Automation in Construction 179 (2025) 106441

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Comparative analysis of fire evacuation decision-making in immersive vs. non-immersive virtual reality environments

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ARTICLE INFO

Keywords:
Exit choice
Evacuation
Fire
Virtual reality

ABSTRACT

Understanding emergency behavior is crucial for designing safer, resilient infrastructure. Immersive Virtual Reality (VR) realistically simulates emergencies but is resource-intensive, so systematic comparisons with non-immersive VR remain scarce. To address this gap, a multifactorial VR fire-evacuation experiment was conducted in which participants navigated a room with three exits under varied conditions (e.g., social influence, smoke presence, exit distance, exit familiarity). Results indicated no significant difference in overall decision-making between immersive and non-immersive VR. Nevertheless, immersion modulated key factors: in immersive VR, participants preferred nearer exits, were more susceptible to social influence, and experienced stronger effects of smoke and exit familiarity. Smoke also reduced the influence of exit distance. Personal factors (e.g., prior VR experience, age, gender) shaped perceptions and emotions; heightened negative emotions and perceived risk were associated with less rational (i.e., suboptimal) choices, particularly in immersive VR. These insights inform VR safety training, guiding simulations that more faithfully replicate real emergencies.

1. Introduction

Understanding and simulating human behavior during disasters is crucial for designing safer and more resilient buildings and transportation infrastructures, such as terminals and tunnels [1–3]. Accurate evacuation simulations are essential, especially when designing for building fires [4]. Currently, many countries require engineers to design solutions that ensure adequate safety levels for occupants in various fire and evacuation scenarios [5,6]. Accurate considerations and assumptions about human behavior in fires are essential for developing and evaluating these scenarios. This design process requires theoretical insights into if and how people are likely to respond, as well as data quantifying their response, particularly regarding pre-travel delay times or actions, route choice, and movement patterns [4,7,8].

Data on human responses to building fires have been collected through various methods, including field studies, evacuation drills, false alarms, and real accidents [9,10]. Both post-fire studies and evacuation drills reveal the actual decisions made by evacuees in real or simulated emergencies, providing valuable data on response time, movement patterns, and potential congestion points [7,11,12]. In both cases, researchers have limited control over variables, such as the type of evacuees, building layout, or crowding levels [9,13].

Data on evacuee behavior can now be collected in laboratory settings by presenting participants with different scenarios [9,10]. While this approach provides greater control over study variables, it lacks real-world authenticity, as participants are aware that they are part of a study. The use of immersive virtual reality (VR) and augmented reality (AR) has grown in fire evacuation research. These new technologies enable researchers to observe real-time decision-making and gather feedback through post-experiment surveys. Specifically, VR environments allow for the safe simulation of conditions, such as smoke or the presence of people with impairments [14–16]. Preliminary research suggests that immersive VR results are comparable to real-world data, although further validation is necessary [17–19]. However, the choice of VR format can significantly influence experimental outcomes and the analysis of human behavior during emergency evacuations. For instance, the level of immersion can affect how participants respond to virtual emergencies [20]. Therefore, it is necessary to examine whether non-immersive and immersive virtual emergencies can generate similar behavioral responses. Non-immersive VR refers to virtual experiences in

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https://doi.org/10.1016/j.autcon.2025.106441
Received 3 February 2025; Received in revised form 25 July 2025; Accepted 28 July 2025
Available online 6 August 2025

which users interact with the virtual environment through a standard screen, without being fully immersed. In contrast, immersive VR fully surrounds users with a three-dimensional virtual environment, often using headsets and other sensory devices, such as Cave Automatic Virtual Environment (CAVE) systems [21]. To our knowledge, no study has yet compared evacuation experimental data generated from both VR formats (immersive and non-immersive).

This paper aims to explore how individuals make decisions in immersive and non-immersive VR environments during evacuation from a fire emergency scenario. Building on the original experiment conducted by [13], which examined evacuation exit choices in immersive VR, this research introduces a second experiment with a non-immersive VR setting and compares the results with those obtained from the immersive VR experiment presented in [13]. Specifically, the study analyzes the evacuation behavior of 146 participants across both VR settings as they navigate a room with three exits. It also investigates how four factors (social influence (the behavior of other evacuees), the presence of smoke, exit distance, and familiarity with the exit) influence participants' exit choices. Furthermore, using a questionnaire, this study examines the impact of prior experience in virtual environments. Finally, participants' user experience in both VR conditions was analyzed, focusing on their perceived realism, usability, emotions, and self-efficacy. Consequently, this research offers valuable insights into how different VR formats can facilitate the study of human behavior in disaster scenarios, contributing to the growing body of knowledge on how and why VR can be leveraged to better simulate and understand decision-making processes in high-stress situations.

2. Literature review

Integrating VR technologies into emergency evacuation research has significantly advanced our understanding of human behavior during crises. Numerous studies have employed various VR formats to investigate this area, raising questions regarding the effectiveness of these different VR formats. This section reviews previous research that focuses on VR experiments related to emergency human behavior and compares the effectiveness of the VR platforms in such studies.

2.1. VR experiments for emergency human behavior study

The integration of VR technologies in the rapidly evolving field of emergency evacuation research marks a significant stride toward understanding and analyzing human behavior during crises. This methodological advancement stems from VR's ability to replicate real-world situations with high fidelity while ensuring participant safety and maintaining controlled experimental conditions [22,23]. Traditional real-world experiments, although invaluable, often pose significant risks and are constrained by numerous uncontrollable environmental variables, such as lighting and noise, as well as safety concerns when participants are exposed to actual hazards, such as smoke [24]. VR addresses these issues by creating safe, reproducible scenarios and serves as a cost-effective alternative to the otherwise expensive setup of physical evacuation drills.

Recent studies leveraging VR technology in evacuation research have provided valuable insights into the dynamics of human behavior during emergencies [19,25–27]. Researchers have effectively simulated complex scenarios such as building fires and natural disasters [28,29], enabling the study of evacuee behavior in response to various stimuli without the logistical and ethical constraints of real-world settings [30]. These VR simulations have allowed researchers to explore how various factors, such as building layout [31], exit locations and sizes [13], visual accessibility [32], and signage [33], and individual behaviors, including following, avoiding, affiliative, cooperative, and competitive actions, affect evacuation decisions [34,35]. These investigations also examine the impact of personal characteristics, knowledge, skills, and experience on evacuation behavior, thereby significantly enhancing our understanding of the factors influencing evacuation actions. For instance, Lin et al. [36] investigated the effects of repeated exposure and mental stress on human wayfinding performance within VR-simulated hazardous fire emergency environments, discovering that such environments could adversely affect wayfinding capabilities. In a subsequent study, Lin et al. [37] examined the influence of crowd dynamics on human evacuation behavior during a simulated building fire emergency by creating a virtual metro station populated with non-player characters (NPCs). Their findings confirmed the effectiveness of VR experiments in capturing the complex social factors influencing human evacuation behavior. Furthermore, Song and Lovreglio [38] employed VR to analyze how individual-specific preferences affect exit choice behavior, using a Hierarchical Bayes estimation approach to identify distinct behavioral groups ("followers" and "non-followers") and demonstrating the significant effects of age, nationality, and education on these behaviors.

These studies collectively underscore the efficacy of VR-based experiments in probing the nuances of individual evacuation and wayfinding behaviors in indoor environments. The immersive quality of VR ensures that participants' responses in virtual settings closely resemble those in real-life scenarios, thus enhancing the reliability of behavioral data collection in ways that traditional methods cannot achieve [13]. Additionally, VR has been shown to improve cognitive functions, such as memory recall and focus, during tasks, further demonstrating its value in emergency behavior research [39]. Krokos et al. [40] and Chittaro and Buttussi [41] revealed that VR's immersive qualities can lead to better recall and knowledge retention performance, likely due to the heightened psychological arousal and engagement that simulate real-life experiences. These findings highlight VR's potential not only for research but also for training purposes, where the realistic replication of stressful conditions can prepare individuals for actual emergencies.

Despite its advantages, the application of VR in evacuation research faces several challenges. One notable issue is the underrepresentation of diverse populations in VR studies. Participant pools are often homogeneous, typically skewed toward younger individuals or students, which may not accurately reflect the broader population's behavior in emergency situations [38]. Additionally, the high costs associated with the most immersive VR formats can limit the scope of studies, restricting the range of data collection essential for robust behavioral predictions and simulations. To overcome these challenges, researchers have begun employing various VR formats and devices, ranging from immersive head-mounted displays (HMDs) to more accessible and less immersive options, such as desktop VR. For example, Zhao et al. [42] utilized desktop VR to examine interactions among multiple participants, while Gao et al. [43] designed a series of desktop-based virtual evacuation scenarios to study exit choice behaviors and decision-making attitudes under uncertain risk scenarios and varying smoke conditions. Expanding on this approach, Bode et al. [44] conducted a large-scale, computer-simulated study involving over 450 participants, providing valuable insights into dynamic exit route choices during crowd evacuations. Further pushing the boundaries of virtual experimentation, Normoyle et al. [45] ingeniously utilized the online platform Second Life, integrating in-game residents with real-world participants to create a hybrid virtual-physical experimental environment. More recently, Shi et al. [46] employed the popular game Minecraft as a non-immersive virtual environment to examine pedestrian behavior and evacuation dynamics under both normal and emergency fire conditions, enabling simultaneous multiplayer interactions. These adaptations not only broaden participation but also facilitate a more nuanced study of interactions among multiple participants in virtual evacuation scenarios, offering valuable insights into human behavior under diverse conditions while significantly reducing research costs. However, despite the increasing use of VR technologies in evacuation research, a critical gap remains: a dearth of comparative analyses assessing the relative effectiveness of different VR formats. This gap is particularly concerning because the choice of VR format can significantly influence experimental outcomes and subsequent analyses of human behavior during emergency evacuations.

To address this critical research gap, this study aims to systematically compare the impact of non-immersive and immersive VR formats on human exit choice behaviors in simulated emergency evacuations. By elucidating the relative strengths and limitations of these VR formats, this research seeks to enhance the methodological rigor of evacuation studies and contribute to the development of more accurate and comprehensive emergency preparedness strategies.

2.2. *Behavioral studies using different VR technologies*

Understanding the impact of different VR technologies on user behavior is crucial for aligning VR experiments with specific research objectives. This is particularly relevant in industries such as construction, where reluctance to adopt VR technology stems from a lack of empirical evidence demonstrating its clear benefits [47]. By identifying effective VR dimensions for specific behaviors, researchers can design more accurate and relevant VR experiments, thereby enhancing performance and facilitating the broader implementation of VR technologies [47,48].

Various studies have demonstrated the impact of different VR technologies on user behavior across domains such as wayfinding, navigation performance, design reviews, and evacuation behaviors [32,49–51]. Han et al. [52] discovered that using HMDs in construction design reviews improved the detection of design errors, although it slightly reduced memory recall compared to desktop VR. Similarly, Arias et al. [19] investigated evacuation behaviors in high-rise buildings using CAVE and HMD VR formats compared with physical experiments. Their findings revealed that HMD VR experiments closely matched physical data on pre-evacuation times and exit choices but differed from the CAVE setup, highlighting discrepancies between the two VR technologies. However, not all studies have reported significant differences between VR technologies. Zhao et al. [53] found no substantial differences in learning outcomes between desktop and immersive virtual field trips, suggesting both VR formats are equally effective. This finding is supported by Ruddle and Péruch [54], who observed no significant differences in wayfinding performance and route knowledge between desktop VR and HMD VR.

Emotional and performance responses to different VR formats also vary. Kim et al. [55] assessed emotional arousal and task performance under stress conditions across multiple VR formats. Their findings indicated that the Duke immersive Virtual Environment (DiVE) system elicited the highest emotional arousal, desktop systems had minimal emotional impact, and HMDs provided the greatest sense of presence but induced the most simulator sickness. Despite the excitement typically associated with new immersive VR formats, challenges such as simulator sickness continue to hinder their widespread adoption [56]. Moreover, several virtual environments exceed the spatial capabilities of immersive VR formats, such as HTC VIVE, which is restricted to a 10 × 10-m area—significantly smaller than many educational or historical virtual environments. This spatial limitation has spurred innovations to navigate larger digital spaces without physical constraints [57]. Furthermore, the continuous motion in immersive VR, which mimics real walking without actual movement, often induces intense simulator sickness due to a mismatch between what users see and feel [58–60]. Although immersive VR formats offer a heightened sense of immersion than low-immersion desktop computers, this deep immersion does not necessarily enhance certain learning outcomes, such as remote collaboration and memory recall. Makransky et al. [61] discovered that participants navigating a virtual science lab using an immersive VR format felt more present but learned less than those using a low-immersion desktop system, likely due to the additional cognitive load imposed by the immersive VR format [41].

Methodologically, existing studies typically employ a diverse array of tools from the onset of experimental design to the conclusion of data analysis. These tools range from questionnaires and performance tasks to environmental manipulations designed to assess the impact of VR on behavior [23,62]. Controlled experimental designs facilitate direct comparisons of user experience and learning outcomes under standardized conditions, as shown in the studies by Zhao et al. [63] and Arias et al. [19]. Customizing virtual environments to fit specific study needs, combined with the use of inferential statistics such as ANOVA, *t*-tests, and regression analyses, enables researchers to accurately assess the impact of VR formats on user behavior [32]. Additionally, qualitative insights gathered through post-experiment interviews or open-ended questions further enrich these findings, providing a more comprehensive understanding of user experiences [13,33]. Despite these methodological strengths, a significant gap remains in the research landscape. Many current studies employ simplified experimental setups that inadequately capture the complexities and unpredictability inherent in real-world environments. This limitation is particularly evident in research simulating emergency situations [19,63], where the stakes are high and the consequences of design choices can be critical. Furthermore, the statistical methods used to compare immersive and non-immersive VR studies are often constrained, potentially overlooking subtle yet significant differences in user behavior and performance. Although VR technology demonstrates considerable potential for enhancing user experience and performance, a more nuanced understanding of its impact across diverse settings and scenarios is essential for its effective application and implementation.

3. Method and materials

This section describes the two conditions of VR experiments conducted in this study, the participants who took part in the experiments, the experimental procedure, and the statistical methods used to analyze the collected data on human behavior and experience.

3.1. *Virtual environment setup*

This section outlines the design and implementation of the VR experiments, focusing on the virtual environment setup, exit configurations, and the key factors influencing participants' decisions. Fig. 1 depicts the layout of the meeting room, which contains minimal furniture and features three exits labeled A, B, and C. The positions of Exits B and C vary depending on the scenario, thereby altering the distances participants must travel to reach these exits during evacuation. These variations are summarized in Table 1. The layout shows the participants' starting location at the beginning of the experiment, with the red square marking the point where the first event (the start of a fire evacuation emergency) was triggered upon participants' arrival. The scenario ended once participants exited through one of the three available exits without experiencing what was behind Exits B and C.

In each scenario, exit conditions varied based on physical, social, and individual factors. Depending on the scenario, the exits differed in their physical distance from the decision-maker and the presence of smoke (entering from the top of some exits). A relatively dense smoke condition, generated using a Unity-based particle system, was incorporated to replicate fire emergency conditions. This choice, guided by previous studies, allows the simulation to capture critical visibility constraints and the associated behavioral impacts on participants' emergency decision-making [35,64]. Additionally, the exits varied in terms of the number of evacuees already using each exit (a social factor) and in participants' familiarity with the exits (an individual factor). Specifically, three conditions at the exit—five people (strong social cue), one person (weak social cue), and no one (no social cue)—were tested, spanning a pronounced group signal to the absence of social guidance [65]. Familiarity was defined by a participant's prior use of an exit. Since Exit A was located along the path participants followed to reach the starting point in the experiment (indicated by the red square in Fig. 1), it was presumed to be more familiar than the other exits.

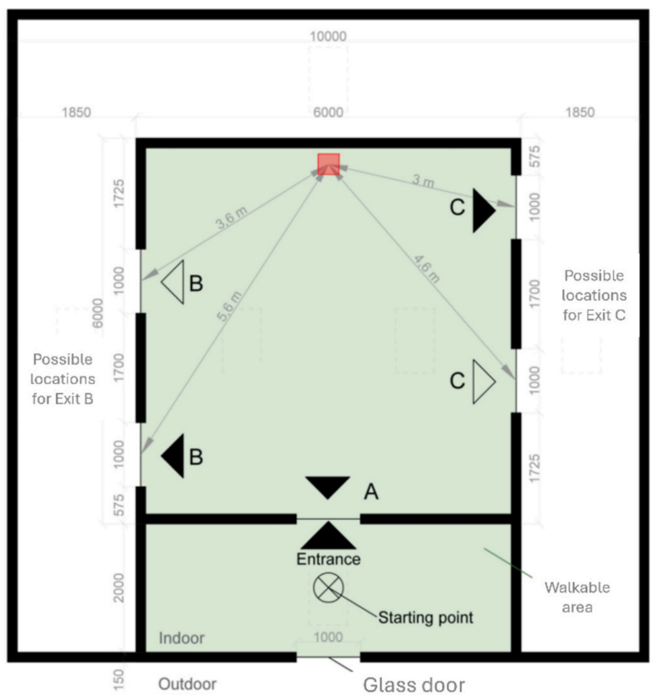


Fig. 1. Layout of the virtual environment used in the experiment. The locations of Exits B and C vary depending on the scenario, as indicated in Table 1 (the distance measurements are in mm).

Table 1
Scenario settings.

Scenario	Exit	Number of People Using an Exit (NP)	Distance from an Exit (DIST)	Presence of Smoke (SMOKE)	Familiarity with an Exit (FAM)
	A	0	6	No	Yes
1	B	10	3.6	Yes	No
	C	5	4.6	Yes	No
	A	5	6	Yes	Yes
2	B	0	5.6	Yes	No
	C	10	3	No	No
	A	1	6	Yes	Yes
3	B	1	5.6	No	No
	C	10	3	No	No
	A	10	6	No	Yes
4	B	0	3.6	No	No
	C	1	4.6	Yes	No
	A	10	6	No	Yes
5	B	1	3.6	Yes	No
	C	0	4.6	No	No
	A	5	6	Yes	Yes
6	B	10	5.6	No	No
	C	0	3	Yes	No
	A	1	6	Yes	Yes
7	B	5	5.6	No	No
	C	1	3	No	No
	A	0	6	No	Yes
8	B	5	3.6	Yes	No
	C	5	4.6	Yes	No

The final scenarios, as outlined in Table 1, were identified by Lovreglio et al. [13] using the Efficient Design method in Ngene 1.4 software [66]. Efficient Design is a fractional factorial design used to select an optimal subset of scenarios from all possible options, aiming to maximize the information extracted within a given sample size. Unlike traditional methods such as orthogonal design, efficient designs enable analysts to obtain reliable estimates of model coefficients with smaller sample sizes.

In the subsequent sections, the variables under investigation are abbreviated as follows:

- NP: Number of people using an exit;
- DIST: Distance of the participant from an exit;
- SMOKE: Presence of smoke;
- FAM: Participant's familiarity with an exit.

The scenario specifications outlined in Table 1 were used to create eight virtual experiences with the Unity game engine. The building layout was modeled directly in Unity, with the furniture and doors sourced from the Unity Asset Store. The other evacuees in the room were represented by NPCs, created using Adobe Fuse and animated through Mixamo. The NPC development pipeline followed the approach described in previous studies [67,68]. Smoke entering the room during the fire emergency was simulated using particle systems in Unity. Fig. 2 presents screenshots of the virtual experience. Fig. 3 shows the physical space used for the immersive VR experiment.

The experiment was conducted using both immersive and non-immersive VR formats. The immersive VR experience was designed for the HTC VIVE Pro headset, utilizing Steam VR packages available in the Unity Asset Store. This setup provided a 110-degree field of view. The application enabled participants to view the digital scenario through the headset and navigate the environment by physically walking within a 7 m × 8 m space. Participant movement within this space was tracked using four HTC base stations positioned at the corners of the rectangular tracking area (7 m × 8 m). This tracking area was sufficiently large to allow participants to move freely within the green-highlighted region depicted in Fig. 1.

The non-immersive VR experience was designed for a standard 15-in. laptop and built using the standard first-person controller setup in Unity. This setup provided an 86-degree diagonal field of view on a 16:9 standard laptop monitor. Participants' viewpoint was controlled with the mouse, while their movement within the virtual environment was managed using either the keyboard arrow keys (up, down, left, and right) or the W, A, S, and D keys.

3.2. *Experimental procedure*

The immersive and non-immersive VR experiments were conducted at Massey University's Albany Campus in New Zealand. The immersive experiment occurred in June 2019 [68], while the non-immersive experiment was conducted in June 2021. Both experiments followed the same structured procedure. First, all participants were required to read a participant information sheet and sign a consent form to ensure ethical compliance. By signing the form, participants confirmed they had no medical conditions that would prevent their participation. Participants then completed a pre-experiment survey to collect demographic information and assess their familiarity with VR and fire emergency procedures. After completing the survey, participants were asked to start the immersive or non-immersive experience.

Participants began by navigating a preliminary scenario featuring only the building layout used in the study. During this familiarization phase, they could move through the green areas indicated in Fig. 1 but were instructed not to use Exits B and C. This phase allowed participants to become accustomed to the environment and the navigation system. All participants entered the virtual space through Entrance (Exit A) and spent 30–40 s exploring the room before returning to their starting position via Exit A, providing an opportunity to become familiar with this exit.

Each participant was then randomly assigned to experience four of the eight fire scenarios. To prevent fatigue, participants did not complete all eight scenarios, and the total session was limited to approximately 30 min. In each scenario, participants entered the room through Exit A and proceeded to a red target (Fig. 1), simulating attendance at a virtual meeting. Unbeknownst to them, the study aimed to observe their exit choices during an unexpected evacuation. To maintain this

(a)

(b)

Fig. 2. Screenshots of the virtual experience: (a) before and (b) during the evacuation.

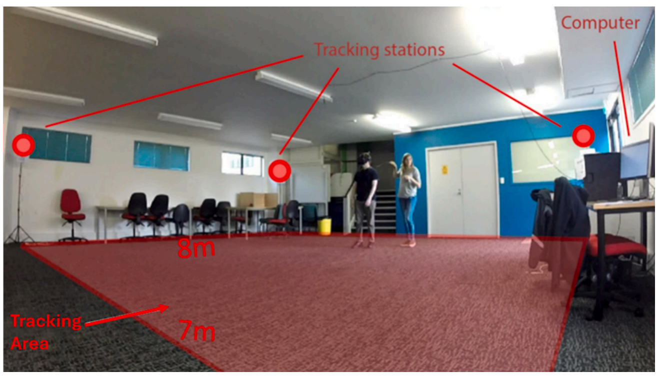


Fig. 3. Physical space used for the immersive VR experiment.

deception, participants were informed that the VR experience was designed to demonstrate the use of virtual environments for meetings.

Once participants reached the red target, the fire alarm sounded, and NPCs in the room stopped their activities, looked around briefly, and then moved toward pre-determined exits, as specified in Table 1. NPCs were assigned random reaction times, ranging from 3 to 9 s, to prevent congestion at the exits. As the alarm sounded, smoke began entering the room through designated doors, depending on the scenario (Table 1). The experiment concluded when participants reached one of the three exits, with their exit choices and navigation paths recorded in a local database (i.e., a CSV file).

After completing the VR scenarios, participants filled out a final questionnaire to provide feedback on the experiment. The survey assessed several factors, including realism, ease of use, emotional responses, urgency perception, and the validity of participants' behavior. Responses were measured on a seven-point Likert scale, ranging from −3 (strongly disagree) to +3 (strongly agree). Participants were asked to rate their level of agreement or disagreement with the following statements:

- The virtual world was adequate/realistic (Realism 1);
- The virtual fire scenario was adequate/realistic (Realism 2);
- The interaction with other virtual people was adequate/realistic (Realism 3);
- I found running this VR scenario easy (Usability);
- This experience makes me feel scared/fearful (Emotion 1);
- Overall, this experience makes me feel tense/nervous (Emotion 2);
- Overall, this experience makes me feel anxious (Emotion 3);
- I felt the urgency to act/do something during the fire emergency (Urgency);
- I would act the same way in real life during a fire emergency (Validity).

3.3. Participants

A total of 146 participants were recruited for this study, comprising 86 individuals for the immersive VR experiment and 60 for the non-immersive VR experiment. Participants were primarily recruited through email campaigns, social media platforms, and referrals from other participants. Additional recruitment efforts involved distributing flyers and placing advertisements across the Massey University campus, targeting multiple student associations. Following Lovreglio et al. [13], the immersive group size was fixed at 86, yielding 344 individual observations (each participant completed four scenarios). Prior to conducting the non-immersive experiment, a power analysis (assuming a medium effect size of 0.25, 80 % power, and $\alpha = 0.05$) indicated that approximately 256 total observations would be needed to adequately compare the immersive and non-immersive conditions, and at least 192 observations would be required to detect significant within-group variance for the non-immersive setting. Since each of the 60 non-immersive participants also completed four scenarios, their total of 240 observations exceeded this threshold. This sample size provides robust statistical power [69], and the combination of multiple observations per participant with an efficient, D-error-minimized experimental design further supports the reliability of the findings [13]. It should be noted that the two groups of participants were distinct individuals, randomly recruited from the same university participant pool during the same time period, thereby minimizing cohort differences and exposure to external history effects.

Fig. 4 presents a comprehensive breakdown of the demographic characteristics of both experimental groups. Gender distribution was relatively balanced across both groups. The immersive VR group consisted of 55.8 % male and 44.2 % female participants, while the non-immersive VR group had a near-even split, with 50.8 % male and 49.2 % female participants. Regarding the age, the immersive VR group was predominantly younger, with 66.7 % of participants aged 18–25 years and 15 % aged 26–29 years. Only 17.9 % of participants were aged 30 or above, including 11 % aged 30–35, 11 % aged 36–45, and 6 % aged 46 and older. In contrast, the non-immersive VR group showed a more diverse age distribution, with 27 % of participants aged 18–29, 22 % aged 30–35, and a substantial representation in older categories: 10 % aged 36–45 and 11 % aged 46 and above, extending up to 70 years. Despite these differences, a Chi-square test ($\chi^2 = 8.84$, $p = 0.116$) showed no statistically significant difference in age distribution between the two VR conditions. Ethnic composition varied between the groups, although both showed a predominance of Asian participants. In the immersive VR group, 52.3 % identified as Asian, followed by 31.4 % as European. The remaining participants were distributed among Middle Eastern (8.1 %), African (5.8 %), and other ethnicities (2.3 %). The non-immersive VR group had an even higher proportion of Asian participants at 60 %, with 21.7 % identifying as European and 18.3 % as other ethnicities. Additionally, prior VR experience was assessed. In the immersive VR group, 74 % of participants had no prior VR experience, while 26 % had used VR before. The non-immersive VR group showed a similar pattern, with 78.3 % reporting no prior VR experience and 21.7

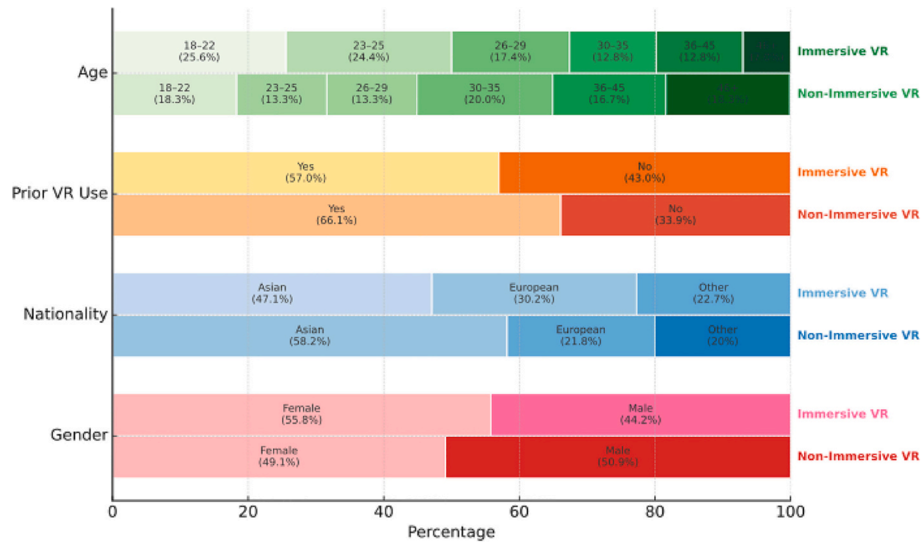


Fig. 4. Distribution of participant characteristics in the immersive and non-immersive VR experiments.

% having used VR previously.

3.4. Statistical analysis

The data collected during the experiments were analyzed using a multifaceted approach to examine participants' decision-making behaviors in VR environments. As depicted in Fig. 5, this comprehensive analysis focused on the influence of various perceived factors and participants' responses to a questionnaire assessing different aspects of the VR experience. Furthermore, the study investigated the interaction effects between these perceived factors and the VR experience on decision-making.

The analysis began with a Chi-Square test to determine whether significant differences exist in exit choices between immersive VR and non-immersive VR across eight scenarios (Fig. 5a). This test, outlined in Eq. 1, compares the observed frequencies of exit decisions in each VR setting with the expected frequencies, calculated under the assumption that there are no differences in exit choice preferences between the two VR settings. In this equation, O_{ij} represents the observed frequency of participants choosing or not choosing an exit in each VR setting for each scenario. The index i denotes the VR settings (immersive and non-immersive), while j indicates the exit decisions (chose exit, did not choose exit). E_{ij} represents the expected frequency, assuming no relationship between the VR setting and the exit decision. Building upon this initial analysis, the study employed random utility models, specifically different forms of the multinomial logit model, to estimate the decision-making processes. These models are founded on the principle that decision-makers select options that maximize their perceived utility, which comprises both a deterministic component and a stochastic error component, as outlined in Eqs. 2 and 3. The utility for each decision-maker and alternative is defined by the deterministic component $V_{q,i}$ and the stochastic error component $\varepsilon_{q,i}$, as shown in Eq. 2. The deterministic component follows a linear specification, where $X_{q,i,j}$ in Eq. 3 represents the observed values of factor j perceived by decision-maker q for alternative i, and $\beta_{i,j}$ denotes the parameters quantifying the decision-maker's preferences regarding factor j. This analysis of the impact of each factor, while controlling for other variables, provides insight into their relative significance and the direction of their effects on participants' exit choices.

$$\chi 2 = \sum \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}} \tag{1}$$

$$U_{q,i} = V_{q,i} + \varepsilon_{q,i} \tag{2}$$

$$V_{q,i} = \sum_j \beta_{i,j} X_{q,i,j} \tag{3}$$

Although logistic regression has been widely used to model human evacuation behavior, it has limitations in distinguishing between correlation and causation due to its observational nature and potential oversight of latent variables. To overcome these limitations, this study incorporates Bayesian networks (BNs) as a more robust alternative. BNs provide a powerful and flexible tool for graphically modeling causal relationships between variables, elucidating the collective impact of various factors on human decisions, and uncovering interactions that logistic regression may miss [70]. The effectiveness of BNs has contributed to their increasing prominence in risk analysis and emergency behavior assessment, with a growing number of publications highlighting their advantages in learning and inference algorithms. BNs excel over traditional methods in their ability to model multi-state variables, requiring fewer parameters and compact probability tables—a particular advantage when empirical data are limited. Their versatility in combining expert knowledge with data-driven methods is crucial in scenarios with scarce failure data, enabling researchers to leverage expert insights while potentially reducing subjective bias

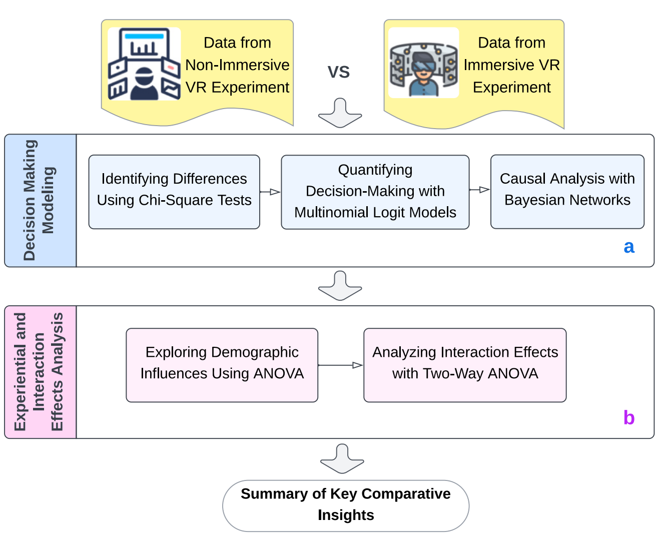


Fig. 5. Statistical analysis framework for VR experiment data.

compared to purely expert-based approaches [71].

A hierarchical BN was constructed to explore the causal relationship between environmental factors and human emergency behavior. Based on graph theory principles, this network models the interactions between human exit choice decisions and environmental factors, including the number of people at the exit, the distance to the exit, the presence of smoke, and individuals' familiarity with the exit. The BN modeling process comprises structure learning and parameter learning. For structure learning, the Hill-Climbing algorithm, a type of greedy algorithm, was employed (Fig. 6). This algorithm iteratively searches the solution space by making local modifications to the current model. These modifications are evaluated using predefined scoring functions, such as the Bayesian Information Criterion and Akaike Information Criterion. This algorithm selects modifications that statistically enhance the model while adhering to specified constraints such as mandatory edges (whitelist) and forbidden edges (blacklist). Upon establishing the structure, Bayesian inference is applied to compute the probabilities of query nodes via Bayesian conditional probability calculations within the BN framework. This approach updates the conditional probability tables (CPTs) by integrating prior distributions with observed data, yielding posterior distributions that encapsulate both prior beliefs and new empirical evidence. This method is particularly beneficial for managing complex models under conditions of uncertainty and data scarcity, enabling a nuanced comparison of causal relationships derived from both immersive and non-immersive VR experiments. Consequently, it offers deeper insights into how environmental factors influence human behavior in emergency situations across different VR settings.

In addition to assessing exit choices in VR settings, this study also considers how personal perceptions, such as self-efficacy, vulnerability, negative emotions, realism, scenario perception, and ecological awareness, influence behavior in immersive and non-immersive VR environments, as depicted in Fig. 5b. An analysis of variance (ANOVA) was initially conducted to examine how personal characteristics—gender, age, and cultural background—influence user experiences across different VR settings. This analysis helps determine whether demographic groups react differently to VR environments and whether specific VR settings can evoke the intended experiential responses necessary for emergency studies. Additionally, it identifies which perceptions most strongly impact various groups, potentially informing the design and development of more effective virtual experiments. Subsequently, a two-way ANOVA was performed to explore the interaction effects between human perceptions (self-efficacy, vulnerability, negative emotions, realism, scenario perception, and ecological factors) and environmental factors (number of persons at an exit, distance to an exit, presence of smoke, and exit familiarity) on emergency decision-making behaviors. Literature suggests that the sense of presence in VR significantly influences emotional responses and consequent behaviors. For example, heightened anxiety can alter decision-making processes, with highly anxious individuals showing more extensive visual scanning and physiological arousal when facing perceived threats in VR [72]. Additionally, the presence and actions of virtual NPCs in emergency scenarios can affect evacuation decisions [17]. By exploring these complex interactions, the analysis aims to uncover subtleties that single-variable analyses may overlook, thereby enhancing our understanding of how environmental and perceptual factors collectively influence decision-making in VR. This comprehensive analysis of interactions across different VR settings will help inform the design of more targeted and effective emergency response experiments tailored to various scenarios, ultimately yielding more accurate and actionable outcomes.

4. Results and analysis

The following section presents findings from analyses of participants' exit-choice behavior and user experiences in immersive versus non-immersive VR environments. Specifically, it compares exit-choice frequencies, models the determinants of exit decisions, examines underlying causal factors, contrasts user experiences between the two settings, and explores how user perceptions correlate with exit choices.

Algorithm 1: Hill Climbing Algorithm for Bayesian Networks Learning

Input: D: Dataset over variables $\{\text{NP}, \text{Dist}, \text{Smoke}, \text{Fam}, \text{Choice}\}$, G_0: Initial DAG, whitelist, blacklist

$G \leftarrow G_0$;
$f_G \leftarrow f(G; D)$;
improvement $\leftarrow$ true;
while *improvement* **do**
  improvement $\leftarrow$ false;
  foreach *pair* (X_i, X_j) **do**
    if *adding* $X_j \rightarrow X_i$ *is valid* **then**
      compute diff$_{add} = f(G + \{X_j \rightarrow X_i\}; D) - f_G$;
      update best improvement;
    end
    if *deleting* $X_j \rightarrow X_i$ *is valid* **then**
      compute diff$_{del} = f(G - \{X_j \rightarrow X_i\}; D) - f_G$;
      update best improvement;
    end
    if *reversing* $X_j \rightarrow X_i$ *is valid* **then**
      compute diff$_{rev} = f(G with X_j \rightarrow X_i$ reversed; D) - f$_G$;
      update best improvement;
    end
  end
  if *there is an improvement* **then**
    $G \leftarrow$ apply best move;
    $f_G \leftarrow$ update score;
    improvement $\leftarrow$ true;
  end
end

Fig. 6. Structural learning of BNs using the Hill-climbing algorithm.

4.1. User exit choice Behavior analysis

4.1.1. Chi-Square analysis of exit choices in immersive and non-immersive VR

To examine exit choice behaviors in diverse VR environments, Chi-Square tests were conducted to investigate the differences between immersive VR and non-immersive VR across eight distinct scenarios. The results (Table 2) generally indicated no significant differences in most scenarios, with *p*-values substantially exceeding the 0.05 threshold, suggesting that decision-making in both VR formats is statistically comparable under standard conditions. However, Scenario 3 presented a notable exception, with a significantly low p-value of 0.00596 highlighting a marked difference in user interactions between the two VR experiments.

The distinctive setting of Scenario 3 (Table 1), which featured smoke at a familiar exit—unlike other scenarios where smoke and crowd density were either uniformly distributed or not combined with familiarity cues—likely heightened the psychological impact on participants in immersive VR. This scenario underscores how immersive VR's enhanced realism and immersion can significantly amplify the perception of smoke and familiarity cues, creating a stark contrast with the non-immersive VR presented on a laptop, where these factors may elicit weaker emotional and cognitive responses.

4.1.2. Exit choice modeling

To further investigate emergency exit choice behavior in virtual environments, logistic regression analysis was applied to data from both non-immersive and immersive VR experiments, with the results presented in Table 3. This analysis provided significant insights into the factors influencing participants' exit choices, revealing distinct patterns under varying experimental conditions. In the non-immersive VR experiment, the "Dist" (distance to the exit) and "Smoke" (presence of smoke) factors emerged as significant predictors, both negatively correlating with the likelihood of exit selection—consistent with safety behavior principles. As distance increases or smoke impairs visibility, the probability of selecting a specific exit decreases, as indicated by *p*-values less than 0.01.

Conversely, the immersive VR experiment revealed significant correlations for all four factors. The "NP" (number of people at an exit) factor had a positive coefficient (0.131), suggesting that more people at an exit increased the likelihood of its selection, possibly due to social proof or herd behavior ($p < 0.001$). The "Fam" (familiarity with an exit) factor also showed a significant positive effect, with a coefficient of 1.379, indicating that familiarity enhances exit selection. This finding highlights the role of environmental cues and prior knowledge in decision-making under high sensory immersion. Meanwhile, the Dist factor retained its negative correlation, with its effect nearly doubling in immersive settings (−0.574), suggesting an amplified spatial awareness. The Smoke factor also showed a more pronounced negative impact (−2.312) in immersive VR, aligning with the expectation that sensory-rich environments amplify hazard perception and subsequently influence behavior more markedly. The differences observed between non-immersive and immersive settings highlight the complex interplay of environmental factors and sensory engagement in shaping behavior during emergency egress. This suggests that immersion intensifies the impact of social and environmental cues on decision-making.

Table 2
Chi-square results for exit choices across VR scenarios.

Scenario	Statistic Value	P-Value	Significance
1	3.260	0.071	Not Significant
2	0.842	0.359	Not Significant
3	7.560	0.005	**Significant**
4	2.650	0.104	Not Significant
5	0.605	0.437	Not Significant
6	3.080	0.0792	Not Significant
7	0.821	0.365	Not Significant
8	3.260	0.071	Not Significant

Fig. 7 presents the effect plots illustrating the impact of Dist and NP on participants' exit choices in non-immersive (red) and immersive VR (blue) environments. The shaded regions around the regression lines represent the 95 % confidence intervals, providing insight into the precision of the estimated effects. Notably, narrower confidence intervals in certain areas reflect higher certainty in these estimates. The impact of these factors was more pronounced in the immersive VR setting, as evidenced by the steeper slopes of the regression lines. Specifically, in the immersive VR condition, distance to the exit had a stronger negative impact on exit choice, with participants significantly less likely to select a distant exit. This steeper gradient reflects the more intense effect of spatial factors when participants are immersed in a more realistic and engaging virtual environment, compared to the more gradual influence observed in the non-immersive VR condition. In addition to distance, an increase in the number of people at an exit correlates with a higher likelihood of participants choosing that exit in the immersive VR environment, suggesting a pronounced herding behavior. This contrasts sharply with the non-immersive VR condition, where the influence of crowding on exit choice appears more complex or less pronounced, indicating that the non-immersive VR may have been less effective at amplifying the social cues necessary for participants' decision-making. Furthermore, the confidence intervals (represented by the shaded areas around the regression lines) for the non-immersive VR condition, particularly regarding the number of people at an exit, are significantly wider. This suggests participants in a lower-immersion environment perceived virtual cues more weakly or inconsistently, resulting in more varied responses and less consensus in behavior. In contrast, the fully immersive VR condition provided stronger sensory cues and a more engaging environment, leading to more uniform responses across participants. These discrepancies may indicate technical limitations (e.g., lower perceived presence) inherent in the current non-immersive VR design, which could reduce user engagement and weaken cue delivery.

4.1.3. Causal analysis of exit choices in VR settings

Following the logistic regression analysis, a causal analysis using BN modeling was performed to elucidate how specific variables influence exit decisions, addressing the complexity of their interrelationships. While logistic regression evaluates direct effects on a binary outcome, BNs capture conditional dependencies and more nuanced interactions. Notably, leveraging established insights into how environmental factors shape exit choices, the Hill-Climbing algorithm was employed to determine the optimal structure of the BN.

Fig. 8 displays the BN constructed from data gathered in both non-immersive and immersive VR experiments. The comparison reveals that participants' decisions to exit or not, under controlled conditions, are generally consistent, highlighting an inherent behavioral pattern in emergency scenarios.

Table 4 presents the conditional probabilities of choosing an exit in response to various environmental factors in both non-immersive and immersive VR settings. Notably, probabilities around 0.5 indicate no significant causal effect from the environmental or social variables tested, suggesting that participant decisions under these conditions are essentially random. In immersive VR, the presence of smoke profoundly affects exit choices, markedly reducing the likelihood of selecting a close exit from 0.352 to 0.069 when smoke is present and no people are at an exit. This significant decrease underscores an increased perception of risk associated with smoke, highlighting the strong aversive reaction elicited by the realistic settings of immersive VR. Furthermore, distance to the exit generally influences choices in smoke-free conditions, with closer exits preferred. However, this preference diminishes when smoke is introduced, suggesting that perceived environmental risks may supersede the usual preference for proximity. Social dynamics, indicated by the number of people at an exit, also significantly influence decision-

Table 3
Correlation analysis.

Factor	Non-immersive VRExperiment					Immersive VR Experiment				
	Coefficient	Standard Error	*Z*-value	P-value		Coefficient	Standard Error	Z-value	P-value	
NP	0.015	0.021	0.7290	0.466		0.131	0.019	6.868	$p < 0.001$	***
Dist	−0.258	0.098	−2.6410	0.008	**	−0.574	0.097	−5.948	p < 0.001	***
Smoke	−0.884	0.170	−5.2070	p < 0.001	***	−2.312	0.174	−13.263	p < 0.001	***
Fam	−0.252	0.257	−0.9820	0.326		1.379	0.242	5.699	p < 0.001	***

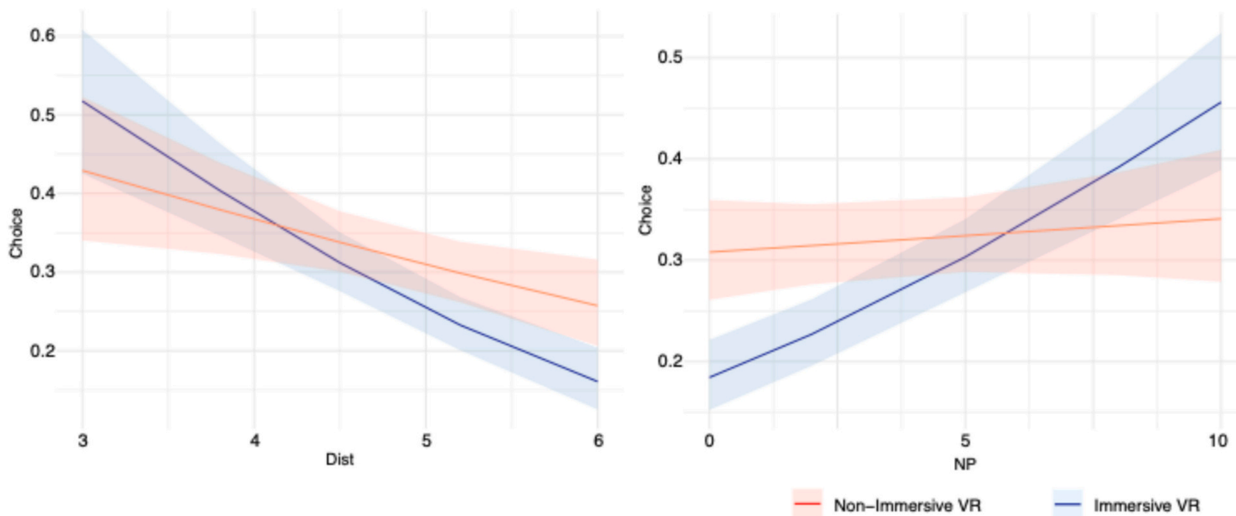


Fig. 7. Effect plot for immersive and non-immersive VR experiments.

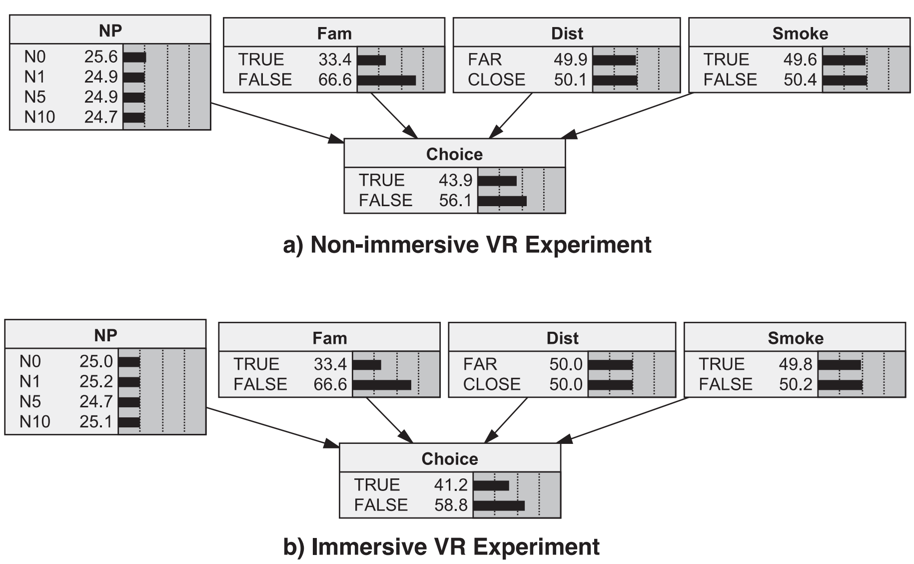


Fig. 8. Bayesian network of environmental factors and exit choice behavior in both non-immersive and immersive VR experiments.

making in immersive VR. The likelihood of choosing an exit increases substantially when more individuals are present, supporting the concept that social cues—such as the presence of others—instill a sense of security or encourage herd behavior, particularly in environments where realism intensifies the perceived stakes of decision-making. In contrast, responses in the non-immersive VR environment show considerably less variability. Neither the presence of smoke nor familiarity with the exit significantly influences exit choices, as evidenced by the minimal changes in probabilities (e.g., from 0.269 to 0.311 when smoke is introduced). This muted response suggests that the diminished sensory engagement and realism of non-immersive VR lessen the impact of environmental cues on behavior, potentially reducing its effectiveness in scenarios that require realistic emotional and cognitive responses. The consistent response patterns in non-immersive VR, particularly regarding the negligible effects of familiarity and smoke, align with previous findings that less realistic environments yield less behavioral variation among participants.

On the other hand, when comparing the results from conditional probability analysis (CPA) with those from logistic regression, both methods consistently highlight the significant negative impact of smoke

Table 4
Conditional probability table.

Settings	Smoke	Fam	Dist	NP = 0	NP = 1	NP = 5	NP = 10
Immersive VR	False	False	Close	0.352	0.651	0.500*	0.823
	False	False	Far	0.500*	0.070	0.256	0.818
	True	False	Close	0.069	0.046	0.127	0.310
	True	False	Far	0.024	0.500*	0.500*	0.500*
	False	True	Close	0.500*	0.500*	0.500*	0.500*
	False	True	Far	0.655	0.500*	0.500*	0.602
	True	True	Close	0.500*	0.500*	0.500*	0.500*
	True	True	Far	0.500*	0.070	0.163	0.500*
Non-immersive VR	False	False	Close	0.269	0.714	0.500*	0.473
	False	False	Far	0.500*	0.048	0.286	0.690
	True	False	Close	0.311	0.314	0.185	0.445
	True	False	Far	0.765	0.500*	0.500*	0.500*
	False	True	Close	0.500*	0.500*	0.500*	0.500*
	False	True	Far	0.500*	0.500*	0.500*	0.418
	True	True	Close	0.500*	0.500*	0.500*	0.500*
	True	True	Far	0.500*	0.018	0.016	0.500*

visibility and the preference for closer exits. Logistic regression reveals highly significant negative coefficients for both smoke (−0.884 in non-immersive, −2.312 in immersive; $p < 0.001$) and distance (−0.258 in non-immersive, −0.574 in immersive; $p < 0.001$), corroborating the trends observed in the CPA data. However, discrepancies emerge in the analysis of familiarity. While CPA often indicates a neutral effect of familiarity (marked as 0.500*, with probabilities around 0.500), suggesting negligible impact, logistic regression identifies a significant positive effect in immersive VR, highlighting a potential limitation of CPA in detecting subtle variable interactions. These differences may stem from the distinct focuses of the two methodologies: CPA concentrates on direct conditional probabilities and local dependencies among variables, capturing how exit choice probabilities vary under specific conditions; meanwhile, logistic regression assesses the overall impact of each predictor on exit choice while controlling for other variables, providing a more defined quantification of each variable's influence.

4.2. User experience analysis in non-immersive and immersive VR experiments

Fig. 9 provides a detailed overview of user experiences in non-immersive (red boxplot) and immersive (blue boxplot) VR experiments. Participants in the non-immersive VR setting reported slightly higher levels of self-efficacy, possibly due to the predictability and familiarity of user interfaces (a laptop and a mouse), which bolstered their confidence in handling emergencies. This observation also extended to their vulnerability experiences. Additionally, scenario perception, the intuitive judgment of an emergency's severity and urgency within a virtual environment, was notably enhanced in non-immersive VR. This finding suggests that reduced immersion may sharpen users' focus on the emergency narrative, a key element in developing VR-based training interventions. Perceived realism, which measures how closely the

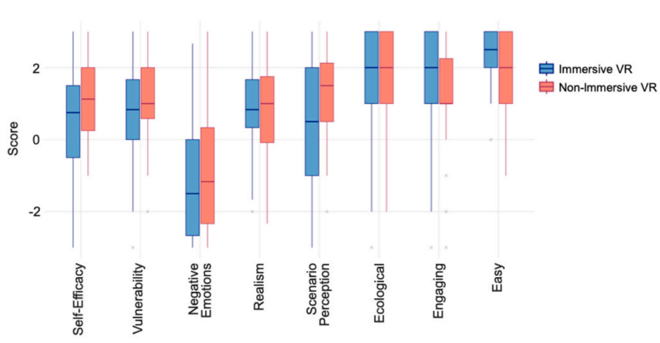


Fig. 9. User experience in immersive and non-immersive VR experiments.

environment, the fire hazard, and the virtual humans resemble reality, received similarly positive ratings in both immersive and non-immersive modes. Conversely, participants in immersive VR reported significantly higher levels of negative emotions, such as fear, tension, and anxiety, alongside a more uniform agreement on the realism of the immersive VR experience. Interestingly, ecological validity, which measures realistic user behavior in VR scenarios, showed no significant differences between the two formats. This finding suggests that both VR settings effectively convinced participants that their behavioral responses and decision-making were similar to those they would exhibit in real-life emergencies. Moreover, immersive VR received higher ratings for user engagement and ease of interaction, indicating that while non-immersive VR may enhance users' confidence through familiar controls, immersive VR excels at creating more engaging and user-friendly environments. This analysis highlights the critical role of immersion in VR experience design, offering valuable insights for improving safety training and other applications involving high-stakes decision-making.

In addition, ANOVA was conducted to investigate the effects of demographic and experiential factors on user perceptions across different VR environments (Table 5). The results indicate that the immersive nature of VR significantly amplifies the impact of variables, such as VR experience, gender, and age, on user perceptions in both non-immersive and immersive settings. Specifically, self-efficacy is substantially enhanced in immersive VR, with VR experience and gender showing significant effects (Mean Sq = 129.980; F-value = 78.650), highlighting the heightened sensitivity of self-efficacy to these factors. Conversely, vulnerability is more influenced by VR experience in non-immersive settings, with the effects of gender and age being less pronounced in immersive VR. This pattern suggests that non-immersive VR may not adequately engage sensory and cognitive faculties, thus minimizing the visibility of age-related differences and their impact on self-efficacy and other factors. However, in immersive VR, there is a marked increase in the influence of both VR experience and age on negative emotions, suggesting that greater immersion amplifies emotional responses. Additionally, while realism is noticeably impacted by age in non-immersive VR, it is less influenced by VR experience in immersive settings, indicating that age-related differences in sensory acuity and cognitive engagement are more pronounced in less immersive conditions. In contrast, immersive VR significantly affects perceptions related to realism and ecological validity, with both age and VR experience intensifying these effects. This demonstrates that enhanced sensory experiences in immersive VR increase sensitivity to age-related variations. Scenario perception in immersive settings is less influenced by VR experience, whereas ecological validity is considerably sensitive to both age and VR experience, especially in immersive environments. This heightened sensitivity suggests that familiarity with immersive VR can reduce vulnerability and bolster perceived control and competence,

Table 5
ANOVA results for user perceptions in VR experiment.

Experience Factor	Personal Factor	Non-immersive VR experiment			Immersive VR experiment		
		Mean Sq	F value	*P* value	Mean Sq	F value	*P* value
	VR Experience	6.148	5.193	< 0.01	15.620	8.857	< 0.01
Self-Efficacy	Gender	74.110	67.610	< 0.001	129.980	78.650	< 0.001
	Age	0.388	0.324	0.570	129.980	78.650	< 0.001
	VR Experience	18.120	16.030	< 0.001	8.949	5.761	0.017
Vulnerability	Gender	60.090	54.860	< 0.001	0.629	0.403	0.526
	Age	8.959	7.679	0.006	0.629	0.403	0.526
	VR Experience	47.250	18.130	< 0.001	56.170	22.930	< 0.001
Negative Emotions	Gender	6.422	2.357	0.125	262.200	116.600	< 0.001
	Age	13.404	4.937	0.027	262.200	116.600	<0.001
	VR Experience	4.806	2.325	< 0.01	0.827	0.530	0.467
Realism	Gender	0.022	0.011	0.918	15.954	10.320	< 0.01
	Age	134.270	71.000	< 0.001	15.954	10.320	0.001
	VR Experience	15.752	11.700	< 0.001	1.291	0.478	0.490
Scenario Perception	Gender	31.250	23.240	< 0.001	17.406	6.477	< 0.05
	Age	14.005	10.230	< 0.01	17.406	6.477	0.011
	VR Experience	4.920	3.238	0.040	19.011	7.165	0.008
Ecological	Gender	7.200	4.734	< 0.05	71.390	27.430	<0.001
	Age	31.800	21.390	< 0.001	71.390	27.430	< 0.001

likely due to users acclimating to the complexities of VR's sensory and interactive elements. These findings highlight the importance of considering the immersive quality of VR when evaluating its psychological effects, as user experience, age, and gender significantly influence user perceptions.

4.3. Correlation between user perception and exit choice

This study examined the interaction effects between user perceptions and the characteristics of emergency scenarios on exit choice behavior in both non-immersive and immersive VR environments. The ANOVA results revealed significant interaction effects ($p < 0.05$) between key variables, as depicted in Figs. 10 and 11 for non-immersive and immersive VR experiments, respectively.

For the non-immersive VR experiment, Fig. 10a illustrates the interaction between exit familiarity and perceived ease of control within the desktop VR environment. Participants familiar with an exit showed an increased likelihood of choosing that exit as their perceived ease of using the VR format increased. This relationship was particularly pronounced for higher ease ratings, suggesting that familiarity enhances the usability benefits of the VR format. Conversely, participants unfamiliar with the exit demonstrated an inverse relationship; as their perceived ease of using the VR environment increased, their likelihood of choosing the unfamiliar exit generally decreased. This unexpected finding may be attributed to the increased ease of use, which encourages unfamiliar users to explore the environment more thoroughly, thereby reducing their reliance on the first encountered exit. Fig. 10b illustrates the complex relationship between exit familiarity and perceived vulnerability in participants' exit choice behavior in the non-immersive VR setting. For participants familiar with an exit, increased perceived vulnerability correlated with a higher likelihood of choosing that familiar exit, indicating that familiarity significantly influences decision-making in stressful situations. Conversely, for participants unfamiliar with an exit, heightened vulnerability decreased the likelihood of selecting that exit. Interestingly, as perceived vulnerability increased, the relative influence of familiarity on exit choice diminished, suggesting that under extreme stress, the immediate need to escape might override the benefits of familiar surroundings.

In the immersive VR experiment, notable interaction effects were observed between familiarity and perceived vulnerability, as well as between familiarity and negative emotion perception. As depicted by the regression lines in Fig. 11a, the influence of familiarity on decision-making varied significantly with the level of perceived vulnerability. Specifically, at lower levels of perceived vulnerability, participants were more likely to choose familiar exits. However, as perceived vulnerability increased, the likelihood of selecting familiar exits decreased markedly. This could be attributed to participants perceiving the consequences of a fire emergency as highly harmful, potentially leading to less rational decision-making during exit selection. Similarly, Fig. 11b illustrates the interaction between familiarity and negative emotions. When

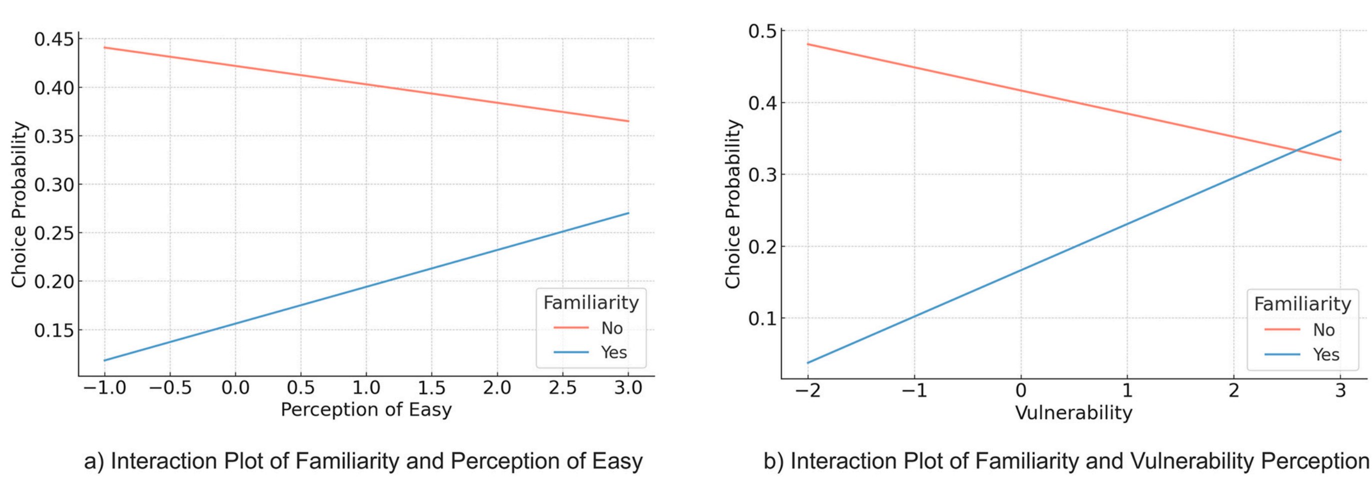
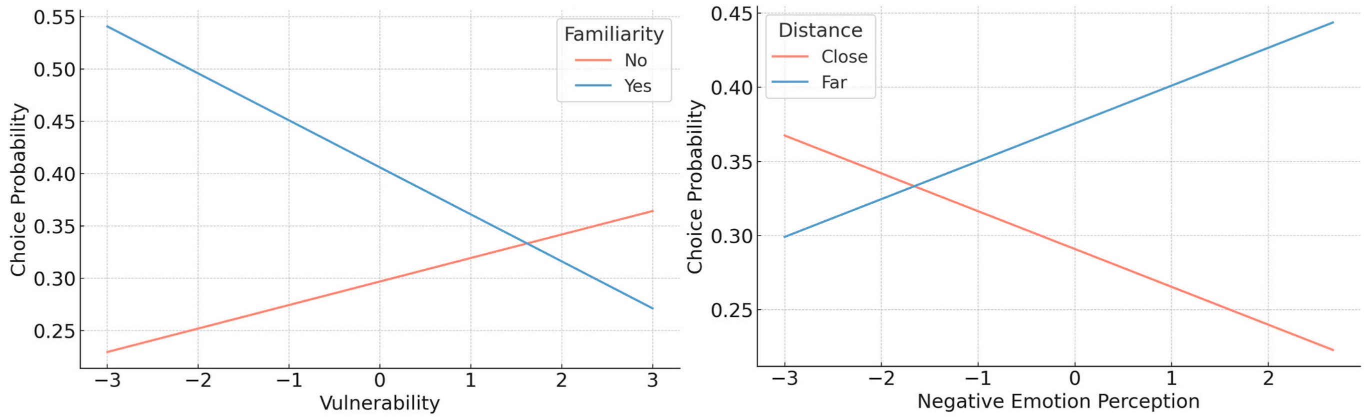


Fig. 10. Interaction plot for non-immersive VR experiment.



a) Interaction Plot of Familiarity and Vulnerability Perception

b) Interaction Plot of Distance and Negative Emotion Perception

Fig. 11. Interaction plot for immersive VR experiment.

participants experienced intense negative emotions, such as heightened anxiety or nervousness, exit distance had minimal impact on their choices, with similar probabilities of selecting close or distant exits. Conversely, participants made more rational decisions under lower emotional stress, preferring closer exits. These findings suggest that high levels of perceived vulnerability and intense negative emotions can result in less rational decision-making during emergency exit selection, potentially overriding the influences of familiarity and proximity.

This highlights the complex interplay between psychological factors (perceived vulnerability and negative emotions) and environmental cues (exit familiarity and distance) in shaping emergency exit choice behavior within VR simulations. The results indicate that emotional states and risk perception can significantly influence decision-making in simulated emergency scenarios, potentially overriding more rational considerations such as exit proximity or familiarity. This understanding has critical implications for emergency preparedness and evacuation planning, emphasizing the need to consider both environmental design and psychological factors in optimizing safety strategies and informing future experimental designs.

5. Conclusions

VR has gained widespread recognition for its ability to simulate realistic environments and evoke emotional responses, providing valuable insights into human behavior during emergencies. However, the high costs associated with immersive VR formats limit their scalability, thereby affecting the breadth of data collection in studies. This paper presented a comparative analysis of the impact of immersive and non-immersive VR environments on exit choices during simulated emergency evacuations. Specifically, it examined how factors, such as the number of people at an exit, smoke presence, exit distance, and familiarity with an exit, shape decision-making, alongside a user experience survey to assess the impact of the virtual environment type. By employing a multifactorial experimental design integrated within a comprehensive analytical framework, this research captures the complex interdependencies among behavioral cues, user perceptions, and situational contexts, examining them collectively as components of a unified system rather than independently. This integrated approach directly addresses a limitation in previous studies, which typically investigated these variables in isolation and static manner. Furthermore, the proposed analytical framework is significantly more robust and layered, which goes beyond basic group comparisons by integrating Chi-square tests, random utility modeling for discrete decision analysis, ANOVA for examining differences across conditions, and a causal analysis to uncover underlying drivers of evacuee choices. This comprehensive approach provides deeper insight into not only what differences exist between immersive and non-immersive VR in emergency scenarios, but also why they arise under stress, enhancing the interpretability of the findings and their relevance to both theoretical understanding and practical applications.

This study revealed several key findings. First, immersive VR enhanced the impact of environmental cues on decision-making, with participants in immersive environments showing a stronger preference for closer exits and greater susceptibility to social influence. The presence of smoke significantly affected exit choices in immersive VR, suggesting that immersive environments are more effective at capturing attention and evoking stronger emotional responses. Additionally, a negative interaction between smoke and exit distance was observed, indicating that proximity to exits was less influential in the presence of smoke, possibly because perceived environmental risks overrode typical decision-making preferences. Regarding user experience, participants in immersive VR reported higher engagement, easier interaction, and stronger negative emotions, such as fear and anxiety. Conversely, non-immersive VR users demonstrated higher self-efficacy and better scenario perception, likely due to the reduced sensory load in non-immersive environments. Despite these differences, both VR formats exhibited comparable self-reported ecological validity, indicating their effectiveness in simulating real-world emergency responses. Furthermore, personal factors, including prior VR experience, age, and gender, significantly influenced perceptions and emotional responses, particularly in immersive VR. In non-immersive VR, prior experience had a greater impact on perceptions of vulnerability. Notably, participants who perceived higher vulnerability tended to choose more familiar exits in the non-immersive VR environment; however, this effect diminished in immersive VR, where emotional stress appeared to override rational decision-making. Additionally, the influence of exit distance on decision-making weakened under high emotional stress, suggesting that negative emotions and perceived risks may lead to less rational exit choices.

Overall, this study makes several key contributions to the fields of emergency evacuation and VR research. First, it provides a comprehensive comparison of exit behavior in immersive and non-immersive VR environments, highlighting how key factors shape decision-making differently in each setting. This comparison is crucial since VR-based evacuation studies vividly demonstrate how occupants choose and move toward exits under pressure, confirming that crowd dynamics and clear visual cues decisively influence split-second decisions. Architects can harness these behavioral insights to optimize exit layouts, underscoring the critical importance of VR simulation experiments for informing architectural design. Thus, by contrasting fully immersive, headset-based VR simulations with non-immersive, screen-based ones, the study clarifies how the level of immersion intensifies—or tempers—participants' responses under stress. These insights deepen our understanding of VR's impact on emergency behavior, helping researchers refine VR-based experimental protocols so that evacuation trials yield more realistic, reliable data. In turn, the improved evidence base supports architects and safety engineers in designing buildings that are not only safer but also more resilient. Second, by examining the interaction between emotional responses and decision-making, this study reveals how different VR formats shape participants' emotional states under stress. This underscores the critical role of immersion in shaping emotional responses, broadening the scope of emergency behavior research and emphasizing how emotional stress can override rational decision-making. Third, this study emphasizes the significant impact of personal factors, such as prior VR experience, age, and gender, on user perceptions and behaviors in VR simulations. It highlights the importance of accounting for these variables when designing and interpreting VR-based evacuation studies to ensure that findings more accurately reflect real-world decision-making.

While this study offers valuable insights, several limitations should be addressed in future research. This study primarily focused on factors such as social influence, smoke presence, exit distance, and familiarity. As such, future studies should explore a broader range of emergency behaviors or the intricate psychological underpinnings (e.g., panic escalation) to provide a more in-depth understanding of individual reactions in virtual emergency scenarios. In addition, the comparison of immersive and non-immersive virtual evacuation environments was constrained by the specific technological setup employed in this study. Varying technical parameters, for example, implementing dynamic field-of-view adjustments to reduce visual-cognitive load or applying spatial-audio solutions such as Meta's de-reverberation to enhance sensory coherence, would clarify how system design influences affective responses and immersion. Such insights can optimize VR emergency-training simulations by aligning technical configurations with behavioral realism. Moreover, tracking arousal dynamically through repeated self-reports and physiological indices (e.g., heart rate, skin conductance) before, during, and after exposure would offer more precise evidence of VR-induced stress and its impact on evacuation decisions. Ecological validity could be further strengthened through multi-modal interaction paradigms, such as haptic feedback, gesture recognition, and dynamic visual rendering, which bridge the gap between virtual and real-world emergency responses. Finally, grounding these design choices in established psychological models of stress, decision-making, and situational awareness will refine VR practice and strengthen its value for high-stakes behavioral research and training.

CRediT authorship contribution statement

Yuxuan Zhang: Methodology, Conceptualization, Writing – original draft. **Daniel Paes:** Conceptualization, Writing – review & editing. **Zhenan Feng:** Investigation, Writing – review & editing. **Dorothy Scorgie:** Resources. **Peijin He:** Resources. **Ruggiero Lovreglio:** Project administration, Methodology, Conceptualization, Writing – original draft.

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.

Acknowledgements

This project was reviewed and approved by the Massey University Human Ethics Committee (Southern A, Application No. 18/21). The authors gratefully acknowledge financial support from the National Natural Science Foundation of China (Grant No. 72401131) and from the Humanities and Social Sciences Research Project of the Ministry of Education of China (Grant No. 23YJCZH311). Any opinions, findings, conclusions, or recommendations expressed in this research are those of the authors and do not necessarily reflect the views of the National Natural Science Foundation of China or the Ministry of Education of China. Prof Ruggiero Lovreglio thanks the collaborators listed in reference 13, in particular Dillie, E, Rahouti, A., for the earlier developments of this research.

Data availability

The authors do not have permission to share data.

References

[1] E. Ronchi, D. Nilsson, Fire evacuation in high-rise buildings: a review of human behaviour and modelling research, Fire Sci. Rev. 2 (2013), https://doi.org/10.1186/2193-0414-2-7.
[2] J. Chen, T. Shi, N. Li, Pedestrian evacuation simulation in indoor emergency situations: approaches, models and tools, Saf. Sci. 142 (2021), https://doi.org/10.1016/j.ssci.2021.105378.
[3] E.R. Galea, J.M. Perez Galparsoro, A computer-based simulation model for the prediction of evacuation from mass-transport vehicles, Fire Saf. J. 22 (1994), https://doi.org/10.1016/0379-7112(94)90040-X.
[4] E.D. Kuligowski, Human Behavior in Fire, in: M.J. Hurley, D. Gottuk, J.R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J.M. Watts, C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering, Springer, New York, New York, NY, 2016, pp. 2070–2114, https://doi.org/10.1007/978-1-4939-2565-0_58.
[5] R. Fahy, Selecting scenarios for deterministic fire safety engineering analysis: life safety for occupants, in: SFPE Handbook of Fire Protection Engineering, 2016, https://doi.org/10.1007/978-1-4939-2565-0_57. Fifth Edition.
[6] T. Gernay, Performance-based design for structures in fire: advances, challenges, and perspectives, Fire Saf. J. 142 (2024), https://doi.org/10.1016/j.firesaf.2023.104036.
[7] R. Lovreglio, E. Kuligowski, S. Gwynne, K. Boyce, A pre-evacuation database for use in egress simulations, Fire Saf. J. 105 (2019), https://doi.org/10.1016/j.firesaf.2018.12.009.
[8] E.D. Gwynne, M.J. Kinsey Kuligowski, Human behaviour in fire—model development and application, in: 6th International Symposium on Human Behaviour in Fire, Interscience Communications, 2015, pp. 23–24. ISBN 9780993393303.
[9] M. Haghani, M. Sarvi, Crowd behaviour and motion: empirical methods, Transp. Res. B Methodol. 107 (2018), https://doi.org/10.1016/j.trb.2017.06.017.
[10] Y. Feng, D. Duives, W. Daamen, S. Hoogendoorn, Data collection methods for studying pedestrian behaviour: a systematic review, Build. Environ. 187 (2021), https://doi.org/10.1016/j.buildenv.2020.107329.
[11] S.M.V. Gwynne, K.E. Boyce, Engineering Data, in: M.J. Hurley, D. Gottuk, J.R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J.M. Watts, C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering, Springer, New York, New York, NY, 2016, pp. 2429–2551, https://doi.org/10.1007/978-1-4939-2565-0_64.
[12] L. Shi, Q. Xie, X. Cheng, L. Chen, Y. Zhou, R. Zhang, Developing a database for emergency evacuation model, Build. Environ. 44 (2009), https://doi.org/10.1016/j.buildenv.2008.11.008.
[13] R. Lovreglio, E. Dillies, E. Kuligowski, A. Rahouti, M. Haghani, Exit choice in built environment evacuation combining immersive virtual reality and discrete choice modelling, Autom. Constr. 141 (2022), https://doi.org/10.1016/j.autcon.2022.104452.
[14] J. Wahlqvist, P. Van, H. Brandforsk, Visualization of Fires in Virtual Reality. http://www.brand.lth.se/english, 2018.
[15] S. Arias, J. Wahlqvist, D. Nilsson, E. Ronchi, H. Frantzich, Pursuing behavioral realism in virtual reality for fire evacuation research, Fire Mater. 45 (2021), https://doi.org/10.1002/fam.2922.
[16] E. Smedberg, G. De Cet, J. Wahlqvist, G. Carlsson, G. Gefenaite, B. Slaug, S. Schmidt, E. Ronchi, The impact of people with mobility limitations on exit choice, Fire Saf. J. 140 (2023), https://doi.org/10.1016/j.firesaf.2023.103900.
[17] M. Kinateder, W.H. Warren, Social influence on evacuation Behavior in real and virtual environments, Front. Robotics and AI 3 (2016), https://doi.org/10.3389/frobt.2016.00043.
[18] A. Shipman, A. Majumdar, Z. Feng, R. Lovreglio, A quantitative comparison of virtual and physical experimental paradigms for the investigation of pedestrian responses in hostile emergencies, Sci. Rep. 14 (2024) 6892, https://doi.org/10.1038/s41598-024-55253-9.
[19] S. Arias, A. Mossberg, D. Nilsson, J. Wahlqvist, A study on evacuation Behavior in physical and virtual reality experiments, Fire. Technol 58 (2022) 817–849, https://doi.org/10.1007/s10694-021-01172-4.
[20] S. Lu, Z. Feng, Z. Xu, D. Paes, N. Li, R. Lovreglio, The Effects of Immersive Environments and Environmental Haptic Feedback on Human Behaviors in Virtual Emergencies, 2024, https://doi.org/10.2139/ssrn.5002582.
[21] R. Lovreglio, D. Paes, Z. Feng, X. Zhao, Digital Technologies for Fire Evacuations, 2024, pp. 439–454, https://doi.org/10.1007/978-3-031-48161-1_18.
[22] Y. Zhang, H. Liu, S.-C. Kang, M. Al-Hussein, Virtual reality applications for the built environment: research trends and opportunities, Autom. Constr. 118 (2020) 103311, https://doi.org/10.1016/j.autcon.2020.103311.

[23] K. Lyu, A. Brambilla, A. Globa, R. de Dear, An immersive multisensory virtual reality approach to the study of human-built environment interactions, Autom. Constr. 150 (2023), https://doi.org/10.1016/j.autcon.2023.104836.
[24] L. Cao, J. Lin, N. Li, A virtual reality based study of indoor fire evacuation after active or passive spatial exploration, Comput. Hum. Behav. 90 (2019) 37–45, https://doi.org/10.1016/j.chb.2018.08.041.
[25] M. Zhang, J. Ke, L. Tong, X. Luo, Investigating the influence of route turning angle on compliance behaviors and evacuation performance in a virtual-reality-based experiment, Adv. Eng. Inform. 48 (2021), https://doi.org/10.1016/j.aei.2021.101259.
[26] G. Bernardini, R. Lovreglio, E. Quagliarini, M. D'Orazio, Can active and passive wayfinding systems support fire evacuation in buildings? Insights from a virtual reality-based experiment, J. Build. Eng. 74 (2023), https://doi.org/10.1016/j.jobe.2023.106778.
[27] M. Fu, R. Liu, Q. Liu, Why individuals do not use emergency exit doors during evacuations: a virtual reality and eye-tracking experimental study, Adv. Eng. Inform. 60 (2024), https://doi.org/10.1016/j.aei.2024.102396.
[28] Z. Feng, V.A. González, R. Amor, M. Spearpoint, J. Thomas, R. Sacks, R. Lovreglio, G. Cabrera-Guerrero, An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings, Adv. Eng. Inform. 45 (2020), https://doi.org/10.1016/j.aei.2020.101118.
[29] Y. Shi, J. Kang, P. Xia, O. Tyagi, R.K. Mehta, J. Du, Spatial knowledge and firefighters' wayfinding performance: a virtual reality search and rescue experiment, Saf. Sci. 139 (2021), https://doi.org/10.1016/j.ssci.2021.105231.
[30] Z. Wang, R. He, F. Rebelo, E. Vilar, P. Noriega, Human interaction with virtual reality: investigating pre-evacuation efficiency in building emergency, Virtual Reality 27 (2023), https://doi.org/10.1007/s10055-022-00710-x.
[31] D. Snopková, P. Ugwitz, Z. Stachoň, J. Hladík, V. Juřík, O. Kvarda, P. Kubíček, Retracing evacuation strategy: a virtual reality game-based investigation into the influence of building's spatial configuration in an emergency, Spat. Cogn. Comput. 22 (2022) 30–50, https://doi.org/10.1080/13875868.2021.1913497.
[32] Y. Feng, D.C. Duives, S.P. Hoogendoorn, Wayfinding behaviour in a multi-level building: a comparative study of HMD VR and desktop VR, Adv. Eng. Inform. 51 (2022), https://doi.org/10.1016/j.aei.2021.101475.
[33] J. Kubota, T. Sano, E. Ronchi, Assessing the compliance with the direction indicated by emergency evacuation signage, Saf. Sci. 138 (2021), https://doi.org/10.1016/j.ssci.2021.105210.
[34] M. Fu, R. Liu, Y. Zhang, Do people follow neighbors? An immersive virtual reality experimental study of social influence on individual risky decisions during evacuations, Autom. Constr. 126 (2021), https://doi.org/10.1016/j.autcon.2021.103644.
[35] M. Fu, R. Liu, Y. Zhang, Why do people make risky decisions during a fire evacuation? Study on the effect of smoke level, individual risk preference, and neighbor behavior, Saf. Sci. 140 (2021), https://doi.org/10.1016/j.ssci.2021.105245.
[36] J. Lin, L. Cao, N. Li, Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology, Adv. Eng. Inform. 39 (2019) 53–61, https://doi.org/10.1016/j.aei.2018.11.007.
[37] J. Lin, R. Zhu, N. Li, B. Becerik-Gerber, Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study, Adv. Eng. Inform. 43 (2020), https://doi.org/10.1016/j.aei.2020.101040.
[38] X. Ben Song, R. Lovreglio, Investigating personalized exit choice behavior in fire accidents using the hierarchical Bayes estimator of the random coefficient logit model, Analyt. Meth. Accident Res. 29 (2021), https://doi.org/10.1016/j.amar.2020.100140.
[39] P.E. Wais, M. Arioli, R. Anguera-Singla, A. Gazzaley, Virtual reality video game improves high-fidelity memory in older adults, Sci. Rep. 11 (2021), https://doi.org/10.1038/s41598-021-82109-3.
[40] E. Krokos, C. Plaisant, A. Varshney, Virtual memory palaces: immersion aids recall, Virtual Reality 23 (2019) 1–15, https://doi.org/10.1007/s10055-018-0346-3.
[41] L. Chittaro, F. Buttussi, Exploring the use of arcade game elements for attitude change: two studies in the aviation safety domain, Int. J. Hum.-Comput. Stud. 127 (2019) 112–123, https://doi.org/10.1016/j.ijhcs.2018.07.006.
[42] Y. Zhao, C.L. Bennett, H. Benko, E. Cutrell, C. Holz, M.R. Morris, M. Sinclair, Enabling People with Visual Impairments to Navigate Virtual Reality with a Haptic and Auditory Cane Simulation, Conference on Human Factors in Computing Systems - Proceedings, 2018-April, 2018, https://doi.org/10.1145/3173574.3173690/SUPPL_FILE/PN1758.MP4.
[43] D.L. Gao, W. Xie, E.W. Ming Lee, Individual-level exit choice behaviour under uncertain risk, Phys. A: Statis. Mechan. Applicat. 604 (2022), https://doi.org/10.1016/j.physa.2022.127873.
[44] N.W.F. Bode, A.U. Kemloh Wagoum, E.A. Codling, Information use by humans during dynamic route choice in virtual crowd evacuations, R. Soc. Open Sci. 2 (2015), https://doi.org/10.1098/rsos.140410.
[45] A. Normoyle, J. Drake, A. Safonova, Egress Online: Towards Leveraging Massively, Multiplayer Environments for Evacuation Studies. https://repository.upenn.edu/handle/20.500.14332/7949, 2012. (Accessed 6 May 2025).
[46] M. Shi, Z. Zhang, W. Zhang, Y. Ma, H. Li, E.W.M. Lee, The study of self-organised behaviours and movement pattern of pedestrians during fire evacuations: virtual experiments and survey, Saf. Sci. 170 (2024), https://doi.org/10.1016/j.ssci.2023.106373.
[47] J.M. Davila Delgado, L. Oyedele, P. Demian, T. Beach, A research agenda for augmented and virtual reality in architecture, engineering and construction, Adv. Eng. Inform. 45 (2020), https://doi.org/10.1016/j.aei.2020.101122.
[48] M. Umair, A. Sharafat, D.E. Lee, J. Seo, Impact of Virtual Reality-Based Design Review System on User's Performance and Cognitive Behavior for Building Design Review Tasks, Appl. Sci. 12 (2022) 7249, https://doi.org/10.3390/APP12147249.
[49] P. Srivastava, A. Rimzhim, P. Vijay, S. Singh, S. Chandra, Desktop VR is better than non-ambulatory HMD VR for spatial learning, Front. Robotics and AI 6 (2019), https://doi.org/10.3389/frobt.2019.00050.
[50] D. Paes, J. Irizarry, D. Pujoni, An evidence of cognitive benefits from immersive design review: comparing three-dimensional perception and presence between immersive and non-immersive virtual environments, Autom. Constr. 130 (2021), https://doi.org/10.1016/j.autcon.2021.103849.
[51] D. Paes, E. Arantes, J. Irizarry, Immersive environment for improving the understanding of architectural 3D models: comparing user spatial perception between immersive and traditional virtual reality systems, Autom. Constr. 84 (2017) 292–303, https://doi.org/10.1016/j.autcon.2017.09.016.
[52] B. Han, F. Leite, Measuring the impact of immersive virtual reality on construction design review applications: head-mounted display versus desktop monitor, J. Constr. Eng. Manag. 147 (2021) 04021042, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002056.
[53] J. Zhao, P. LaFemina, J. Carr, P. Sajjadi, J.O. Wallgrun, A. Klippel, Learning in the Field: Comparison of Desktop, Immersive Virtual Reality, and Actual Field Trips for Place-Based STEM Education, 2020, pp. 893–902, https://doi.org/10.1109/VR46266.2020.00012.
[54] R.A. Ruddle, P. Péruch, Effects of proprioceptive feedback and environmental characteristics on spatial learning in virtual environments, Int. J. Human-Computer Studies 60 (2004) 299–326, https://doi.org/10.1016/J.IJHCS.2003.10.001.
[55] K. Kim, M.Z. Rosenthal, D.J. Zielinski, R. Brady, Effects of virtual environment platforms on emotional responses, Comput. Methods Prog. Biomed. 113 (2014) 882–893, https://doi.org/10.1016/J.CMPB.2013.12.024.
[56] T.M. Porcino, E. Clua, D. Trevisan, C.N. Vasconcelos, L. Valente, Minimizing cyber sickness in head mounted display systems: Design guidelines and applications, in: 2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH), IEEE, 2017, pp. 1–6, https://doi.org/10.1109/SeGAH.2017.7939283.
[57] C. Boletsis, The new era of virtual reality locomotion: a systematic literature review of techniques and a proposed typology, Multimodal Technol. Interact. 1 (2017), https://doi.org/10.3390/mti1040024.
[58] J. Guna, G. Geršak, I. Humar, M. Krebl, M. Orel, H. Lu, M. Pogačnik, Virtual reality sickness and challenges behind different technology and content settings, Mobile Netw. Applicat. 25 (2020) 1436–1445, https://doi.org/10.1007/S11036-019-01373-W/METRICS.
[59] I. Karaseitanidis, A. Amditis, H. Patel, S. Sharples, E. Bekiaris, A. Bullinger, J. Tromp, Evaluation of virtual reality products and applications from individual, organizational and societal perspectives—the "VIEW" case study, Int. J. Human-Computer Studies 64 (2006) 251–266, https://doi.org/10.1016/J.IJHCS.2005.08.013.
[60] L. Rebenitsch, C. Owen, Review on cybersickness in applications and visual displays, Virtual Reality 20 (2016) 101–125, https://doi.org/10.1007/S10055-016-0285-9/METRICS.
[61] G. Makransky, T.S. Terkildsen, R.E. Mayer, Adding immersive virtual reality to a science lab simulation causes more presence but less learning, Learn. Instr. 60 (2019) 225–236, https://doi.org/10.1016/J.LEARNINSTRUC.2017.12.007.
[62] C. Chokwitthaya, Y. Zhu, W. Lu, Ontology for experimentation of human-building interactions using virtual reality, Adv. Eng. Inform. 55 (2023), https://doi.org/10.1016/j.aei.2023.101903.
[63] J. Zhao, T. Sensibaugh, B. Bodenheimer, T.P. McNamara, A. Nazareth, N. Newcombe, M. Minear, A. Klippel, Desktop versus immersive virtual environments: effects on spatial learning, Spat. Cogn. Comput. 20 (2020), https://doi.org/10.1080/13875868.2020.1817925.
[64] S. Cao, L. Fu, P. Wang, G. Zeng, W. Song, Experimental and modeling study on evacuation under good and limited visibility in a supermarket, Fire Saf. J. 102 (2018), https://doi.org/10.1016/j.firesaf.2018.10.003.
[65] R. Lovreglio, A. Fonzone, L. dell'Olio, D. Borri, A study of herding behaviour in exit choice during emergencies based on random utility theory, Saf. Sci. 82 (2016), https://doi.org/10.1016/j.ssci.2015.10.015.
[66] ChoiceMetrics, Ngene 1.4 User Manual & Reference Guide. www.choice-metrics.com, 2024.
[67] A. Rahouti, R. Lovreglio, S. Datoussaïd, T. Descamps, Prototyping and validating a non-immersive virtual reality serious game for healthcare fire safety training, Fire. Technol 57 (2021), https://doi.org/10.1007/s10694-021-01098-x.
[68] R. Lovreglio, V. Gonzalez, Z. Feng, R. Amor, M. Spearpoint, J. Thomas, M. Trotter, R. Sacks, Prototyping virtual reality serious games for building earthquake preparedness: the Auckland City Hospital case study, Adv. Eng. Inform. 38 (2018) 670–682, https://doi.org/10.1016/j.aei.2018.08.018.
[69] J. Cohen, Statistical power analysis for the behavioral sciences, Routledge, 2013, https://doi.org/10.4324/9780203771587.
[70] M.J. Akhtar, I.B. Utne, Human fatigue's effect on the risk of maritime groundings - a Bayesian network modeling approach, Saf. Sci. 62 (2014) 427–440, https://doi.org/10.1016/j.ssci.2013.10.002.
[71] S. Fan, E. Blanco-Davis, Z. Yang, J. Zhang, X. Yan, Incorporation of human factors into maritime accident analysis using a data-driven Bayesian network, Reliab. Eng. Syst. Saf. 203 (2020) 107070, https://doi.org/10.1016/J.RESS.2020.107070.
[72] J. Diemer, G.W. Alpers, H.M. Peperkorn, Y. Shiban, A. Mühlberger, The impact of perception and presence on emotional reactions: a review of research in virtual reality, Front. Psychol. 6 (2015), https://doi.org/10.3389/fpsyg.2015.00026.