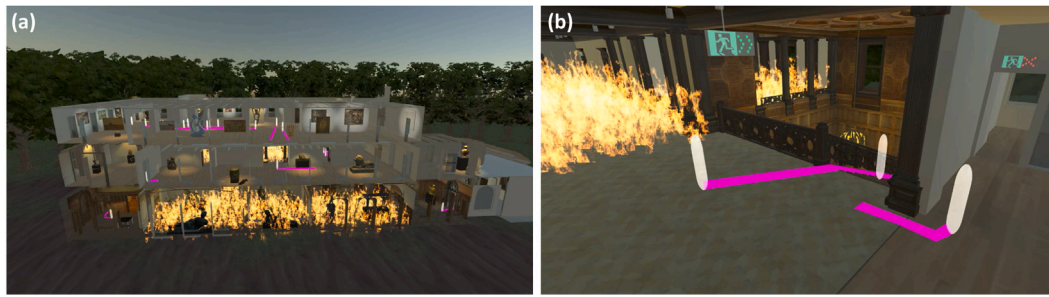


Fig. 10. (a) Overview visualization of the agent simulation. Each agent is represented by a white cylinder. The pink lines represent the projected trajectories. (b) A closer view of the agent simulation on the second floor of the building. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Nonetheless, in our simulations, computational time for the decentralized system was always below 2 s and much faster than the theoretical worst case for computing the optimal route after both the detection of a fire and node failure. In contrast, the centralized system could not have adapted the optimal route based on the failure of only one node. These results clearly show the utility of the decentralized adaptive signage system over the centralized system for fire evacuation. Despite its merits, the decentralized system has the disadvantages of relatively larger computational time cost and a more complex implementation process. Therefore, both systems are designed and provided here for practitioners to choose the design that better fits the needs and applied contexts.

5. Agent validation for the computational framework

In order to validate the decentralized adaptive framework, we describe an agent model that is grounded in spatial decision-making and considers the signage system. The agent simulations were implemented in Unity with C#, and the signs indicated directions as generated by the decentralized system (see Fig. 10). During a wayfinding task, these agents search and interpret signs to help them find the exit during an evacuation. For all of these simulations, agents were initialized in open spaces (i.e., outside of areas with fires) with at least one agent per room. Each agent kept track of the areas visited by itself and recorded them as “memory points” so that it could backtrack to the last decision point in case it reached a dead-end. Each agent also checked whether it was near the building exit. If the agent was near the exit, the agent went to the exit directly. If the agent was not near the exit, the agent could enter either *Exploration* or *Signage following* mode (see Fig. 11). No real participants were involved during the simulation.

In our model, signs were detected by rays cast from within a simulated vision cone that had a field of view of 120 degrees (accounting for head rotation). During the exploration mode, the agent classified every detected sign as indicating either “Enter” (i.e., display arrows) or “Do Not Enter” (i.e., display red “X”). If a sign was not detected, the agent set a temporary destination point and walked towards it. This destination point could not be near a previously visited point, outside of the walkable area of the environment, or in the direction of a sign indicating “Do Not Enter”. If there was not a point that satisfied these criteria, the agent randomly selected whether to turn left, turn right, or return to a previously visited point. Once the agent reached a temporary destination point, the agent repeated *Exploration* mode until it reached the exit. If the exit was on a different level, the agent cleared its memory of all the destination points from the previous floor and started a new *Exploration* mode on the current floor. If a sign was detected and indicated “Enter”, the agent transitioned into *Signage following* mode.

In *Signage following* mode, the agent walked into the direction of a chosen sign. If multiple visible signs indicated “Enter”, the agent moved towards the closest visible sign and followed its indicated direction. After reaching the chosen sign, the agent transitioned back into

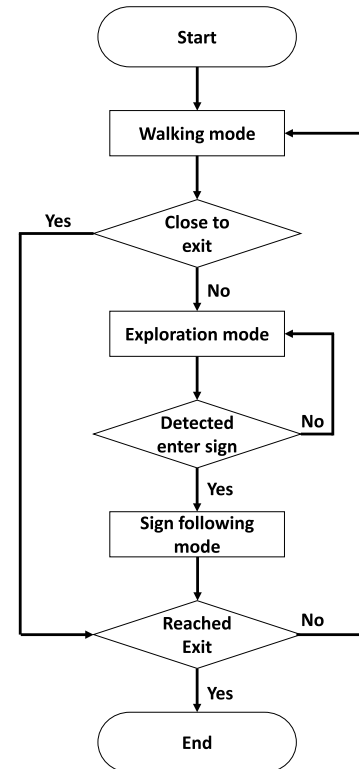


Fig. 11. Illustration of the agent model.

Exploration mode. The agent continued to switch between *Exploration* and *Signage following* modes until the agent reached the exit or died from exposure to the fire. Detailed algorithms can be found in the supplementary material).

5.1. Results

We simulated six fire scenarios that were the same for adaptive and non-adaptive conditions. Multiple agents moved through the environment in each scenario (between 14 and 41) but could not interact or interfere with each other's trajectories. One agent began in each room without a fire. Each fire scenario was conducted twice to obtain between 100 and 200 agents that survived the non-adaptive condition in total. These simulations revealed that 45% of agents in the non-adaptive condition survived and that 94% of agents in the adaptive condition survived. A two-proportion Z-test confirmed that the difference between conditions was significant, $Z = 15.977$, $p < .001$.

We then matched the agents that survived the non-adaptive condition with the agents with the same starting location and fire scenario

from the adaptive condition. This approach is important because surviving agents from the non-adaptive condition were more likely to have started near the exit. Two-tailed, paired-samples t-tests were used to compare these agents from the non-adaptive and adaptive conditions in terms of distance and time. As expected, these agents were comparable in terms of both distance, $t(194) = 0.254$, $se = 2.735$, $p = .800$, and time, $t(194) = -1.361$, $se = 1.345$, $p = .175$.

5.2. Discussion

These agent simulations demonstrate the benefits of adaptive over non-adaptive signs for a decentralized signage system. This is evident in the large difference in survival rate of agents between the adaptive and non-adaptive conditions. The surviving agents in the two conditions evacuated in a similar amount of time and traveled a similar distance. This may be attributable to the agents' near perfect memory for nodes already traveled and accurate interpretation of the directions indicated by signs. In general, these agent simulations allowed us to test the advantages of adaptive signs over non-adaptive signs for the decentralized system more efficiently and over a larger number of replications and scenarios than another VR experiment would provide.

6. General discussion

In this paper, we have presented a decentralized adaptive signage system that may facilitate evacuations by computing the safest and most efficient routes towards an exit given the locations of fire hazards. We also showed the advantages of adaptive signs over non-adaptive signs using both VR and agent-based modeling. In the VR experiment, we demonstrated that adaptive signs allowed human participants to evacuate with less self-reported distress, higher health scores, lower fire damage, shorter path lengths, and less evacuation times compared to participants using non-adaptive signs. Using a graph-based approach, we then developed and compared centralized and decentralized systems for detecting hazards and communicating the safest route to evacuees via directional signs. Specifically, we propose a system in which the optimal evacuation route is computed locally and communicated by individual signs. This redundancy allows the system to easily recover in the event of a sign malfunction (Colson et al., 2011). Using agent simulations, we then demonstrated that adaptive signs can lead to a higher survival rate than non-adaptive signs for a large variety of starting locations and fire scenarios.

6.1. Research overview

For our validation of the decentralized adaptive signage system, we considered the principles of universality, adaptability, autonomy, and robustness. For the present study, we tested the system using a virtual replica of an existing museum (i.e., the Cooper Hewitt) in New York City. However, the system may be universal in that future studies can easily deploy the system in any building with similar design features. The system is also adaptable because we show that its utility generalizes over a wide range of fire scenarios using our agent simulations. The system is also autonomous because the directions indicated by signs can be automatically updated without the intervention of a building manager. In our comparison of centralized and decentralized systems, we also show that the decentralized system is robust to malfunctioning sensors/nodes.

6.2. Adaptive signage

Previously, researchers have developed signage displays (Goel et al., 2004; Hsu et al., 2014; Lee et al., 2017; Kim et al., 2016; Ran et al., 2014; Olander et al., 2017), routing algorithms (Tabirca et al., 2009; Zeng et al., 2010), and wireless sensor networks (Barnes et al., 2007; Chen et al., 2012) for evacuation. Signage designs that incorporate

ground installations (Ran et al., 2014), directional information (Kim et al., 2016), and/or animations (e.g., a red blinking "X") (Olander et al., 2017) have been found to positively affect wayfinding decisions and efficiency during evacuation. Future research can further examine different design choices for the signage in order to devise better visual effects and animations for the adaptive signage. In real buildings, such designs may benefit from directions from an intelligent routing mechanism and connections to wireless sensor networks. Routing mechanisms can adapt to the emergency situation (e.g., fire hazard) using dynamic graphs (Tabirca et al., 2009) without information regarding the exact location of each sensor and without synchronization among sensors (Zeng et al., 2010). Researchers have also simulated (Chen et al., 2012) and prototyped (Barnes et al., 2007) wireless sensor networks for informing and testing routing algorithms. Some researchers have designed similar systems in which a central computing entity determines the safest route and coordinates different displays given a network of integrated wireless sensors (e.g., radio-frequency identification devices) (Hsu et al., 2014; Lee et al., 2017). With the proposed methods in our study, similar functionalities can be achieved with both the centralized and decentralized computational systems. While the centralized system is simpler to implement and takes less time to generate the safe route, the decentralized system requires continuous communication between nodes and signs and takes longer time to converge after both the detection of a fire and node failure. However, the computational time for the decentralized system was still much faster than the theoretical worst case for computing the optimal route (an average 0.838 s compared to the theoretical worst case of 4.1 s for fire scenarios and an average 1.306 s compared to the theoretical worst of 5.3 s for node malfunction scenarios). Such time cost may be outweighed in evacuation scenarios by the benefits of decentralization, especially considering the recovery ability of decentralized systems in the case of the failure or prompt disconnection of certain nodes. In those cases, the decentralized system can adapt the optimal route with the mechanism of constant detection and communication between the nodes. These features and results clearly show the advantage of the decentralized adaptive signage system over the centralized system for guiding evacuees.

6.3. Behavior in VR

In the present paper, we extended previous approaches by decentralizing computations and coordination among the sensors and by validating the system with human participants in VR and agent simulations. Despite the simplification of the interactions between the evacuees and the fire, VR allowed us to measure human behavior in situations that would be otherwise too difficult and dangerous to create. Similarly, previous research has successfully used VR to investigate evacuations from tunnel fires (Kinatader et al., 2015) and office buildings (Shaw et al., 2019). Our desktop virtual reality setup provided realistic interaction between the participants' movements and the visual feedback that they received while allowing them to remain stationary for physiological recording. In general, head-mounted displays (HMD) can make participants feel more immersed by isolating them from the environment outside of the experiment. This advantage of HMDs may be particularly useful for studies in stressful environments that allow participants to be mobile. Nonetheless, desktop VR can have several benefits compared to HMDs. First, evacuation studies require fine control of movements through the virtual environment, which is easier if the controls are visible. Second, participants are also less familiar with HMDs and tend not to move their heads as often as expected (Pausch et al., 1996). This may be attributable to the lower resolution of most HMDs compared to desktop VR. Third, using HMDs often leads to simulator sickness and discomfort (Chattha and Shah, 2018). In contrast, our participants did not report any discomfort during the experiment. Future research should investigate the specific

differences in evacuation performance and stress responses between desktop VR and HMDs.

While we captured several behavioral differences between the adaptive and non-adaptive conditions in our VR study, our physiological measures were not sufficiently sensitive to reflect these potential differences. In the future, more immersive systems may be employed in order to provide multisensory cues such as heat and smell (Shaw et al., 2019) that typically accompany fire hazards. In order to test for the stress caused by VR itself, researchers could also add a control group in which participants would watch an evacuation video without controlling their own movement. In addition to VR experiments, agent simulations allowed us to efficiently and artificially generate responses to a wider range of evacuation scenarios (Schadschneider et al., 2009). Future agent simulations could incorporate a more realistic health score for estimating casualties caused by their movement near the fire.

6.4. Limitations

Our work represents a first step towards incorporating a decentralized and adaptive signage system into a real building, although for now, our findings and methods are limited to virtual reality. One limitation of virtual reality and any other lab-based experiment is that users' behavior may differ from that in real environments. This may be attributable to the manner in which navigation was controlled with a mouse and keyboard or lack of physical feedback from the fire. In addition, we necessarily defined a simplified fire damage mechanism. However, the dangerous nature of real fire scenarios suggests that it is practically impossible to replicate these hazardous events for the purpose of an experiment in an ethical manner. The ethical concerns and the potential risks to the health of participants prevent researchers from investigating such behaviors in the real world. In addition, it was not possible to reproduce the scale of the environment in our study in the real world without an enormous monetary cost. Future research could consider to apply the signage system with at a small scale in order to further validate its application in the real world.

One aspect of fire accidents that was not fully addressed in this study is the effect of smoke. While we have simulated the thermal damage caused by the fire, the harmful effect of smoke was simplified by simulating the general time spent in the building. Previous research has demonstrated the harmful effect of inhalation of toxic gases produced during combustion (Stefanidou et al., 2008). Additionally, the physiological effects of smoke can also potentially impair the judgment and orientation of the evacuee, leading to decreased ability to move or remain conscious (Hartzell, 2001). The introduction of smoke simulation could help researchers develop a more advanced approach to study fire evacuation (Luo et al., 2013). Since the current study focuses on the effect of signage, we specifically used time and proximity to fire as a simple representation of the harmful effect of smoke and the thermal effect of fire, respectively. Future research should aim to integrate smoke simulation models (Liu et al., 2020; Qin et al., 2009) that can potentially replicate the spatio-temporal aspects of the smoke within the indoor environment. The smoke's movement can also affect route choices during the evacuation, since the density and velocity of the toxic smoke can also depend on the smoke's vertical position (McGrattan et al., 1998). Smoke towards the ceiling could still allow evacuees to escape if they are located closer to the floor or at a lower floor. The real-world implementation of the sensors should consider its relative position within the room and the coverage of the area. Advanced techniques such as smoke simulation (Chu and Sun, 2008) and the wireless (Shu-Guang, 2011) technologies can be applied in future research that seeks the optimal positioning of sensors.

While the agents have demonstrated the effectiveness of the signage system, their behavior is limited to reading the signs and following the indicated directions. Future research should consider including more complex behaviors such as evacuation simulation with the influence of smoke (Zheng et al., 2017; Zhang et al., 2021a), panic (Helbing et al., 2000), and the decision uncertainty from the signage information (Dubey et al., 2019).

7. Conclusion

In this study, we demonstrate the efficiency and effectiveness of visual guidances that indicate different directions depending on the location of a hazard during a fire evacuation. This research paves the way for future work on multi-user frameworks that can account for crowd dynamics in public spaces during large-scale disasters (Helbing et al., 2007; Aguilar et al., 2019). Crowds may increase the amount of time required for route computations as each individual agent attempts to optimize their own escape. If these agents are directed along the same route, congestion can further complicate the evacuation. Here, it may be useful to connect mobile devices to the building system in order to personalize evacuation instructions (Yan et al., 2019). Decentralization may be an especially robust approach in such a scenario because of the larger number and diversity of connected nodes.

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.

Acknowledgments

The experiment was approved by the ethics commission of ETH Zürich (proposal number 2015-N-37). Participants were recruited via the University Registration Center for Study Participants (<http://uast.uzh.ch>).

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.ssci.2021.105451>.

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