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Review

Characterization and future perspectives of Virtual Reality Evacuation Drills for safe built environments: A Systematic Literature Review

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ABSTRACT

Physical evacuation drills are pre-planned activities to train building occupants in facing emergencies and evaluate safety performances. Nowadays, technologies including Virtual Reality (VR) and Immersive Virtual Reality (IVR) are shifting from the *physical* to the *virtual* paradigm. AR enables just to extend real-world environment, while VR and IVR allow to (re)create and manipulate digital environments. VR and IVR simulation systems have been observed to guarantee higher involvement and long-term information retention — leveraging more attractive experiences and psychological arousal. However, efforts should be provided to improve end-user training while assessing occupants' behaviors and the effectiveness of the emergency plan. This paper proposes a systematic literature review of VR and IVR evacuation solutions. To support and guide such effort, we formulated thirteen structured research questions investigating scenarios, recipients, requirements, objectives, methods, and technologies. The results mainly show that VR and IVR drills almost entirely tackle a single hazard, considers occupants as sole system recipients, and lack systems formalization. Among the most relevant outcomes, the paper analyzes the need for enhancing the modeling of emergency systems (e.g., signage, alarms), user inclusiveness (i.e., impaired individuals), devices, non-player characters, and additional effects (e.g., heat reproduction, sounds, and smells). These measures can improve the level of realism experienced by the user of IVR simulators and pave the way to more reliable outcomes.

1. Introduction

Evacuation drills represent one of the most common and significant activities to train and educate about disaster/hazards in the built environments — either single buildings, neighborhoods, or urban area (Gwynne et al., 2020; Kwegyir-Afful, 2022). They aim at training different typologies of occupants to face emergency conditions according to their roles, emergency procedures, and depending on the considered disaster scenario (Gwynne et al., 2020; Abir et al., 2022; Kinateder et al., 2021a; Shi et al., 2021). In particular, they can undertake specific tasks, such as identifying possible risk and safety elements, performing individual safety procedures, selecting the proper routes to reach an assembly area, assisting vulnerable occupants (for the staff), and hazards damage containment (for firefighters and rescuers). Drills are also widely used to assess the safety performances of emergency procedures also in relation to the built environment features and the adopted risk-mitigation strategies (e.g., by evaluating response and evacuation times and the order of performed actions) (Gwynne et al., 2020; Abir et al., 2022; Kinateder et al., 2021a; Yoshida, 1995; Çğdaş and Sağlamer, 1995). Thus, evacuation drills are widely recognized as significant educational support in becoming familiar with the built environments and the hazard-related procedures (when possible) besides just facing possible real-world critical situations (Gwynne et al., 2020; Ramachandrail, 1985; Villagràn de León, 2006; Lin et al., 2020a; van der Wal et al., 2021; Lin et al., 2020c; Leder et al., 2019).

Many countries provide guidelines and drill-based training for several kinds of disasters in buildings (e.g., earthquake hazards)[1]

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[1] E.g., for US, https://www.osha.gov/earthquakes/preparedness; for New Zealand (MCDEM, 2015); for Canada, https://www.iclr.org/wp-content/uploads/PDFS/earthquake-planning-for-business.pdf; for Greece, https://www.oasp.gr/userfiles/Earthquakes%20and%20Workplaces_final.pdf.

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(Bernardini et al., 2019), requirements of national safety regulations and building codes support the definition of evacuation drills, by mainly orienting their adoption in the field of fire hazards, and in coordination with fire evacuation plans (Gwynne et al., 2020; Kwegyir-Afful, 2022).

In most cases, in-building fire drills stage an emergency, activating the fire alarm system and entailing the evacuation through the nearest or the most familiar exit/safest route. The procedures of the exercise change depending on variables such as the scope of the building (i.e., supermarket, school, or hospital) and its physical dimension (single house, apartment building, or skyscraper). Nevertheless, since drills are "models" of emergency conditions, the efficiency of the evacuation process can be affected by biases and oversimplifications of real-world situations (i.e., oversimplification of getting to safety/leaving the building, reaching a meeting point, and of the actual environmental conditions) (Gwynne et al., 2020; Yoshida, 1995; Lin et al., 2020c; Shih et al., 2000). Indeed, conventional emergency drills are often done outside of normal/peaks business hours to minimize the risks for occupants and costs for business continuity (in terms of both monitoring devices/human resources and loss of services supply) (Kinateder et al., 2021a; Gwynne et al., 2019), thus simplifying the tests and reparations if needed. Too often, vulnerable and fragile groups (i.e., individuals with medical issues or physically impaired (Lally and Crome, 2007; Pel-Littel et al., 2009)) are not considered/involved in the tests. Nevertheless, their engagement should be a priority, in light of their risk exposure exacerbated by their specific features/needs (Tancogne-Dejean and Laclémence, 2016). A further limitation is the inconsistent and/or partial data collection during the emergency physical drills, often due to the lack of systematic and objective data collection methods (Kinateder et al., 2021b). The results obtained by such studies provide a limited understanding of the drills and the ability to compare them and assess whether the exercises constitute a valid evacuation model (Kinateder et al., 2021b). Moreover, previous works point out the limited evidence of lasting benefits, given the high contrast between testing scenarios and real-world (Gwynne et al., 2020; van der Wal et al., 2021; Bernardini et al., 2019). Virtual Reality (VR) systems are composed of monitors (displays) rendering the environment in which the user can operate through the use of joysticks or a keyboard/mouse (like in video games). Immersive Virtual Reality (IVR) immerses the user in the environment through dedicated devices such Head-Mounted Displays (i.e., Oculus Lovreglio et al., 2018) or Cave Automatic Virtual Environment (i.e., CAVE Ronchi et al., 2015), which are capable of providing a fully immersive 360-degree view of the environment. This innovative technologies such as VR and IVR have been identified to cope with the challenges mentioned above and possibly improve the planning capabilities, exercise observation, and analysis of tests highly consistent with semi-realistic hazards (Shi et al., 2021; Lin et al., 2020c; Feng et al., 2018; Kinateder et al., 2014; Kinateder and Warren, 2016; Zhang et al., 2020; Li et al., 2018; Paes et al., 2021; Feng et al., 2021). Furthermore, the employment of VR and IVR outlines potential cost reductions, improved long-term training effectiveness, and a more accurate assessment of occupant behavior. In the last two decades, IVR has been increasingly adopted and accessible as a training and assessment tool in view of its application sustainability and feasibility (Shi et al., 2021; Feng et al., 2021; Quagliarini et al., 2021; Lovreglio et al., 2017; Fu et al., 2021; Xu et al., 2020; Natapov et al., 2022). Studies such as Gwynne et al. (2020) have pointed out that the cost-effectiveness of training tools promotes their adoption for both individual and group tests. To this end, they can be easily combined with serious game approaches (Feng et al., 2018; Solinska-Nowak et al., 2018). Moreover, VR and IVR allow to not disrupt the workplace's productivity and, most importantly, engage the users emotionally. They can also be employed to test the effectiveness of different emergency systems, including the ones relating to wayfinding tasks as one of the fundamental issues in evacuation (Lin et al., 2020a; Feng et al., 2021; Chen et al., 2021; Kubota et al., 2021; Dubovi, 2022).

VR and IVR can enhance automatized design and evaluation of building safety procedures, avoiding unnecessary implementation in real-world settings, thus possibly reducing resource waste (Zhang et al., 2020; Li et al., 2018).

Indeed, the studies on VR and IVR have skyrocketed in the last decade, focusing on individual features, related solutions, methodologies, techniques, and both single-hazards and multi-hazard settings. According to UNRR, "hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potentially interrelated effects" (UNDRR, 2020). However, as of today, studies on VR/IVR environments for safety drills still show restrictions, limitations, and lacks.

This work aims to update previous literature reviews on the matter (Feng et al., 2018) and widen the characterization of methods, techniques, and tools to perform VR and IVR drills. In particular, it proposes a Systematic Literature Review (SLR) (conducted in January 2022) adhering to the rigorous and reproducible methodology proposed by Kitchenman (Kitchenham and Charters, 2007) as extended and amended by Calvaresi et al. (2017). Starting from the general remarks of previous works on VR and IVR based approaches (Gwynne et al., 2020; Kwegyir-Afful, 2022; Shi et al., 2021; van der Wal et al., 2021; Tancogne-Dejean and Laclémence, 2016; Feng et al., 2018; Paes et al., 2021; Quagliarini et al., 2021), this work leverages 13 structured research questions addressing topics including involved research institutes, contributions' abstraction level, application scenario, intended recipients characterization (i.e., user health conditions, initial position, environmental knowledge, etc.) perspective (i.e., user's point of view), and non-player characters, systems' requirements and objectives, systems assessment/analysis methods, technologies, strengths, limitations, and future challenges of single and multi-hazard VR and IVR simulation systems.

The rest of the paper is structured as follows: Section 2 describes the SLR methodology. Section 3 presents and analyzes the results. Section 4 discusses the information elicited from the aggregated data. Finally, Section 5 concludes the paper.

2. Methodology

Fig. 1 schematizes the SLR methodology characterizing this study. It composes of three main activities, including (a) planning the review – definition of the general and structured research questions, (b) performing the review – location, selection, and analysis of relevant articles, and (c) documenting the review – aggregation, discussion, and documentation of the obtained results. Hereafter, the elaborated research papers are referred to as primary studies.

Following the Goal-Question-Metric (GQM) approach, we set the generic free-form question (GQ) as follows:

GQ : How are VR and IVR solutions for (multi-)hazard drills characterized, and what have they achieved?

Such a GQ has been decomposed into the following 13 structured research questions (SQR).

Demographics. To investigate the distribution of interest in single/multi-hazard virtual simulators (in terms of time, country, and institutes), we set the following question.

SRQ1: How time- and geographic-wise are the research efforts distributed? i.e., when (year) and where (the geographical indication of the scientific institute).

Abstraction. To understand the nature of the contribution conveyed by the primary studies, we set the following question.

SRQ2: What is the abstraction level of the elaborated scientific contributions?
(i.e., conceptual (C), prototype (P), or tested (T)).

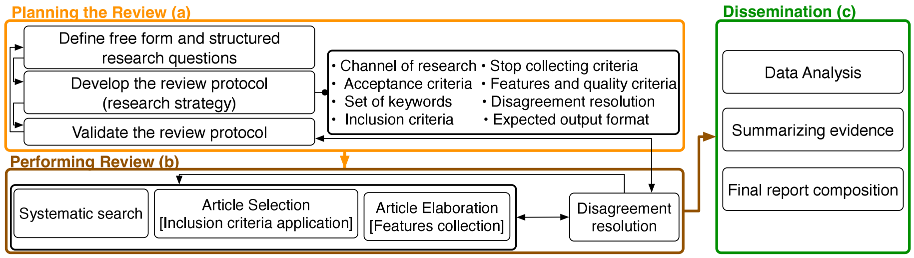

Fig. 1. Systematic literature review methodology schema.
Source: Adapted from Anjomshoae et al. (2019).

Application scenarios. To understand the context and domain of the primary studies, we set the following question.

SRQ3: In which areas and settings have the users' behaviors been simulated via VR and IVR? (e.g., structures, open spaces, etc.)

Recipients. To analyze the beneficiary and subject involved in the studies, we set the following question.

SRQ4 (A): Who are the users considered within the VR and IVR simulators/studies?

Secondary Actors. To evaluate the possible involvement of other subjects implicated in the research, we set the following question.

SRQ4 (B): What are the classes of the secondary users or non-player characters (NPC) considered in the VR and IVR simulators/studies?

Requirements. To formalize and cluster the needs expressed by the studies with respect to (w.r.t.) recipients, environments, hazards, and interactions, we set the following questions.

SRQ5: Which requirements have been defined for the recipient(s), environment(s), (multi-)hazard interactions, and level of stress, within the investigated systems?

Objectives. To understand the primary studies' directions, we set the following question.

SRQ6: What are the goals set by the elaborated studies? (i.e., evaluation, training, entertaining, etc.)

Methods, user characterization, and perspectives. To understand the methodologies & techniques, and recipients characterization employed by the elaborated studies, we set the following questions.

SRQ7 (A): What are the methodologies/techniques used in the case study?
SRQ7 (B): User characterization. What are the users' cognitive/physical/motor skills used in the case study?
SRQ7 (C): What are the users' approaches/perspectives (first or third-person) through the virtual reality used in the case study?

Technology and interfaces. To understand which technologies and related interfaces have been employed, as well as user behaviors w.r.t. to them, we set the following question.

SRQ8: Which are the technologies employed in the researches (VR or IVR) (e.g., monitors, Oculus, smartphones, …), and how are the replated interfaces characterized?

Analysis methodologies. To assess the evaluations performed by the primary studies, we set the following question.

SRQ9: How have the results been analyzed?

Strengths. To elicit the advantages/benefits provided by the primary studies, we set the following question.

SRQ10: What are the benefits produced by the primary studies?

Limitations. To acknowledge the drawbacks of the existing systems and facilitate further research, we set the following question.

SRQ11: What are the limits/barriers/uncertainties raised by the primary studies?

Solutions. To understand how the primary studies' authors have dealt with the known limitations (if mentioned), we set the following question.

SRQ12: Which are the solutions to the stated limitations proposed by the primary studies?

Future Challenges. To unveil the ongoing/envisioned research directions of the primary studies' authors, we set the following question.

SRQ13: What challenges are awaited by the authors of the primary studies?

The selected research channels (web crawler) include google scholar, IEEE Xplore, Elsevier. The semi-automatic search through them has been performed querying the following list of keywords keeping the keyword "Virtual Reality" as the root of contextualization: Virtual reality AND (hazard simulation OR evacuation OR multi-hazard simulation OR simulator OR users' behavior/behaviour OR hazard OR users' behavior/behaviour OR multi-hazard).

The initial collection counted ∼ 1400 articles. According to the SLR methodology (Calvaresi et al., 2017), such a batch has been coarse-grain filtered by applying the following seven *selection criteria* to the papers' abstract:

(A) Relevance & Technologies: The paper must employ VR technologies for evacuation and hazard response.
(B) Primary Study: Only papers providing a direct contribution to VR (e.g., models, architectures, implementations, or tests) are included. Secondary studies (i.e., surveys) are excluded.
(C) Accessibility: To be included, the article's content should be accessible via one of the portals mentioned above.
(D) Singularity/Originality: Duplicates or papers that have been extended are discarded, including only the extended/complete version.
(E) Contribution characterization: the study must provide theories, frameworks, or tests relevant to the study.
(F) Behavioral assessment: In the context of VR and IVR-based simulators, the papers must address human behavior during the evacuation drill.
(G) Environment: The setting object of the study must be related to the built environment or open spaces in the proximity of built environments (possibly tangent to built or elements directly affected by hazards).

Applying such criteria cut down the papers to approximately 100. Nevertheless, for some studies, processing the sole abstract did not allow an explicit "inclusion/exclusion". Such ambiguity has been shed by fast reading the papers' body which has set to 37 the number of relevant articles composing the set to be analyzed.

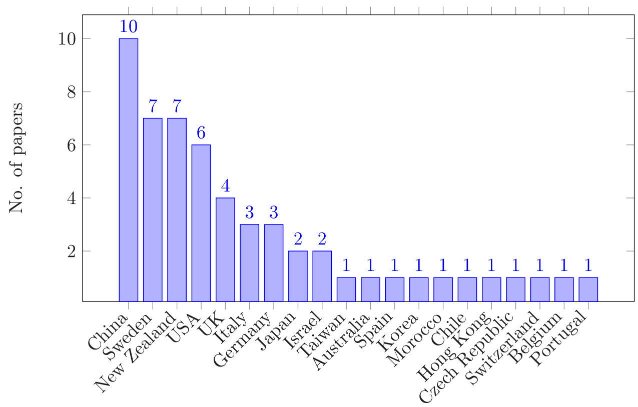

Fig. 2. Number of primary studies per country of publication.

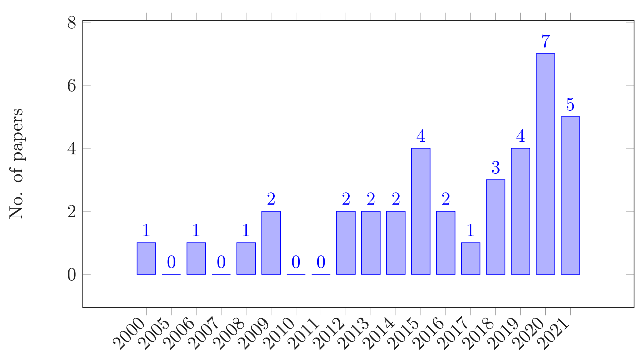

Fig. 3. Number of primary studies per year.

3. Results

3.1. SRQ1: Demographics

Fig. 2 and Fig. 3 show, respectively, the geographic and chronological distribution of the analyzed works. It is noticeable that the most economically developed countries are leading the research on VR and IVR-based systems for emergency scenarios (i.e., China, Sweden, USA and Italy, Germany, and Japan). It is worth highlighting that 15 out of 37 papers represent collaborations between two or more countries, which have been evenly counted for fairness. From a timing perspective, while European countries and the US had a steadily growing trend in terms of publication between 2010 and today, China's contribution peaked in the biennium 2019–2021. Looking at the universities invested in the topic, it is noticeable that most of the studies are carried out by Massey University for New Zealand (4 papers), University of Würzburg (3 papers), Tsinghua University for China, and Lund University for Sweden (7 papers each). Furthermore, while all the studies are carried out by at least one university, seven of them have been conducted in collaboration with private or public companies and institutes. The number of selected papers seems to grow exponentially over the years, with a remarkable inclination from 2012 and a surge in the last two years. Indeed, 86% of the papers have been written after 2012. A possible reason can be the accessibility (technology- and cost-wise) of the IVR technology – although it dates back to the late 80 s.

3.2. SRQ2: Abstraction

The contributions are classified as conceptual (C), prototype frameworks/architectures with no explicit analysis (P), and clearly tested frameworks and architectures with results/analysis included (T). To this end, two studies are conceptual, five present prototypes, and thirty studies propose tests and results. It is appreciable that this field of scientific research is applied and strives to cope with real-world challenges. Indeed, having 81% (see Fig. 4) of the papers presenting tests and concrete applications for hazard drills via VR and IVR can suggest the maturity of the approach(es) and an increasing level of reliability of VR and IVR technologies (see Table 1).

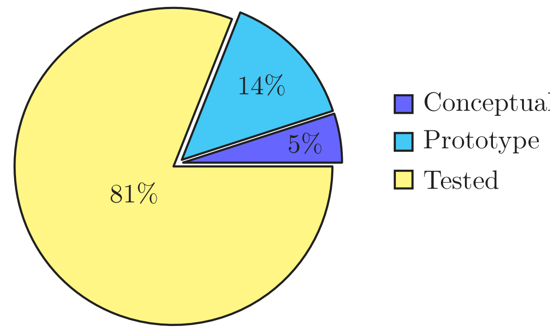

Fig. 4. Typologies of abstraction according to the primary studies and related frequency percentages.

Table 1
Primary studies organized by typologies of abstraction.

Abstraction	Papers
Conceptual	Uno and Kashiyama (2008), Sharma et al. (2014)
Prototype	Lovreglio et al. (2018), Kwok et al. (2019), Cha et al. (2012), Ren et al. (2006), Rahouti et al. (2017)
Tested	Shih et al. (2000), Ronchi et al. (2015), Xu et al. (2014), Tucker et al. (2018), Kinateder et al. (2015), Smith and Ericson (2009), Cavalcanti et al. (2021), Lu et al. (2020), Bourhim and Cherkaoui (2020), Mossberg et al. (2021), Cao et al. (2019), Lin et al. (2020b), Feng et al. (2020a), Zhang et al. (2021), Fujimi and Fujimura (2020) Arias et al. (2021), Farra et al. (2019), Andrée et al. (2016), Snopková et al. (2021), Arias et al. (2019), Feng et al. (2020b), Cosma et al. (2016), Chittaro and Ranon (2009), Meng and Zhang (2014), Chittaro and Sioni (2015), Silva et al. (2013), Kinateder et al. (2013), Shaw et al. (2019), Xia et al. (2021), Ronchi et al. (2016)

3.3. SRQ3: Application scenarios

The elaborated studies targeted multiple applications. Fig. 5 shows the characterization of the three scenarios' macro areas, which include buildings, tunnels, and stations. The main differences between the three classes are the geometric characterization (i.e., size and complexity of the plan), the interactions (i.e., following predetermined paths (Smith and Ericson, 2009; Lu et al., 2020; Cao et al., 2019), extinguish fires (Cha et al., 2012; Ren et al., 2006; Cavalcanti et al., 2021; Bourhim and Cherkaoui, 2020), grabbing and handling various scene's objects (Rahouti et al., 2017; Bourhim and Cherkaoui, 2020; Feng et al., 2020a; Snopková et al., 2021; Arias et al., 2019; Chittaro and Ranon, 2009), and simply opening doors (Zhang et al., 2021; Arias et al., 2021; Andrée et al., 2016)), and the (un)familiarity with the environment (i.e., workers vs. clients aware or not about the environment conformation). Moreover, it is possible to distinguish the scenarios

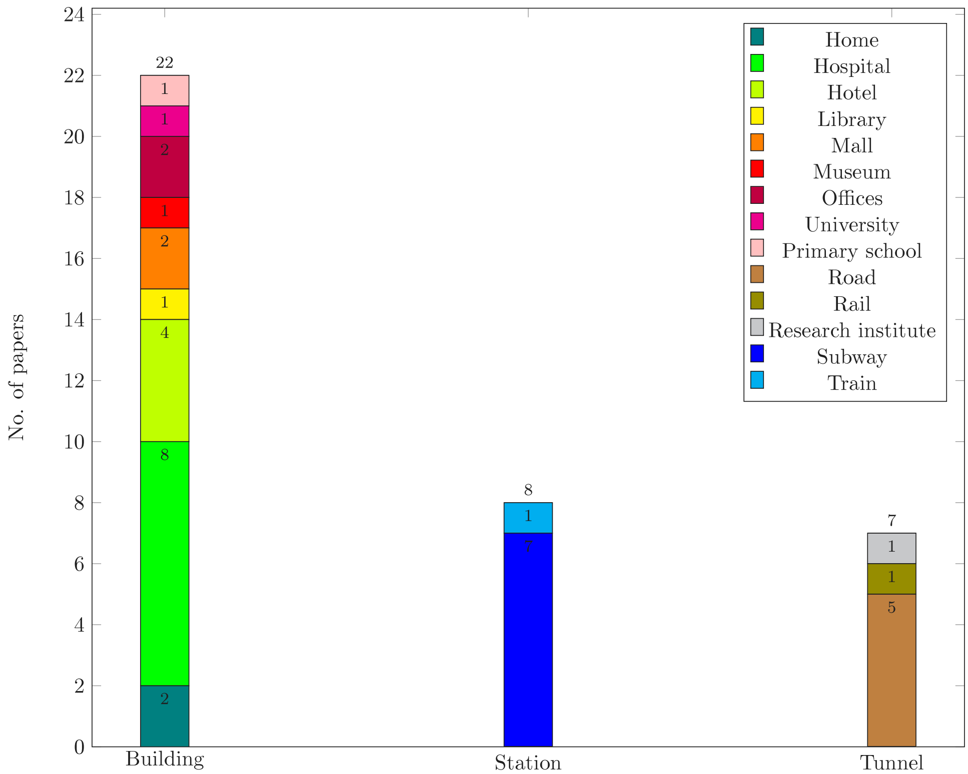

Fig. 5. Number of primary studies depending on the application Domains, by including differences with respect to specific intended uses.

within the main classes based on the intended use. For example, the "building" category includes nine different environments.

More than half of the studies (59%) has studied emergency scenarios through the use of VR in buildings, (22%) have focused on metro or railway stations, and the remaining (19%) on tunnels. The research institute was placed in the tunnel category with respect to tunnels because the paper (Arias et al., 2019) deals with CERN, a research institute having tunnel-like architectural features, although it has a different function than vehicular or rail-trail traffic. Within the buildings category, most of the studies targeted hospitals and hotel environments. Within the station category, subway stations got most of the attention. Such choices suggest that the possible factors categorizing the scientific interest include (i) presence of ill/sensitive people, (ii) possibly overcrowded spaces, and (iii) limited knowledge about the surroundings.

3.4. SRQ4 (A): Recipients

The main actors considered in the elaborated studies can be in seven main classes, which are, of course, related to the intended use of the building (see Fig. 6). In particular, the occupants – recipient of the systems – are home residents, staff, students and professors, firefighters, visitors, drivers, and customers. This latter can be characterized as "people purchasing goods/services from a store or business" with limited knowledge of the surrounding. The class customers is composed of: housing guests – mainly present hostelry scenarios (Arias et al., 2021; Andrée et al., 2016; Snopková et al., 2021; Meng and Zhang, 2014), shoppers – mainly present in supermarkets (Shih et al., 2000; Anjomshoae et al., 2019; Zhang et al., 2021) and libraries (Tucker et al., 2018), and travelers – mainly present in subway stations (Sharma et al., 2014; Ren et al., 2006; Xu et al., 2014; Mossberg et al., 2021; Lin et al., 2020b; Xia et al., 2021).

Unlike customers, visitors are defined as people who visit someone or somewhere, mainly socially (e.g., tourists). This category is preeminent in hospitals as they are intended to be relatives or acquaintances of patients inhabiting the facility (Rahouti et al., 2017; Feng et al., 2020a,b). In turn, patients are the individuals occupying the facility and receiving medical care. Their knowledge of the surrounding might be higher w.r.t. the visitors. However, their functional capacity must be considered dramatically inferior. The scenarios' personnel include hospitality, medical, and possibly surveillance staff. They are considered to have a discrete knowledge of the environment and possibly play a role in the evacuations (Rahouti et al., 2017; Feng et al., 2020a; Farra et al., 2019; Feng et al., 2020b; Silva et al., 2013). Finally, firefighters are key players in the training and education case studies. They are in charge of mitigating the hazards (i.e., extinguishing the fire or reducing the flooding) and supporting the evacuation of the endangered occupants (Xu et al., 2014; Smith and Ericson, 2009; Lu et al., 2020). Drivers (people who drive a vehicle) are the key players for the road tunnel scenarios (Ronchi et al., 2015; Kinateder et al., 2015; Cosma et al., 2016; Kinateder et al., 2013; Ronchi et al., 2016). Students and professors are the "personnel" primarily endangered in schools and universities setups (Chittaro and Ranon, 2009), libraries (Tucker et al., 2018), and museums (Cao et al., 2019). Finally, home residents are persons inhabiting an environment permanently or for long-terms (Uno and Kashiyama, 2008; Bourhim and Cherkaoui, 2020; Fujimi and Fujimura, 2020),

Overall, it is possible to assert that most of the recipients of the elaborated studies are people who use services or buy goods, who therefore have (at least) limited knowledge of the environment in which they have been tested.

3.5. SRQ4 (B): Secondary actors

Besides the primary "player/user", eight studies (27%) involve secondary actors as NPCs in the scene. The NPC belong to the same categories characterizing the primary actors (see Fig. 7). Their initiatives, actions, emotions, and plans are hard-coded or delegated to AI engines. Although the NPC's "intelligence" might not be outstanding in all the implementations, their presence already ensures a more realistic immersive environment and experience (given the almost always

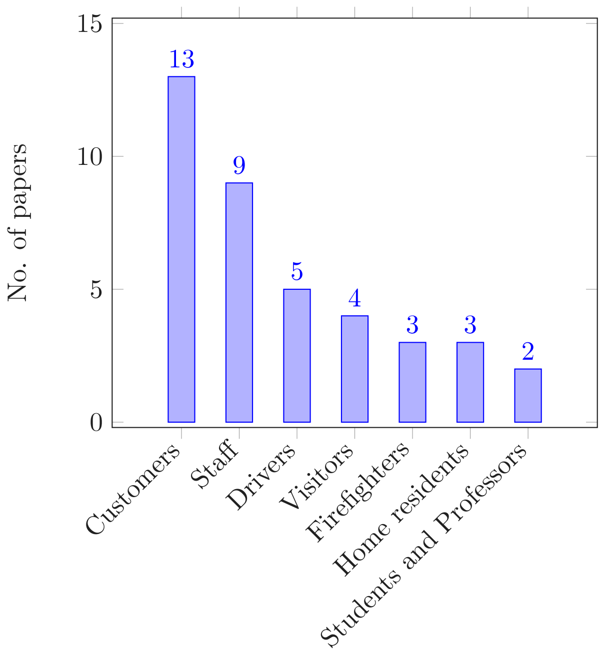

Fig. 6. Number of primary studies with respect to the classes of Recipients.

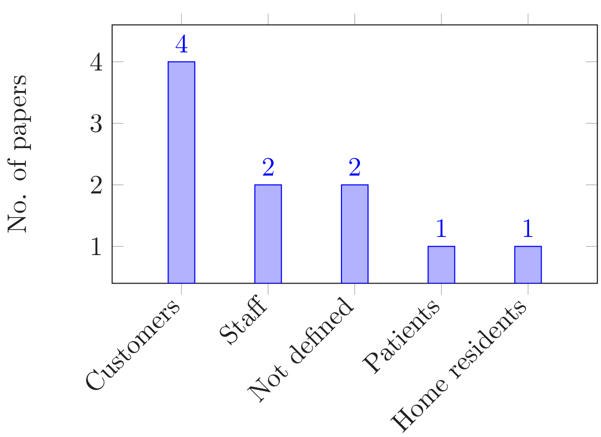

Fig. 7. Number of primary studies considering the NPC's presence and their typology.

crowded nature of the studied environments). The most represented category by the NPC is the occupants, followed by the others, thus following the same classes of Fig. 6, as discussed for SRQ4(A). Two studies (Lovreglio et al., 2018; Shaw et al., 2019) instead report the presence of NPCs without otherwise specifying their role in the scene.

3.6. SRQ5: Requirements

The requirements characterizing the studies affect the recipients, environments, type of hazard involved on the scene, interactions with the environment and NPCs, and stress level within the system. The most common requirement is the user's starting point (either inside/outside the building), which can be part of a user's routinely circulation within/around the building, and an ending point (either inside the building – yet an area declared safe – or outside the building) in emergency conditions (i.e. evacuation). All the primary studies confer all users an optimal visual capacity (neglecting any user-related impairments). The only factors harming their visibility are (multi-)hazard-related (e.g., fire/flash flood/earthquake/terror attack). Concerning the anxiety and stress level assessment (via sensors or survey after drills), eleven articles explicitly specific technologies — detailed in SRQ7(A).

The familiarity (or not) with the environment, and so also the knowledge of the procedures and evacuation routes, is the only transverse requirement concerning the user, which associates all the studies (see Fig. 8), as also discussed for SQR4(A). In particular, (35%) of the studies (13) assumed full/partial knowledge of the built environment, given their possible familiarity with it. To ensure compliance with such a requirement, the users have been asked to practice and get confident with the virtual environment before executing the test. Conversely, (22%) of the studies (8) imposed no prior knowledge of the environment. The papers not explicating environmental requirements for the users are (27%) (10 studies). Three studies (8%) limited the knowledge assumption solely to staff members, not conferring any information to the visitors. These studies are set in hospital environments, thus leveraging the assumption that medical staff is more familiar with the environment than patients' relatives (Rahouti et al., 2017; Feng et al., 2020a,b). Finally, three studies (8%) divide the users into teams: the control group (no proper knowledge of the environment) and the treatment one (environmental awareness, e.g., through the use of test scene plans and detailed escaping info) to analyze any differences in data collection during the test (Cao et al., 2019; Chittaro and Sioni, 2015; Kinateder et al., 2013).

The environmental requirements have mostly been treated implicitly (see Fig. 9. Indeed, the majority (12 studies) lack any formalization. Some studies mention the presence of alarm systems and emergency signage among the default settings. In particular, 3 studies present only emergency signage (Zhang et al., 2021; Snopková et al., 2021; Cosma et al., 2016), while 2 studies mention only alarm systems (Fujimi and Fujimura, 2020; Silva et al., 2013). Eleven studies present a combination of alarm systems and emergency signage. In real-world settings, these two components are both present in buildings to ensure efficiency during the evacuation process.

Fire is the leading cause of accident and death for building occupants, essentially because risk assessment and mitigation tasks concerning this hazard are well codified by regulations which also widely include fire and evacuation training, as well as emergency planning as a priority task for building safety all over the World. Indeed, among the hazards investigated, fire is the most prevalent (59%), possibly combined with earthquakes (3%) (see Fig. 10). In the elaborated studies, fire is characterized as a static element in a given point without any or very limited propagation. Earthquakes are characterized as a shaking scene with, possibly, falling and breaking furniture and elements of the scene (Lovreglio et al., 2018). Floodings (5%) are characterized as a "simil-liquid" rising its level and filling a given room/area. Terrorist attacks (3%) are characterized as accidental and unpredictable explosions.

However, in 19% of the studies, the user has not been given any information about the hazard. The only indications have been to "find a way out and get safe". The hazards in such cases are represented by the activation of alarm sirens or voices.

Overall, although some elements of the environments, users, and interactions have been (in)directly mentioned, there is a lack of formalization and alignment among the studies. This harms an extensive characterization, extendibility, and comparison among the VR and IVR systems for emergency drills.

Although the level of stress is highly influencing the decision-making process under pressure, 16 studies (43%) do not address its characterization explicitly (see Fig. 11). Fourteen studies (38%) identify smoke as the most relevant element connected to the users' stress. Indeed, smoke is the first factor of death (by asphyxiation) and the main obstacle placed along the building layout. Therefore, having a realistic representation of smoke spreading in the built environment is crucial in both terms of graphics and dynamics. The obstacles are also required to be physical such as books, ceiling panels, office equipment, furniture, and exhibition elements present in museums. On the one hand, some studies limit their settings to ground obstacles (Lovreglio et al., 2018; Bourhim and Cherkaoui, 2020; Feng et al., 2020a,b). On

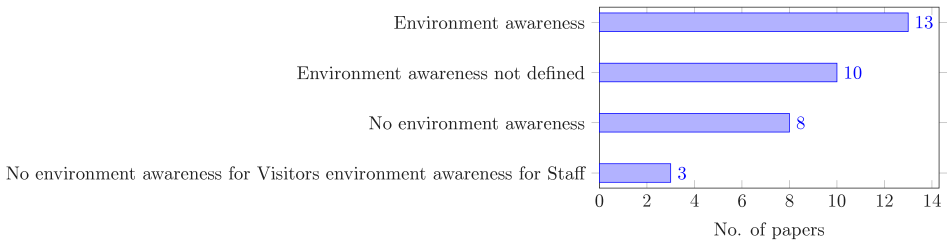

Fig. 8. Number of primary studies considering the typologies of recipients requirements.

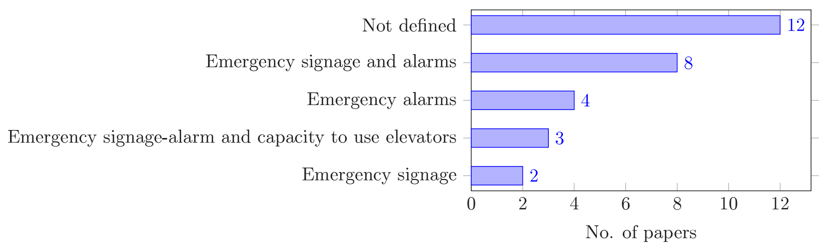

Fig. 9. Number of primary studies considering the typologies of environment requirements.

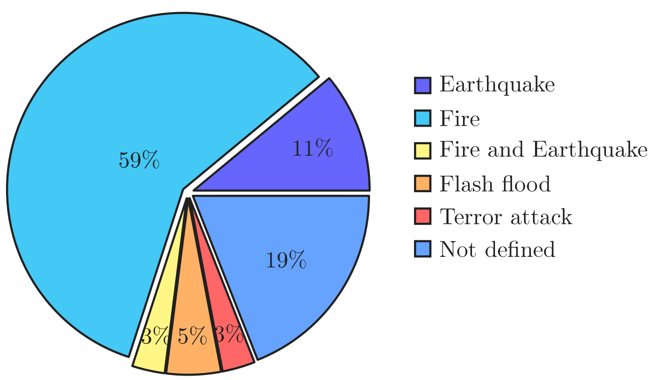

Fig. 10. Percentage of hazards considered in the primary studies.

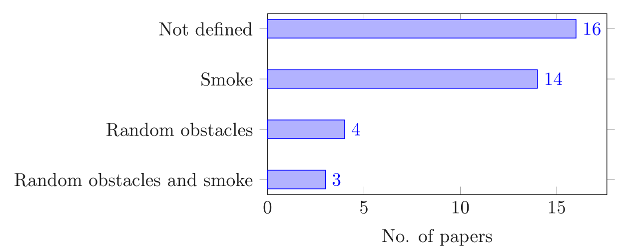

Fig. 11. Number of primary studies considering environmental stressors due to the hazard and the built environment modifications.

the other hand, more sophisticated studies combine obstacles on the floor with smoke (Tucker et al., 2018; Lu et al., 2020; Cao et al., 2019).

The interactions between users and the environment have different natures and complexity. For example, players can extinguish fire (Cha et al., 2012; Ren et al., 2006; Cavalcanti et al., 2021; Bourhim and Cherkaoui, 2020), or grab and handle scene's objects (Rahouti et al., 2017; Bourhim and Cherkaoui, 2020; Feng et al., 2020a; Snopková et al., 2021; Arias et al., 2019; Chittaro and Ranon, 2009; Shaw et al., 2019), and simply follow predefined rescue/safety paths and open doors (features in common among all the studies).

Finally, the interactions between the main player and the NPC(s) are shaped as:

- The player is surrounded by a crowd (of NPCs). The sole interaction is the body-bumping and freedom of movement reduction, using simple movement algorithms (Lovreglio et al., 2018; Lin et al., 2020b; Shaw et al., 2019; Xia et al., 2021).
- The NPCs can provide useful information (audio or displaying text on the screen/visor) supporting the evacuation process (Tucker et al., 2018; Feng et al., 2020a,b).

3.7. SRQ6: Objectives

Twelve analyzed studies (32%) aim at evaluating the user behaviors when facing dangerous scenarios in VR and IVR. Thus, maximizing immersiveness and realism of the environment created are priorities. Therefore, they seek to detect the danger perception and understand the consequent undertaken actions. The remaining 25 papers (68%) target the behavioral (the outstanding objective) and technical analysis.

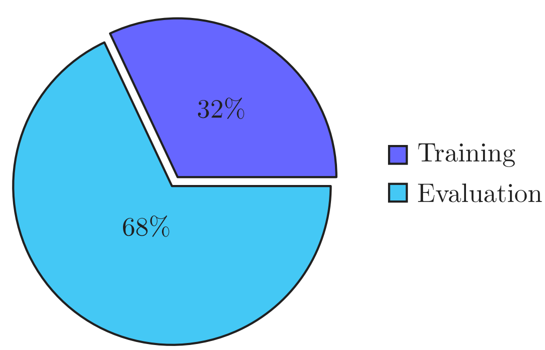

Fig. 12. Percentages of primary studies with respect to performed test objectives.

Overall, as shown in Fig. 12 and Table 2, the ultimate finality of the studies can be clustered in:

- *educating* the occupants of a building about possible dangers demanding to evacuate the building;
- *testing* the user capabilities within the simulated environment and solutions' viability (e.g., if they respond adequately to the given danger, how they interact with the environment, if possible).

Table 2
Primary studies organized by Objectives.

Objective	Papers
Training	Shih et al. (2000), Lovreglio et al. (2018), Ronchi et al. (2015), Kwok et al. (2019), Cha et al. (2012), Rahouti et al. (2017), Xu et al. (2014), Smith and Ericson (2009), Lu et al. (2020), Farra et al. (2019), Silva et al. (2013)
Evaluation	Uno and Kashiyama (2008), Sharma et al. (2014), Ren et al. (2006), Tucker et al. (2018), Kinateder et al. (2015), Cavalcanti et al. (2021), Bourhim and Cherkaoui (2020), Mossberg et al. (2021), Cao et al. (2019), Lin et al. (2020b), Feng et al. (2020a), Zhang et al. (2021), Fujimi and Fujimura (2020), Arias et al. (2021) Andrée et al. (2016), Snopková et al. (2021), Arias et al. (2019), Feng et al. (2020b), Cosma et al. (2016), Chittaro and Ranon (2009), Meng and Zhang (2014), Chittaro and Sioni (2015), Kinateder et al. (2013), Shaw et al. (2019), Xia et al. (2021), Ronchi et al. (2016)

3.8. SRQ7 (A): Methods characterization

The study of the evacuation process (i.e., approaching a gathering area/an exit) is the focus of 34 studies. In particular, they assessed the travel time, speed, paths & trajectories, and distance covered to reach a given safe point. While the evacuation analysis is conducted on the data extracted from the experiments, the anxiety and immersion degree evaluation has been studied ''off-line',' with surveys conducted at the end of the simulation. Nevertheless, in a few cases, the anxiety has been assessed during the simulation via sensors recording blood pressure and sweat (i.e., Heart Rate – HR, Galvanic Skin Response – GSR, electrodermal activity as BIOCAP) (Uno and Kashiyama, 2008; Tucker et al., 2018; Meng and Zhang, 2014; Chittaro and Sioni, 2015; Xia et al., 2021). Two articles solely focused on the paths selection driven by emergency signage (Rahouti et al., 2017; Feng et al., 2020b), while (Lovreglio et al., 2018) presents only a prototype simulator that can be implemented in evacuation trials. See Table 3.

3.9. SRQ7 (B): Users characterization

The user has been granted full access to the virtual environments without being imposed paths/areas in 30 studies. Only two studies report that users are obliged to follow a previously studied escape route (Smith and Ericson, 2009; Lu et al., 2020). Except Farra et al. (2019), who do not state it explicitly, the rest of the studies define the test starting point, as also remarked in SRQ5. In particular, it can be:

- The users start the drills inside or outside the building, possibly being given the possibility of constructing prior environmental knowledge preceding the hazard(s) outburst (Fujimi and Fujimura, 2020; Snopková et al., 2021; Shaw et al., 2019).
- Next to a car (in the case of tunnel-related studies) (Ronchi et al., 2015; Cha et al., 2012; Kinateder et al., 2015; Ronchi et al., 2016).

The evacuation drills' ending point (target) is often placed outside the building (represented as passing through a perimeter building door) or "embodied" by a safe area (elevator, lobby, or stairs) — see Table 4. Conversely, three studies do not need to explicitly define the exit point/safe area. In particular, Farra et al. (2019) and Lovreglio et al. (2018) focus just on getting ready to face an evacuation, Uno and Kashiyama (2008) provide a conceptual contribution, and finally, Fujimi and Fujimura (2020) set the end of the test and not the ending point (safe point) is when, seeing the hazard, the user decides to start the evacuation process.

Table 3
Primary studies organized by Methodologies and techniques involved.

Methodologies and techniques	Papers
Evacuation	Shih et al. (2000), Ronchi et al. (2015), Sharma et al. (2014), Ren et al. (2006), Rahouti et al. (2017), Xu et al. (2014), Tucker et al. (2018), Kinateder et al. (2015), Smith and Ericson (2009), Cavalcanti et al. (2021), Lu et al. (2020), Bourhim and Cherkaoui (2020) Bourhim and Cherkaoui (2020), Mossberg et al. (2021), Cao et al. (2019), Lin et al. (2020b), Feng et al. (2020a), Zhang et al. (2021), Fujimi and Fujimura (2020), Arias et al. (2021), Farra et al. (2019), Andrée et al. (2016), Snopková et al. (2021) Arias et al. (2019), Feng et al. (2020b), Cosma et al. (2016), Chittaro and Ranon (2009), Meng and Zhang (2014), Chittaro and Sioni (2015), Silva et al. (2013), Kinateder et al. (2013), Shaw et al. (2019), Xia et al. (2021), Ronchi et al. (2016)
Survey anxiety assessment	Ronchi et al. (2015), Kinateder et al. (2015), Cao et al. (2019), Lin et al. (2020b), Arias et al. (2019), Meng and Zhang (2014), Kinateder et al. (2013), Shaw et al. (2019)
Survey VR experience	Kwok et al. (2019), Tucker et al. (2018), Bourhim and Cherkaoui (2020), Arias et al. (2021), Snopková et al. (2021), Arias et al. (2019), Cosma et al. (2016), Kinateder et al. (2013), Shaw et al. (2019), Xia et al. (2021)
Sensors (HR, GSR, BIOCAP)	Uno and Kashiyama (2008), Tucker et al. (2018), Meng and Zhang (2014), Chittaro and Sioni (2015), Xia et al. (2021)

Table 4
Primary studies organized by Ending point on the case studies.

Ending points	Papers
Outside	Shih et al. (2000), Ronchi et al. (2015), Sharma et al. (2014), Kwok et al. (2019), Cha et al. (2012), Kinateder et al. (2015), Cavalcanti et al. (2021), Lu et al. (2020), Bourhim and Cherkaoui (2020), Cao et al. (2019), Lin et al. (2020b), Feng et al. (2020a), Zhang et al. (2021) Arias et al. (2019), Feng et al. (2020b), Cosma et al. (2016), Chittaro and Ranon (2009), Meng and Zhang (2014), Chittaro and Sioni (2015), Silva et al. (2013), Xia et al. (2021), Ronchi et al. (2016), Shaw et al. (2019)
Safe area	Ren et al. (2006), Rahouti et al. (2017), Xu et al. (2014), Tucker et al. (2018), Smith and Ericson (2009), Mossberg et al. (2021), Arias et al. (2021), Andrée et al. (2016), Snopková et al. (2021), Kinateder et al. (2013)

Moreover, a few studies allowed the user to interact with the environment (i.e., grabbing objects and extinguishing fire) beyond simply opening doors (Cha et al., 2012; Ren et al., 2006; Cavalcanti et al., 2021; Bourhim and Cherkaoui, 2020; Shaw et al., 2019). Besides possible spacial limitations, a common line is a time (to evacuate) limitation. Finally, three articles do not explicitly mention the interaction characteristics (Uno and Kashiyama, 2008; Farra et al., 2019; Ronchi et al., 2016).

Summarizing, besides the NPCs' body impenetrability, structural impediments, bloodstains on the user's display (Chittaro and Sioni,

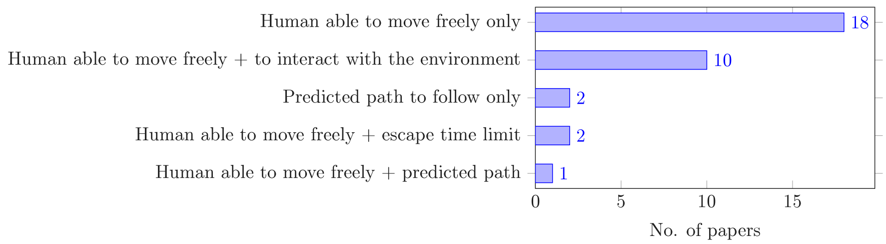

Fig. 13. Number of primary studies considering the user's characterization in simulation.

2015), and smoke may affect the users' field of view (Ronchi et al., 2015; Xu et al., 2014; Kinateder et al., 2015; Smith and Ericson, 2009; Lu et al., 2020). Indeed, the user is intended able to move freely in more than half of the studies analyzed (86%) — see Fig. 13. This aspect is fundamental to allow the tester to get immersed in the scenario with no limits and restrictions of movement, like in a potential real-world scenario. However, all the studies have assumed the users to be healthy individuals. Indeed, the users have always an optimal (standard) visual capability and good motion skills (not physically injured) (same walking/running pace for all the users). Such a naive assumption push far back the effectiveness of the studies, given that physically/visually impaired subjects are subject to the hazards too (reasonably being affected more than healthy individuals).

The set of interactions a tester/user is able to perform includes to: follow predefined paths (Smith and Ericson, 2009; Lu et al., 2020; Cao et al., 2019), extinguish fire (Cha et al., 2012; Cavalcanti et al., 2021), find victims (Cha et al., 2012), grab and handle various scene's objects (i.e., pick up and use a watering can (Snopková et al., 2021), and just being able to open doors (Zhang et al., 2021; Andrée et al., 2016).

Among the interactions mentioned above, Arias et al. (2021) report that participants struggled with the mechanism set in place to open doors.

NPCs play an important role in several studies (Lovreglio et al., 2018; Sharma et al., 2014; Rahouti et al., 2017; Lin et al., 2020b; Fujimi and Fujimura, 2020; Xia et al., 2021). They can just implement a physical impediment or source of stress, or supply the users with useful information about the evacuation process (Tucker et al., 2018; Feng et al., 2020a,b).

3.10. SRQ7 (C): User's perspective

The user's perspective is not explicitly stated by the analyzed studies (84%). It can vary between 1st and 3rd person view, and the distinction seems to mainly follow the technology employed. For example, in the case of IVR (e.g., via Oculus or CAVE technologies), only the 1st person view has been provided. Conversely, in the case of the PC-based VR, the analyzed studies provided either 1st or 3rd person view on the screen.

3.11. SRQ8: Technology and interfaces

The technologies actualizing the IVR are employed in 29 (78%) of the analyzed studies (see Table 5).

Nineteen studies have realized immersive environments via Head Mounted Display (a screen mounted on the head of the viewer through an ad-hoc helmet and can be monocular or binocular (i.e the reproduction of a small display optic in front of one (monocular) or each eye (binocular)) (Lovreglio et al., 2018; Sharma et al., 2014; Kwok et al., 2019; Cha et al., 2012; Ren et al., 2006; Tucker et al., 2018; Cavalcanti et al., 2021; Bourhim and Cherkaoui, 2020; Mossberg et al., 2021; Cao et al., 2019; Lin et al., 2020b; Feng et al., 2020a; Zhang et al., 2021; Fujimi and Fujimura, 2020; Arias et al., 2021; Farra et al., 2019; Snopková et al., 2021; Arias et al., 2019; Feng et al., 2020b; Cosma et al., 2016; Kinateder et al., 2013; Shaw et al., 2019; Xia et al., 2021), and seven via Cave Automatic Virtual Environment (CAVE technologies (Ronchi et al., 2015; Kinateder et al., 2015; Smith and Ericson, 2009; Lu et al., 2020; Andrée et al., 2016; Ronchi et al., 2016) which consist of a cube-shaped room and video projectors directed on its faces (see Fig. 14)).

Table 5
Primary studies organized by Interface implemented.

Interface	Papers
IVR	Lovreglio et al. (2018), Ronchi et al. (2015), Sharma et al. (2014), Kwok et al. (2019), Cha et al. (2012), Ren et al. (2006), Tucker et al. (2018), Kinateder et al. (2015), Smith and Ericson (2009), Cavalcanti et al. (2021), Lu et al. (2020), Bourhim and Cherkaoui (2020), Mossberg et al. (2021), Cao et al. (2019), Feng et al. (2020a), Zhang et al. (2021), Fujimi and Fujimura (2020), Arias et al. (2021) Farra et al. (2019), Andrée et al. (2016), Snopková et al. (2021), Arias et al. (2019), Feng et al. (2020b), Cosma et al. (2016), Kinateder et al. (2013), Shaw et al. (2019), Xia et al. (2021), Ronchi et al. (2016)
VR	Shih et al. (2000), Uno and Kashiyama (2008), Rahouti et al. (2017), Xu et al. (2014), Chittaro and Ranon (2009), Meng and Zhang (2014), Chittaro and Sioni (2015), Silva et al. (2013)

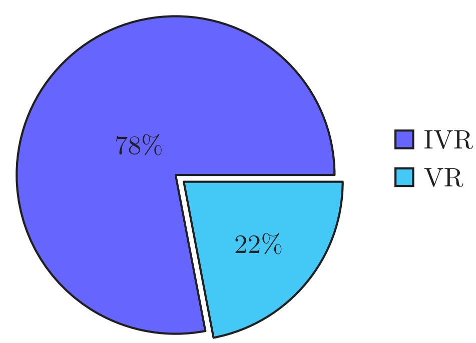

Fig. 14. Percentages of primary studies considering the Interaction interfaces.

The primary studies focusing on VR employed a PC monitor (Shih et al., 2000), 6 LCD monitors and a smoke generator (Meng and Zhang, 2014), and PC and wii Joystick with visual and audio stimuli (Chittaro and Sioni, 2015)) technologies. Finally, six studies did not specify the involved technology/interface. Fig. 15 shows the different VR and IVR technologies used in the tests.

The underlying technologies powering the modeling and implementation of graphic engines for both VR and IVR are multiple.

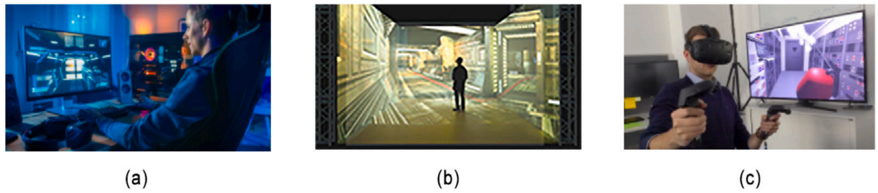

Fig. 15. Examples of VR interfaces: (a) the interaction occur via monitor and a joystick (Anon, 0000c); Examples of IVR interfaces: (b) Cave Automatic Virtual Environment (Anon, 0000a), and (c) Head Mounted Display (Anon, 0000b).

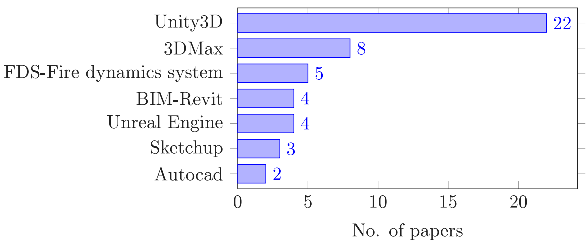

Fig. 16. Number of primary studies considering the used software.

The most used modeling software to generate the environments are Revit (BIM program[2]), Sketchup, and Autocad, (see Fig. 16). 3D Studio Max is also used as a modeling program. However, in the studies analyzed, it is generally used to integrate effects such as lights, materials, or objects within the created space. Unity 3D is the most used graphics engine for modeling (especially for environment animation), with Unreal Engine in second place. Finally, to increase the credibility of the virtual environment, semi-realistic effects are added, such as the dynamics and density of the smoke enveloping the environment, which increases with the passage of time and fire. Indeed, five case studies feature Fire Dynamic Simulator technologies (Cha et al., 2012; Ren et al., 2006; Xu et al., 2014; Tucker et al., 2018; Lu et al., 2020). An additional study (Meng and Zhang, 2014) reports the use of smoke generators as an alternative to these fluid dynamics systems but only for VR use. Alternatively to these fluid dynamics systems, some studies report the use of smoke generators (Meng and Zhang, 2014),(visual and audio stimuli) (Chittaro and Sioni, 2015), heat generators (Shaw et al., 2019), and a chair-shaking system (Lovreglio et al., 2018; Feng et al., 2020b). An example of a complete technological pipeline is Revit for modeling, 3D Studio Max for the integration of effects, Unity 3D to make the model interactive, and finally, FDS software to generate and develop fire and smoke patterns. The study of dynamic fluid employed in the tests (Xu et al., 2014; Lu et al., 2020). is best explained in SRQ10.

3.12. SRQ9: Analysis methodologies

The methodologies used by the primary studies to assess their findings are quite heterogeneous (see Fig. 17). Eleven studies explicitly target the assessment of VR realism. The users who participated in the experiment have been surveyed right after completing the test. The stress level (especially in proximity of the danger) has been analyzed during the tests' execution (Lin et al., 2020b; Shaw et al., 2019), while similar aspects such as frustration and dizziness have been assessed both during and after the tests' completion (Smith and Ericson, 2009).

[2] Building information modeling (BIM) is a 3D digital construction process where all project information is controlled and shared for the entire team during all construction phases and for the duration of the building life cycle. BIM is not properly a tool for designing or visualizing. It is a procedure that makes it possible to develop a common data model. Each and every stakeholder has access to this model.

Although VR and IVR can cause the disturbs mentioned above, the assessment of their usefulness in the process of educating/testing emergency drills has reported positive marks (Sharma et al., 2014; Kwok et al., 2019; Tucker et al., 2018; Cavalcanti et al., 2021; Bourhim and Cherkaoui, 2020; Lin et al., 2020b; Arias et al., 2021; Silva et al., 2013) Furthermore, Feng et al. (2020a) found that visitors (mostly unaware of the environment) have dramatically improved their performances over the tests, reaching the level of the hospital staff (already confident with the environment). Furthermore, Chittaro and Sioni (2015) state that the interactive team (players can choose and make dietary decisions on their behalf) had a better risk assessment than the non-interactive team. However, both have increased their knowledge of the evacuation process (proven via the post-test surveys).

Five papers also analyze the decision-making process and the escape routes taken during the tests. According to their analysis, $\sim 70\%$ of the players use the same routes taken at the entrance to escape (because it is the only one or the one they know) and trusted that more than the quest of following the emergency signage (Tucker et al., 2018). Additionally, Shih et al. (2000) and Ronchi et al. (2015) highlight that the safety routes might not be the shortest, yet they are the safest. Nevertheless, this aspect seems to raise little interest in the user, and it is overruled by many danger-related emotions. To solve this problem, Snopková et al. (2021), and Chittaro and Ranon (2009) state that through a proper building/spaces design and putting signs in clear sight the tendencies to retrace known routes can be less appealing than following proper safety paths.

Thus, the signs' visibility is crucial, and their use must be encouraged (Shih et al., 2000; Kinateder et al., 2015; Snopková et al., 2021; Chittaro and Ranon, 2009). Greenlight is reported to be more tolerable than blue light and especially at a rate of 1 to 4 Hz (Ronchi et al., 2016). Cosma et al. (2016) did not find such differences in user evacuation behavior. The implementation of voice alarm systems can give critical information to ensure a smoother and more consistent evacuation process (Andrée et al., 2016; Xia et al., 2021). Another relevant research employs smartphones to provide instructions to reach the emergency exits (Mossberg et al., 2021).

Two studies assessed anxiety, stress, behavioral choices, and escape time by splitting the users into two teams: one team having the possibility to move freely in the generated environment, the other team having to follow a predetermined route (simulating limited environmental knowledge) (Cao et al., 2019; Meng and Zhang, 2014). The experiments found that the team with the ability to move freely took much longer to escape and was more stressed than the "limited-range" team.

3.13. SRQ10: Strengths

All the studies agree on the importance played by VR and IVR simulators to enhance the efficiency and effective learning of evacuation training (Arias et al., 2021; Kinateder et al., 2013; Xia et al., 2021), although some limitations are still retrieved, as shown by SQR11 insights. The combination of conventional emergency static signage has been accompanied by voice alarm systems, and the use of devices such as smartphones have also shown promising results and benefits (Cavalcanti et al., 2021; Mossberg et al., 2021). Particular attention should be paid to the contribution of NPCs within the hazard scenario

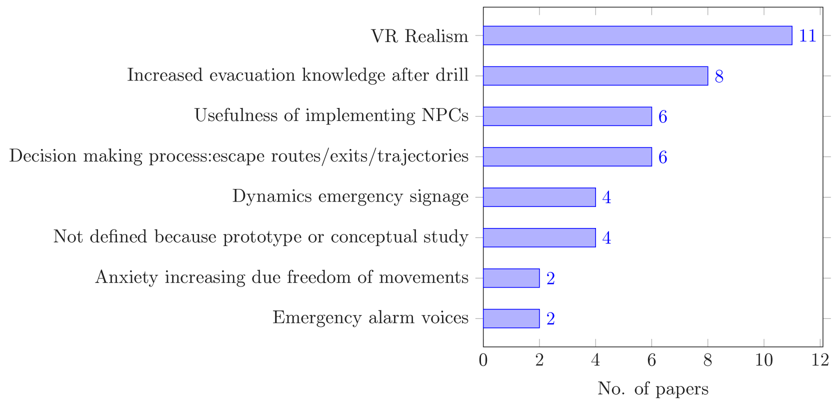

Fig. 17. Number of primary studies considering types of analysis of the results.

as they influence the decision-making and behavioral process of the user bringing it closer to the reality (Lovreglio et al., 2018; Lin et al., 2020b). Shaw et al. (2019) denounce the importance of heaters and smells in increasing anxiety ratings. Finally, a further benefit is related to the use of fluid dynamic computation systems (FDS). In particular, Xu et al. (2014), and Lu et al. (2020) divide space into discrete volumes which increase their opacity (representation of smoke in space) in time steps consistent with FDS. Thus, it is possible to conclude that leveraging FDS boosts the credibility of the simulator and allows the achievement of more realistic levels of engagement and stress.

However, it is worth highlighting that 20 papers do not explicitly elaborate on the strengths, benefits, and advantages of their research.

3.14. SRQ11: Limitations

Twenty articles (59%) do not mention nor address the limitations and barriers entailed in their studies. The rest of the papers point out four types of limitations:

- the participants are alone in the test environment, harming the credibility of the system (Kinateder et al., 2015; Bourhim and Cherkaoui, 2020; Mossberg et al., 2021; Zhang et al., 2021; Kinateder et al., 2013);
- the lack of effects and/or sensors that can reproduce heat, humidity, smells, smoke density for a more realistic environment is reported in another (Tucker et al., 2018; Kinateder et al., 2015; Bourhim and Cherkaoui, 2020; Zhang et al., 2021; Cosma et al., 2016).
- unpleasant users' sensation/feeling due to technological drawbacks. For example, some users have experienced dizzying due to the virtual environment's lack of fluidity — frame-rate irregularity, loss of focus, depth alteration) (Lovreglio et al., 2018; Bourhim and Cherkaoui, 2020; Mossberg et al., 2021; Andrée et al., 2016; Feng et al., 2020b).
- unbalanced users population, almost only young individuals took part in the studies (Zhang et al., 2021; Ronchi et al., 2016).

Some studies report combinations of these four major limitations as (Kinateder et al., 2015; Bourhim and Cherkaoui, 2020; Mossberg et al., 2021; Zhang et al., 2021).

3.15. SRQ12: Solutions

Most of the papers have delegated such an analysis to future research or just mentioned them as potential challenges. Only three studies mention solutions to cope with the limitations pointed out in SRQ11. In particular, the studies analyzed (both concerning VR and IVR) offer only single-user – as the main protagonist – scenarios. To cope with such a limitation, some solutions proposed by two primary studies would be to develop the multi-player concept and coordinate simultaneous tests. By doing so, possibly adding NPCs, the simulated scene can become more crowded (getting closer to real-world scenarios) – henceforth more realistic (Tucker et al., 2018; Lovreglio et al., 2018). Another aspect defined is the employment of sensors to reproduce sounds, smells, and heat to increase the credibility of the generated virtual world (Bourhim and Cherkaoui, 2020; Cao et al., 2019). Finally, a study proposes the use of a treadmill as a measure of overcoming the movement limitations of virtual reality (Bourhim and Cherkaoui, 2020).

3.16. SRQ13: Future challenges

Twenty-four studies (73%) expressed the intention (to be verified) to follow the presented studies. Some of the future challenges indicated by the primary studies overlap with the elicited limitations. Eight studies that provide the implementation of physical stimuli such as the sensation of heat, smoke production (via specific generators), and environmental sounds reproduction foresee the use of sensors, such as heart rate and sweat sensors, to perceive stress levels (Kwok et al., 2019; Cha et al., 2012; Tucker et al., 2018; Bourhim and Cherkaoui, 2020; Arias et al., 2019; Chittaro and Ranon, 2009; Meng and Zhang, 2014; Xia et al., 2021). Shaw et al. (2019)propose to compare the effects of interaction between the senses. Several studies propose to introduce the multi-player setting and behavioral group analysis (Ren et al., 2006; Rahouti et al., 2017; Mossberg et al., 2021; Meng and Zhang, 2014; Silva et al., 2013; Kinateder et al., 2013; Shaw et al., 2019), aligned with the proposal of Zhang et al. (2021) to involve a crowd-flow to explain social behaviors. Chittaro and Sioni (2015) plans to implement the third-person perspective to investigate changes in the decision-making behavior of the individual given another (wider) perspective. Cavalcanti et al. (2021) propose to involve an audience of users of different gender and age (including possible movement limitations) to have a more plausible framework and user representation. The environment also plays an important role in the study as the complexity of the building can give users anxiety, loss of orientation, and difficulty finding their way out. To this end, the studies such as Lin et al. (2020b) and Silva et al. (2013) aim at modeling a more complex environment in the upcoming studies (i.e., more realistic objects on the scene with an accurate hazard-related representation).

Moreover, Smith and Ericson (2009) and Chittaro and Sioni (2015) highlight the need to implement multi-hazard and dynamic-hazard studies. It can be translated into a fire and smoke initiation and development, possibly via FDS (fire dynamics system) software.

Finally, recalling that VR and IVR training can instill a high level of stress on the user and increase the evacuation's knowledge retention, research such as Feng et al. (2020a), Chittaro and Sioni (2015) propose to study long-term effects via a survey carried out at a relatively distant time from the day of the evacuation test.

4. Discussion

The analysis of SRQs allows us to trace key findings concerning two main implication areas: (1) a common framework for future VR/IVR tests, which are also correlated to the ”blind spots” to be solved by future research, also implying improvements from technological perspectives; (2) applications should move towards a multi-domain perspective, that essentially imply multi-risk conditions and the possibility to extend the existing and improved approach to other scenarios.

4.1. Towards a common framework: From ontological to technological improvements

Technologies involved in VR and IVR drill systems have rapidly evolved in the last twenty years. However, they are still relatively unexplored to their full potential, thus indicating the infancy of this field. An element that justifies this statement is the absence of a framework (requirements and characterization of the procedures) that standardizes the creation of simulators having the purpose of evacuation exercises. Elaborating on the results elicited by our investigation, it is possible to assert the relevance of employing VR and IVR technologies for evacuation drills. Hence, the results obtained by the mostly practical studies (applied and tested) testify a growing performance efficiency (Feng et al., 2020a; Kinateder et al., 2013), emotional involvement (Anjomshoae et al., 2019; Meng and Zhang, 2014; Chittaro and Sioni, 2015) scientific interest, information retainment, enhanced outreach, a broader set of “testable” scenarios, and a wider spectrum of observable key variables in the users’ behavior.

Since VR would succeed in overcoming the previously mentioned limitations of physical evacuation tests, such as in data collection or saving costs for business continuity (Gwynne et al., 2019; Kinateder et al., 2021b), the idea of replacing physical tests with drills done through virtual reality is not intended to be considered valid, but to use such technology as an aid to the collection and subsequent processing of data.

It would be interesting to focus on the study of pertinent differences between the quiet situation with which users start the test (circulation) and the evacuation situation because most studies start from a quiet situation, typically to allow the user to become familiar with the context and virtual reality technology (evacuation).

However, such solutions introduce several limitations and are characterized by several severe blind spots. In particular, the requirements formulation (concerning the user, the hazard scenario and the hazard effects spreading over time, and the built environment) seems to be too often weak and approximate. The definition of formal requirements would pave the way towards standardization and, therefore, a more uniform and structured systems’ evolution, thus providing:

1. extension of recipients’ sample dimension and types also depending on the effective users of the buildings;
2. moving towards the inclusion of normal to emergency conditions in the tests, e.g., by firstly involving users’ circulation in the buildings and then the involvement in the evacuation process, so as to replicate familiarity awareness increase for building use as in real-world scenarios;
3. simulation-based representation of hazard effects (e.g., through FDS-based dynamics);
4. moving towards the inclusion of normal to emergency conditions in the tests, e.g., by firstly involving users’ circulation in the buildings and then the evacuation process;
5. adequate level of accuracy and realism of the building environment in terms of architectural components and building components (including audio stimuli);
6. improved levels of the main following literature factors concerning the concept of presence in the virtual environment (Kwegyir-Afful, 2022):
   - (a) sensory, as the “the degree of movement” in the environment;
   - (b) realism, as the closeness “to reality” that participants perceive considering both the scenes and the structures in the IVR environment, e.g., by focusing on fatigue-based approaches or familiarity-related issues before the tests;
   - (c) involvement quality, that concerns “visual display and controllers” that participants use to accomplish the task in the IVR environment;
   - (d) control of IVR elements;
   - (e) distraction, as the “ease of adaptation” to the IVR environment.

Such actions would shed some light on the several naive assumptions that, as of today, strongly characterize the recipients/users. For example, among all the studies, the main user/player has no impairments – complete motor and visual skills. Nevertheless, designing and implementing the main player with several motions speeds, heights, visual capabilities, or grabbing/reaching settings would boost the inclusiveness and the significance of the system/study, which would finally consider ill, harmed, and disabled individuals among the recipients to be educated or trained against possible hazards. Furthermore, it is necessary to better characterize the initial setups and assumptions, the interface functionalities and projections, and the analysis of the final results. In this sense, the implementation of formal requirements and the actualization of a proper “framework” to characterize VR and IVR emergency drill systems could be used to compare rigorous methods with naive assumptions and understand if operational simplifications could still be tolerated to assess behaviors or adequately train people.

The technologies involved in VR and IVR drill systems have rapidly evolved. However, they are still relatively unexplored to their full potential, especially when coupled with wearable garments and sensors (involving more human senses at once). This affects the engagement level, which should definitely be increased to trigger higher levels of sensory, realism, and involvement quality, and reduce distraction factors (Bourhim and Cherkaoui, 2020; Cao et al., 2019).

4.2. Towards a multi-domain perspective: From application scenarios to multi-risk assessment

It is worth highlighting that most of the attention is dedicated to (A) simulating indoor environments such as hospitals, hotels, and mall centers – rather than private environments (mostly neglected) – (B) limiting the scenario to the building itself –rather than also including the interconnected public outdoor space facing the building– and (C) considering the occurrence of a single hazard. In this sense, three main issues can be noticed to make future efforts more capable of facing challenging conditions.

About point (A), when staging such crowded environments, NPCs play a very crucial role with the user, the only real player in the scene. Yet, they are undeservedly under-addressed, and further efforts are needed, for instance, in coupling a single hazard with more realistic crowd phenomena via NPC (Xu et al., 2020). Improving their representation/characterization (e.g., from a strategic or AI perspective) and involvement in the drills (either as obstacles or resources) would dramatically increase the benefits and realism of the systems, since previous studies like Lovreglio et al. (2018) implements NPCs using simple movement-based triggers and algorithms. In this sense, evacuation model trajectories in VR/IVR solutions could be an interesting opportunity to better link different tools for risk assessment in a built environment. For instance, results from evacuation simulation models could be implemented in the test environment in a more structured manner, also thanks to future capabilities of quasi-real-time simulation, while VR/IVR trajectories derived from VR/IVR tests could also be implemented in the tools by substituting simulation results, especially when the NPCs do not interact with the tester but could be visible on the scene.

About point (B), the correlation between indoor and public outdoor spaces could be relevant in view of the possibility that additional conditions of the built environment facing the building could imply different critical interactions for the occupants at the end of the evacuation, such as the arrival of rescuers' vehicles, overlapping of evacuation phenomena in case of crowded public spaces and/or wide complexes of buildings, overlapping of risks in outdoor due to multi-hazard scenarios (i.e., fires following earthquakes) (Lin et al., 2020c; Quagliarini et al., 2021; Feng et al., 2020a).

About point (C), further research should move from hazard, as the main requirement, to the concept of risk as a leading factor, by considering that the risk depends on the combination of hazard, physical vulnerability, and occupants' exposure (thus including their number and density) and individual/social vulnerability, as well as their ability to cope with the danger and all the psycho-physiological variables pertaining to the user (Villagràn de León, 2006; Tancogne-Dejean and Laclémence, 2016). In this general context, the hazards can have different natures, and when considering multi-hazard, the scenario would be dramatically more complicated, inducing greater psychological arousal and retention of the information (Smith, 1982). Thus, "simply" evacuating a building using the emergency routes and exits as represented by the current systems might not be sufficiently motivating. For instance, in a multi-hazard scenario like in the case of fire following an earthquake, building damages should be summed to fire spreading, thus making users undergo additional stress conditions. Meanwhile, the same built environment scenario could be analyzed by making users face different hazards, one at a time, to assess users' behaviors and risk-reduction strategies under different scenarios.

In this way, hazard representation can also be linked to physical vulnerability variations (e.g., layout, wayfinding signs, alarm, other emergency systems, and facilities), thus also pursuing the effectiveness test of fundamental solutions for occupants' evacuation support (Lin et al., 2020a; Chen et al., 2021; Gath-Morad et al., 2022). Further research should also urgently develop formal requirements for the identification of users' characterization issues by also actively involving more vulnerable individuals (e.g., with motion or visual impairments, patients) as recipients (see SQR4 (A)). NPCs' characterization assumes a relevant rule for social vulnerability factors connected to the aforementioned crowd phenomena and underlying exposure issues. Given the above, typological (relevant due to statistical recurrence) combinations between hazards, environment features (and so vulnerability), and users' factors (exposure and vulnerability) can be then used to focus on the most meaningful scenario conditions for behavioral analysis and training activities expecting the users' preparedness to increase.

5. Conclusion

This paper conducted an SLR collecting 37 papers (conducted in January 2022) focusing on VR and IVR systems for evacuation drills under hazardous conditions in buildings. It presented the review methodology, organized the elicited results, and discussed the aggregated information. The elaborated studies open to VR and IVR technologies, providing promising results. However, they introduce several limitations (i.e., users' dizziness, lack of engagement, and lack of realism) and neglect crucial aspects (i.e., user inclusiveness – ills, impaired, or disabled).

Elaborating on both positive and negative sides, a possible road map might include smartphones with augmented reality solutions (possibly interacting with IoT-enabled environments), which could dynamically redefine emergency strategies, morphed according to the evolution of the environment/hazard. Furthermore, introducing smartphone-based applications can make the systems more affordable and maximize outreach. Moreover, as mentioned in the previous section, this new generation of systems could be coupled with wearable sensors and actuators to boost the immersiveness of the experience.

Concerning the characterization of the environment, moving towards more realistic conditions should be a priority, also by better linking specific case studies with VR and IVR activities. Adopting more realistic settings with a more practical degree of damage (more objects should be added to the scene and should be affected accordingly) can instill a more adequate perception of the danger. Therefore, attention should be paid to developing a more precise and, therefore, realistic propagation of the elements (e.g., fire and smoke). The user should also be allowed to manipulate or "break" – even accidentally – scene objects, and the consequences of such actions should be reflected. For example, opening or accidentally breaking a window would imply a change in the virtual environment perimeter, which would allow for the smoke to leave the area and possibly decrease its density. Finally, the characterization and involvement of NPCs should be among the highest priorities. This will require extensive studies, given the broad contribution such "actors" can bring. From a future research and application perspective, the definition of such formal requirements and procedures to improve VR and IVR testing could then support: (1) researchers in a proper assessment of human behaviors in emergency and evacuation scenarios, without any risk for participants, also to collect more reliable data for evacuation and emergency modeling and simulation; (2) safety managers and designers in the preliminary test of deployed emergency facilities and emergency plans before their application; (3) stakeholders such as emergency staff and firefighters to understand the main critical issues in emergency situations because of human behaviors, and to get trained on it; (4) end-users, including occupants, to increase risk awareness towards a proactive engagement in emergency preparedness in (un)familiar environments.

CRediT authorship contribution statement

Emanuele Gagliardi: Investigation, Formal analysis, Data curation. **Gabriele Bernardini:** Writing – review & editing, Validation, Supervision. **Enrico Quagliarini:** Supervision. **Michael Schumacher:** Supervision. **Davide Calvaresi:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization.

References

Abir, I.M., Ibrahim, A.M., Toha, S.F., Shafie, A.A., 2022. A review on the hospital evacuation simulation models. Int. J. Disaster Risk Reduct. 103083. http://dx.doi.org/10.1016/j.ijdrr.2022.103083, URL https://linkinghub.elsevier.com/retrieve/pii/S2212420922003028.

Andrée, K., Nilsson, D., Eriksson, J., 2016. Evacuation experiments in a virtual reality high-rise building: Exit choice and waiting time for evacuation elevators. Fire Mater. 40 (4), 554–567.

Anjomshoae, S., Najjar, A., Calvaresi, D., Främling, K., 2019. Explainable agents and robots: Results from a systematic literature review. In: 18th International Conference on Autonomous Agents and Multiagent Systems. AAMAS 2019, Montreal, Canada, May 13–17 2019, International Foundation for Autonomous Agents and Multiagent Systems, pp. 1078–1088.

Anon, 0000a. Cave Automatic Virtual Environment, [cited 2023]. URL https://www.votanic.com/services/.

Anon, 0000b. Head Mounted Display, [cited 2023]. URL https://en.wikipedia.org/wiki/Virtual_reality.

Anon, 0000c. interaction using monitor and joysticks, [cited 2023], URL https://dailyplanetdc.com/2022/01/14/tips-for-designing-a-video-gaming-room-in-your-home/.

Arias, S., La Mendola, S., Wahlqvist, J., Rios, O., Nilsson, D., Ronchi, E., 2019. Virtual reality evacuation experiments on way-finding systems for the future circular collider. Fire Technol. 55 (6), 2319–2340.

Arias, S., Mossberg, A., Nilsson, D., Wahlqvist, J., 2021. A study on evacuation behavior in physical and virtual reality experiments. Fire Technol. 1–33.

Bernardini, G., Lovreglio, R., Quagliarini, E., 2019. Proposing behavior-oriented strategies for earthquake emergency evacuation: A behavioral data analysis from New Zealand, Italy and Japan. Saf. Sci. 116, 295–309. http://dx.doi.org/10.1016/j.ssci.2019.03.023, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753518303333.

Bourhim, E.M., Cherkaoui, A., 2020. Efficacy of virtual reality for studying people's pre-evacuation behavior under fire. Int. J. Hum.-Comput. Stud. 142, 102484.

Calvaresi, D., Cesarini, D., Sernani, P., Marinoni, M., Dragoni, A.F., Sturm, A., 2017. Exploring the ambient assisted living domain: A systematic review. J. Ambient Intell. Humaniz. Comput. 8 (2), 239–257.

Cao, L., Lin, J., Li, N., 2019. A virtual reality based study of indoor fire evacuation after active or passive spatial exploration. Comput. Hum. Behav. 90, 37–45.

Cavalcanti, J., Valls, V., Contero, M., Fonseca, D., 2021. Gamification and hazard communication in virtual reality: A qualitative study. Sensors 21 (14), 4663.

Çğdaş, G., Sağlamer, G., 1995. A simulation model to predict the emptying times of buildings. Archit. Sci. Rev. 38 (1), 9–19.

Cha, M., Han, S., Lee, J., Choi, B., 2012. A virtual reality based fire training simulator integrated with fire dynamics data. Fire Saf. J. 50, 12–24.

Chen, H., Hou, L., Zhang, G.K., Moon, S., 2021. Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. Autom. Constr. 125, 103631. http://dx.doi.org/10.1016/j.autcon.2021.103631, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580521000820.

Chittaro, L., Ranon, R., 2009. Serious games for training occupants of a building in personal fire safety skills. In: 2009 Conference in Games and Virtual Worlds for Serious Applications. IEEE, pp. 76–83.

Chittaro, L., Sioni, R., 2015. Serious games for emergency preparedness: Evaluation of an interactive vs. a non-interactive simulation of a terror attack. Comput. Human Behav. 50, 508–519.

Cosma, G., Ronchi, E., Nilsson, D., 2016. Way-finding lighting systems for rail tunnel evacuation: A virtual reality experiment with oculus rift®. J. Transp. Saf. Secur. 8 (sup1), 101–117.

Dubovi, I., 2022. Cognitive and emotional engagement while learning with vr: The perspective of multimodal methodology. Comput. Educ. 183, 104495.

Farra, S., Hodgson, E., Miller, E.T., Timm, N., Brady, W., Gneuhs, M., Ying, J., Hausfeld, J., Cosgrove, E., Simon, A., et al., 2019. Effects of virtual reality simulation on worker emergency evacuation of neonates. Disaster Med. Public Health Prep. 13 (2), 301–308.

Feng, Y., Duives, D.C., Hoogendoorn, S.P., 2021. Using virtual reality to study pedestrian exit choice behaviour during evacuations. Saf. Sci. 137, 105158. http://dx.doi.org/10.1016/j.ssci.2021.105158, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753521000011.

Feng, Z., González, V.A., Amor, R., Lovreglio, R., Cabrera-Guerrero, G., 2018. Immersive virtual reality serious games for evacuation training and research: A systematic literature review. Comput. Educ. 127, 252–266.

Feng, Z., González, V.A., Amor, R., Spearpoint, M., Thomas, J., Sacks, R., Lovreglio, R., Cabrera-Guerrero, G., 2020a. An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings. Adv. Eng. Inform. 45, 101118.

Feng, Z., González, V.A., Trotter, M., Spearpoint, M., Thomas, J., Ellis, D., Lovreglio, R., 2020b. How people make decisions during earthquakes and post-earthquake evacuation: Using verbal protocol analysis in immersive virtual reality. Saf. Sci. 129, 104837.

Fu, M., Liu, R., Zhang, Y., 2021. Do people follow neighbors? An immersive virtual reality experimental study of social influence on individual risky decisions during evacuations. Autom. Constr. 126, 103644. http://dx.doi.org/10.1016/j.autcon.2021.103644, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580521000959.

Fujimi, T., Fujimura, K., 2020. Testing public interventions for flash flood evacuation through environmental and social cues: The merit of virtual reality experiments. Int. J. Disaster Risk Reduct. 50, 101690.

Gath-Morad, M., Aguilar Melgar, L.E., Conroy-Dalton, R., Hölscher, C., 2022. Beyond the shortest-path: Towards cognitive occupancy modeling in BIM. Autom. Constr. 135, 104131. http://dx.doi.org/10.1016/J.AUTCON.2022.104131.

Gwynne, S., Amos, M., Kinateder, M., Bénichou, N., Boyce, K., Natalie van der Wal, C., Ronchi, E., 2020. The future of evacuation drills: Assessing and enhancing evacuee performance. Saf. Sci. 129, 104767. http://dx.doi.org/10.1016/j.ssci.2020.104767, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753520301648.

Gwynne, S., Kuligowski, E.D., Boyce, K.E., Nilsson, D., Robbins, A., Lovreglio, R., Thomas, J., Roy-Poirier, A., 2019. Enhancing egress drills: Preparation and assessment of evacuee performance. Fire Mater. 43 (6), 613–631.

Kinateder, M., Gromer, D., Gast, P., Buld, S., Müller, M., Jost, M., Nehfischer, M., Mühlberger, A., Pauli, P., 2015. The effect of dangerous goods transporters on hazard perception and evacuation behavior–A virtual reality experiment on tunnel emergencies. Fire Saf. J. 78, 24–30.

Kinateder, M., Ma, C., Gwynne, S., Amos, M., Bénichou, N., 2021a. Where drills differ from evacuations: A case study on Canadian buildings. Saf. Sci. 135, 105114. http://dx.doi.org/10.1016/j.ssci.2020.105114, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753520305117.

Kinateder, M., Ma, C., Gwynne, S., Amos, M., Benichou, N., 2021b. Where drills differ from evacuations: A case study on Canadian buildings. Saf. Sci. 135, 105114.

Kinateder, M., Pauli, P., Müller, M., Krieger, J., Heimbecher, F., Rönnau, I., Bergerhausen, U., Vollmann, G., Vogt, P., Mühlberger, A., 2013. Human behaviour in severe tunnel accidents: Effects of information and behavioural training. Transp. Res. Part F: Traffic Psychol. Behav. 17, 20–32.

Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., Mühlberger, A., 2014. Virtual reality for fire evacuation research. In: 2014 Federated Conference on Computer Science and Information Systems. IEEE, pp. 313–321.

Kinateder, M., Warren, W.H., 2016. Social influence on evacuation behavior in real and virtual environments. Front. Robot. AI 3, 43.

Kitchenham, B., Charters, S., 2007. Guidelines for performing systematic literature reviews in software engineering.

Kubota, J., Sano, T., Ronchi, E., 2021. Assessing the compliance with the direction indicated by emergency evacuation signage. Saf. Sci. 138, 105210. http://dx.doi.org/10.1016/j.ssci.2021.105210, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753521000552.

Kwegyir-Afful, E., 2022. Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality. Int. J. Disaster Risk Reduct. 67, 102681. http://dx.doi.org/10.1016/j.ijdrr.2021.102681, URL https://linkinghub.elsevier.com/retrieve/pii/S2212420921006427.

Kwok, P.K., Yan, M., Chan, B.K., Lau, H.Y., 2019. Crisis management training using discrete-event simulation and virtual reality techniques. Comput. Ind. Eng. 135, 711–722.

Lally, F., Crome, P., 2007. Understanding frailty. Postgrad. Med. J. 83 (975), 16–20.

Leder, J., Horlitz, T., Puschmann, P., Wittstock, V., Schütz, A., 2019. Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, Learning, and Decision Making. Saf. Sci. 111, 271–286. http://dx.doi.org/10.1016/j.ssci.2018.07.021, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753518302832.

Li, X., Yi, W., Chi, H.-L., Wang, X., Chan, A.P., 2018. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom. Constr. 86, 150–162. http://dx.doi.org/10.1016/j.autcon.2017.11.003, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580517309962.

Lin, J., Cao, L., Li, N., 2020a. How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations: A VR-based experimental study. Autom. Constr. 113, 103136. http://dx.doi.org/10.1016/j.autcon.2020.103136, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580519312452.

Lin, J., Zhu, R., Li, N., Becerik-Gerber, B., 2020b. Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study. Adv. Eng. Inform. 43, 101040.

Lin, J., Zhu, R., Li, N., Becerik-Gerber, B., 2020c. How occupants respond to building emergencies: A systematic review of behavioral characteristics and behavioral theories. Saf. Sci. 122, 104540. http://dx.doi.org/10.1016/j.ssci.2019.104540, URL https://linkinghub.elsevier.com/retrieve/pii/S0925753519321514.

Lovreglio, R., Gonzalez, V., Amor, R., Spearpoint, M., Thomas, J., Trotter, M., Sacks, R., 2017. The need for enhancing earthquake evacuee safety by using virtual reality serious games. In: Lean & Computing in Construction Congress. p. 2017.

Lovreglio, R., Gonzalez, V., Feng, Z., Amor, R., Spearpoint, M., Thomas, J., Trotter, M., Sacks, R., 2018. Prototyping virtual reality serious games for building earthquake preparedness: The auckland city hospital case study. Adv. Eng. Inform. 38, 670–682.

Lu, X., Yang, Z., Xu, Z., Xiong, C., 2020. Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality. Adv. Eng. Softw. 143, 102792.

MCDEM, 2015. Working from the Same Page Consistent Messages for CDEM - Part B: Hazard Specific Information (Messages) - Earthquake. Tech. Rep., URL https://www.civildefence.govt.nz/assets/Uploads/publications/CM-01.1-earthquakes-June-2015-v2.pdf.

Meng, F., Zhang, W., 2014. Way-finding during a fire emergency: An experimental study in a virtual environment. Ergonomics 57 (6), 816–827.

Mossberg, A., Nilsson, D., Wahlqvist, J., 2021. Evacuation elevators in an underground metro station: A virtual reality evacuation experiment. Fire Saf. J. 120, 103091.

Natapov, A., Parush, A., Laufer, L., Fisher-Gewirtzman, D., 2022. Architectural features and indoor evacuation wayfinding: The starting point matters. Saf. Sci. 145, 105483. http://dx.doi.org/10.1016/j.ssci.2021.105483, URL https://linkinghub.elsevier.com/retrieve/pii/S092575352100326X.

Paes, D., Irizarry, J., Pujoni, D., 2021. 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, 103849. http://dx.doi.org/10.1016/j.autcon.2021.103849, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580521003009.

Pel-Littel, R., Schuurmans, M., Emmelot-Vonk, M., Verhaar, H., 2009. Frailty: Defining and measuring of a concept. JNHA-J. Nutr., Health Aging 13 (4), 390–394.

Quagliarini, E., Lucesoli, M., Bernardini, G., 2021. Understanding human behaviors in earthquakes to improve safety in built environment: A State of the art on sustainable and validated investigation tools. In: Littlewood, J., Howlett, R., Jain, L. (Eds.), Sustainability in Energy and Buildings 2020 (Part of the Smart Innovation, Systems and Technologies Book Series - SIST, Volume 203 - ISSN: 2190-3018). Springer, Singapore, pp. 297–307. http://dx.doi.org/10.1007/978-981-15-8783-2_25, URL http://link.springer.com/10.1007/978-981-15-8783-2_25.

Rahouti, A., Salze, G., Lovreglio, R., Datoussaïd, S., 2017. An immersive serious game for firefighting and evacuation training in healthcare facilities. Int. J. Comput. Inf. Eng. 11 (9), 1088–1094.

Ramachandrail, G., 1985. The human aspects of fires in buildings—A review of research in the United Kingdom. In: Fire Safety, Science and Engineering: A Symposium, (no. 882), ASTM International, p. 386.

Ren, A., Chen, C., Shi, J., Zou, L., 2006. Application of virtual reality technology to evacuation simulation in fire disaster. In: CGVR. Citeseer, pp. 15–21.

Ronchi, E., Kinateder, M., Müller, M., Jost, M., Nehfischer, M., Pauli, P., Mühlberger, A., 2015. Evacuation travel paths in virtual reality experiments for tunnel safety analysis. Fire Saf. J. 71, 257–267.

Ronchi, E., Nilsson, D., Kojić, S., Eriksson, J., Lovreglio, R., Modig, H., Walter, A.L., 2016. A virtual reality experiment on flashing lights at emergency exit portals for road tunnel evacuation. Fire Technol. 52 (3), 623–647.

Sharma, S., Jerripothula, S., Mackey, S., Soumare, O., 2014. Immersive virtual reality environment of a subway evacuation on a cloud for disaster preparedness and response training. In: 2014 IEEE Symposium on Computational Intelligence for Human-Like Intelligence. CIHLI, IEEE, pp. 1–6.

Shaw, E., Roper, T., Nilsson, T., Lawson, G., Cobb, S.V., Miller, D., 2019. The heat is on: Exploring user behaviour in a multisensory virtual environment for fire evacuation. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. pp. 1–13.

Shi, Y., Kang, J., Xia, P., Tyagi, O., Mehta, R.K., Du, J., 2021. Spatial knowledge and firefighters' wayfinding performance: A virtual reality search and rescue experiment. Saf. Sci. 139, 105231. http://dx.doi.org/10.1016/j.ssci.2021.105231, URL https://linkinghub.elsevier.com/retrieve/pii/S092575352100076X.

Shih, N.-J., Lin, C.-Y., Yang, C.-H., 2000. A virtual-reality-based feasibility study of evacuation time compared to the traditional calculation method. Fire Saf. J. 34 (4), 377–391.

Silva, J.F., Almeida, J.E., Rossetti, R.J., Coelho, A.L., 2013. A serious game for evacuation training. In: 2013 IEEE 2nd International Conference on Serious Games and Applications for Health. SeGAH, IEEE, pp. 1–6.

Smith, S.M., 1982. Enhancement of recall using multiple environmental contexts during learning. Memory Cogn. 10 (5), 405–412.

Smith, S., Ericson, E., 2009. Using immersive game-based virtual reality to teach fire-safety skills to children. Virtual Real. 13 (2), 87–99.

Snopková, D., Ugwitz, P., Stachoň, Z., Hladík, J., Juřík, V., Kvarda, O., Kubíček, P., 2021. Retracing evacuation strategy: A virtual reality game-based investigation into the influence of building's spatial configuration in an emergency. Spa. Cogn. Comput. 1–21.

Solinska-Nowak, A., Magnuszewski, P., Curl, M., French, A., Keating, A., Mochizuki, J., Liu, W., Mechler, R., Kulakowska, M., Jarzabek, L., 2018. An overview of serious games for disaster risk management – Prospects and limitations for informing actions to arrest increasing risk. Int. J. Disaster Risk Reduct. 31, 1013–1029. http://dx.doi.org/10.1016/j.ijdrr.2018.09.001, URL https://linkinghub.elsevier.com/retrieve/pii/S2212420917304090.

Tancogne-Dejean, M., Laclémence, P., 2016. Fire risk perception and building evacuation by vulnerable persons: Points of view of laypersons, Fire Victims and Experts. Fire Saf. J. 80, 9–19. http://dx.doi.org/10.1016/j.firesaf.2015.11.009, URL http://www.sciencedirect.com/science/article/pii/S0379711215300370, http://linkinghub.elsevier.com/retrieve/pii/S0379711215300370.

Tucker, A., Marsh, K., Gifford, T., Lu, X., Luh, P., Astur, R., 2018. The effects of information and hazard on evacuee behavior in virtual reality. Fire Saf. J. 99, 1–11.

UNDRR, 2020. [Terminology] [cited 2020]. URL https://www.undrr.org/terminology#R.

Uno, K., Kashiyama, K., 2008. Development of simulation system for the disaster evacuation based on multi-agent model using gis. Tsinghua Sci. Technol. 13 (S1), 348–353.

Villagràn de León, J.C., 2006. Vulnerability: A conceptual and methodological review. Tech. Rep. 4, UNU-EHS, URL http://collections.unu.edu/eserv/UNU:1871/pdf3904.pdf.

van der Wal, C.N., Robinson, M.A., Bruine de Bruin, W., Gwynne, S., 2021. Evacuation behaviors and emergency communications: An analysis of real-world incident videos. Saf. Sci. 136, 105121. http://dx.doi.org/10.1016/j.ssci.2020.105121, URL https://linkinghub.elsevier.com/retrieve/pii/S092575352030518X.

Xia, X., Li, N., González, V.A., 2021. Exploring the influence of emergency broadcasts on human evacuation behavior during building emergencies using virtual reality technology. J. Comput. Civ. Eng. 35 (2), 04020065.

Xu, Z., Lu, X., Guan, H., Chen, C., Ren, A., 2014. A virtual reality based fire training simulator with smoke hazard assessment capacity. Adv. Eng. Softw. 68, 1–8.

Xu, Z., Wei, W., Jin, W., Xue, Q.-r., 2020. Virtual drill for indoor fire evacuations considering occupant physical collisions. Autom. Constr. 109, 102999. http://dx.doi.org/10.1016/j.autcon.2019.102999, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580519309689.

Yoshida, Y., 1995. Evaluating building fire safety through egress prediction: A standard application in Japan. Fire Technol. 31 (2), 158–174.

Zhang, M., Ke, J., Tong, L., Luo, X., 2021. Investigating the influence of route turning angle on compliance behaviors and evacuation performance in a virtual-reality-based experiment. Adv. Eng. Inform. 48, 101259.

Zhang, Y., Liu, H., Kang, S.C., Al-Hussein, M., 2020. Virtual reality applications for the built environment: Research trends and opportunities. Autom. Constr. 118, 103311. http://dx.doi.org/10.1016/J.AUTCON.2020.103311.