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Review

Virtual Reality in Building Evacuation: A Review

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Abstract: This study systematically reviews the application of virtual reality (VR) in building evacuation scenarios in disaster contexts, highlighting its transformative potential to enhance preparedness, evacuation strategies, and safety training. Disasters such as fires, earthquakes, and multi-hazard emergencies pose significant challenges in densely populated urban environments, requiring innovative solutions beyond traditional methods. Analyzing 48 peer-reviewed studies (2014–2024) following PRISMA guidelines, this review focuses on VR applications in public buildings, transportation hubs, and high-risk workplaces, with VR simulations emerging as the predominant methodology. Key findings demonstrate VR's ability to simulate realistic scenarios, improve spatial navigation, and optimize crowd dynamics and mobility accessibility. VR enhances evacuation efficiency and safety compliance by enabling adaptive training for diverse populations, including students, professionals, and vulnerable groups. In public and high-risk environments, VR addresses challenges such as visibility limitations, structural complexity, and the need for customized evacuation protocols. However, gaps remain in exploring multi-hazard environments and mixed-use spaces and ensuring scalability. Future research should integrate VR with artificial intelligence and machine learning for predictive and adaptive evacuation models. Expanding VR applications to underrepresented groups, including individuals with disabilities and the elderly, and collaborating with policymakers and urban planners are vital for translating research into practice. Overall, VR provides a scalable, adaptable, and inclusive solution for building evacuation preparedness, offering actionable insights to enhance resilience and safety in diverse architectural and disaster contexts. Its ability to transform evacuation strategies positions VR as a pivotal tool in advancing disaster management.

Keywords: virtual reality; building evacuation; wayfinding; egress and exit

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1. Introduction

The International Federation of Red Cross and Red Crescent Societies (IFRC) [1] describes disasters as events, either natural or human-made, that severely disrupt societal functions, exceeding the community's ability to manage the consequences. Examples of natural disasters include floods, hurricanes, earthquakes, and tsunamis, while human-made disasters encompass incidents like terrorist attacks and toxic chemical spills. The IFRC also outlines disaster management as the structured coordination and deployment of resources to address the humanitarian dimensions of emergencies, focusing on mitigation, preparedness, response, and recovery efforts. Over the past few decades, the global frequency of disasters has surged significantly, with 7348 incidents recorded between 2000 and 2019—a 73% rise compared to the 1980–1999 period [2]. Such geophysical disasters have led to widespread loss of life, displacement of populations, and extensive destruction of infrastructure worldwide [3].

As urban environments grow increasingly complex and the frequency of disasters such as fires, earthquakes, and multi-hazard emergencies rises, ensuring the safety of occupants in built environments has become a critical priority. Major disasters often result in devastating consequences, such as fires in densely populated urban areas leading to significant loss of life, with thousands of injuries and fatalities reported annually. Firefighting in such scenarios is exceptionally hazardous, with the potential for severe harm, particularly during oil tank fires, where the risks are magnified [4]. In smoky and dark environments, such as those in burning buildings, both civilians and firefighters face significant challenges. Disorientation not only impedes civilians trying to escape but also hinders firefighters' ability to navigate, locate, and rescue trapped individuals, placing everyone at greater risk. Rapid navigation in these conditions is critical, as faster response times directly correlate with higher survival rates for those trapped [5]. This underscores the urgent need for strategies that enhance firefighter safety in hazardous conditions [6]. Additionally, underground pipeline safety is a significant concern for residents in densely populated cities, as pipeline leaks can cause severe damage, making it essential to identify high-risk areas and implement preventive measures [7]. Earthquakes, like fires, can result in severe casualties. In large-scale earthquake disasters, such as the Ecuador earthquake in April 2016, which resulted in approximately 650 fatalities (Wyss, 2016), chaotic evacuations may lead to crowd instability, increasing the risk of stampedes. This can cause two major issues: first, evacuation routes may become obstructed due to collisions, and second, panic can rapidly spread within the crowd, exacerbating the impact on those involved [8]. Furthermore, earthquakes often lead to widespread infrastructure damage and displacement, leaving communities in a vulnerable state for an extended period. Hurricanes and their resulting floods have profound impacts on communities, as evidenced by Hurricanes Harvey and Irma, which caused widespread and catastrophic damage in the Caribbean, Texas, and Florida in September 2017, resulting in over 200 fatalities and forcing tens of thousands to evacuate (El País, 2017). The challenges posed by large-scale evacuations in urban areas during floods have therefore become a critical issue in disaster management today [9].

Traditional evacuation preparedness methods, such as physical drills and static evacuation plans, face several limitations, including logistical challenges, high costs, and a lack of realism. Digital tools have shown promise in addressing some of these challenges. For example, a study [10] exploring the application of a smartphone voice-guided evacuation system (SVGES) in fire scenarios demonstrated its effectiveness. In a simulated fire experiment, the SVGES successfully guided users to the safest evacuation routes, achieving a 100% evacuation success rate and showcasing the potential of digital tools in enhancing evacuation safety. Building on advancements in technology, virtual reality (VR) has emerged as a powerful tool in disaster management, particularly in evacuation research. VR enables the creation of immersive simulations to study human behavior, optimize evacuation strategies, and enhance disaster preparedness with precision and adaptability. Its flexibility allows for the recreation of various building environments and scenarios, supporting the development of realistic and efficient safety measures. By integrating VR technology into serious games for disaster education and training, trainees can better understand and apply mitigation measures through realistic simulations of varied scenarios, enhancing their practical preparedness [11].

Recent studies have focused on using VR in evacuation scenarios, primarily in public buildings, transportation hubs, and high-risk workplaces. These investigations address key aspects such as evacuation decision-making, pre-evacuation behaviors, and crowd dynamics under different environmental conditions. VR's ability to simulate realistic scenarios has proven effective for training diverse groups, including students, professionals, and individuals with mobility impairments. Through interactive and gamified experiences, VR continues to advance safety strategies within built environments.

This study conducts a systematic review on VR applications in building evacuation, aiming to map the current research landscape, identify knowledge gaps, and categorize findings by disaster type, target populations, and methodological approaches. By synthesizing these research findings, this review provides a structured foundation for future studies, prioritizing areas with the greatest potential for impact and practical implementation. Furthermore, it examines the methodologies and real-world applicability of VR research, emphasizing opportunities to bridge the gap between theoretical advancements and practical disaster management solutions

2. Materials and Methods

This systematic review adhered to PRISMA guidelines to identify studies exploring the applications of virtual reality in building evacuations. A comprehensive search was conducted across four major academic databases: Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2014 to July 1, 2024. The search employed specific keywords, including "Virtual AND Reality AND Building AND Evacuation", "Building AND Virtual AND Reality AND Egress", "Building AND Virtual AND Reality AND Exit", and "Building AND Virtual AND Reality AND Wayfinding". Only peer-reviewed English-language articles were included, while conference proceedings and gray literature were excluded to ensure the quality of the review.

The search identified a total of 1218 records, with 415 records from Scopus, 106 records from Web of Science, 137 records from ScienceDirect, and 400 records from Google Scholar. After removing 285 duplicate records, 933 records remained for screening. Titles and abstracts were reviewed to determine relevance, focusing on studies addressing VR applications in building evacuations, including egress, exit strategies, and wayfinding. During this phase, 767 records were excluded, leaving 154 reports sought for full-text retrieval. Of these, 12 reports could not be retrieved, resulting in 142 reports assessed for eligibility.

During the eligibility assessment phase, 94 articles were excluded for the following reasons: 41 articles did not focus on VR as the primary method, 22 articles were not written in English, and 31 articles lacked methodological rigor or relevance to building evacuations. Finally, 48 studies met the inclusion criteria and were included in the review (Figure 1) [12].

This study conducted a thematic analysis to identify trends, research gaps, and major contributions, with recurring themes including training effectiveness, evacuation decision-making, crowd dynamics, spatial navigation, and the influence of environmental design on emergency responses. Accordingly, once selected, the studies were categorized into key themes to facilitate synthesis, including built environment types (e.g., public buildings, transportation hubs), disaster scenarios (e.g., fire, earthquake, multiple disasters), target populations (e.g., students, professionals, and special populations), and methodological focus (e.g., VR simulations, serious games, comparative studies, and theoretical frameworks).

This research aims to explore how VR technology can be utilized to enhance disaster preparedness, evacuation strategies, and safety protocols in diverse built environments. Specifically, this study addresses the following questions:

- Research Fields: How does VR enhance emergency response capabilities across different building environments, such as public buildings, transportation hubs, high-risk workplaces, and mixed-use spaces?

- Disaster Scenarios: How does VR address behavioral, spatial, and decision-making challenges when simulating various disaster scenarios, including fires, earthquakes, and multi-disaster emergencies?
- Target Populations: How effectively does VR-based training cater to diverse populations, such as professionals, students, individuals with disabilities, and the general public, in improving their evacuation preparedness and decision-making during emergencies?
- Methodological Applications: What methodologies and frameworks, including VR simulations, serious games, and comparative studies, are most effective in advancing the understanding of human behavior and spatial dynamics during emergency evacuations?

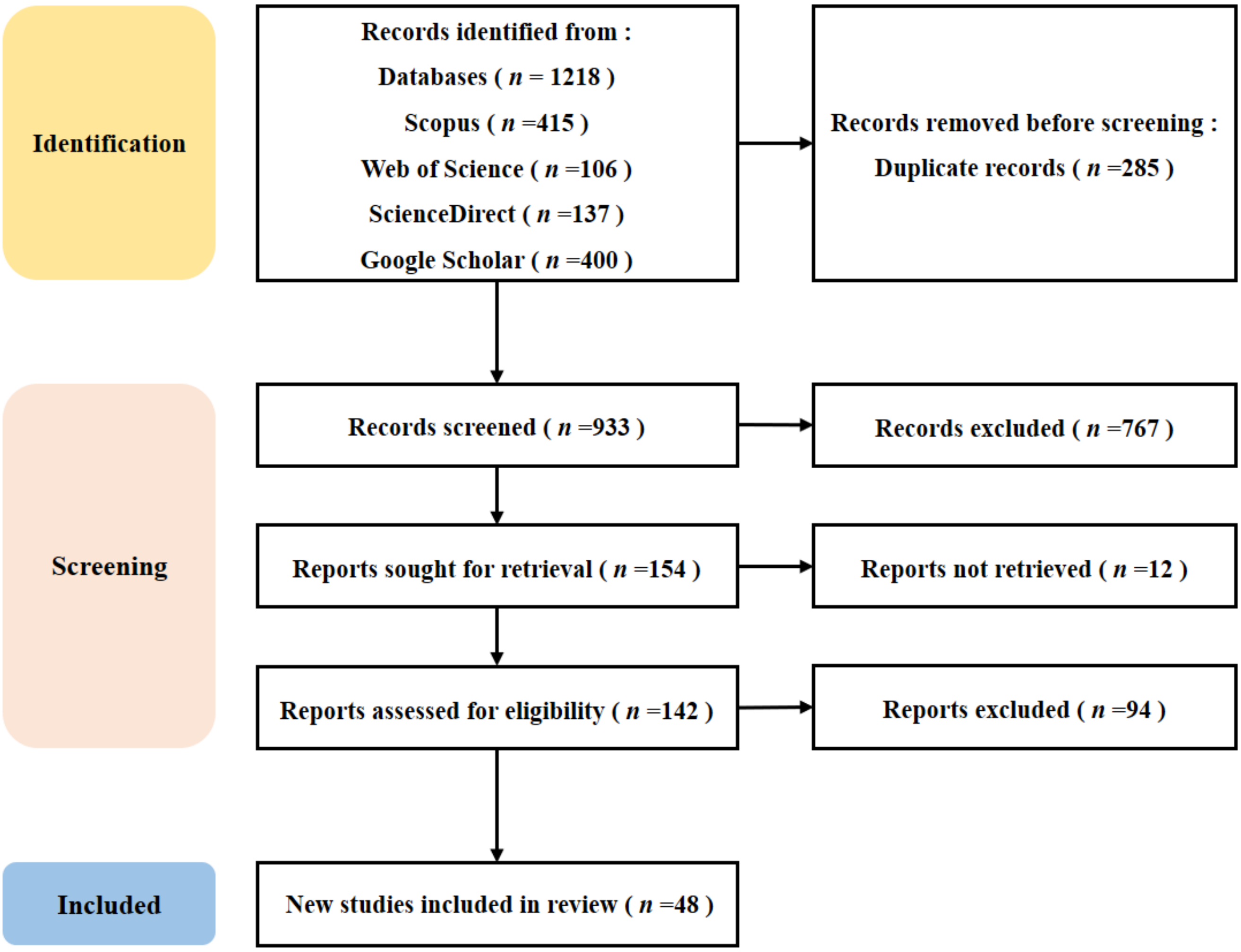

Figure 1. The flowchart of PRISMA.

By addressing these questions, this study aims to bridge existing gaps in the application of VR technology in building evacuation and disaster management. It focuses on VR's adaptability, scalability, and inclusivity across diverse building contexts and populations. Furthermore, the research seeks to identify trends, challenges, and opportunities for future studies, leveraging VR to enhance safety and resilience in disaster-prone environments.

3. Results and Discussion

3.1. Research Fields

3.1.1. Public Buildings

Public buildings, including schools, shopping centers, hospitals, office buildings, and museums, serve as critical hubs for education, commerce, healthcare, and cultural activities. Given their central importance and high occupant density, ensuring safety during emergencies such as fires, earthquakes, or other disasters is a top priority. VR has emerged as an innovative tool for enhancing disaster preparedness and emergency evacuation strategies in these environments.

VR technology plays a primary role in disaster preparedness and evacuation strategies in educational settings. Feng et al. (2021) [13] and Tucker et al. (2018) [14] explored fire evacuations in multi-story school buildings, highlighting the importance of exit strategies in workshops and libraries. Mystakidis et al. (2022) [15] extended this research to teachers, demonstrating how VR simulations enhance their emergency decision-making capabilities. In higher education, Fu, Liu, and Ragan (2024) [16] and Fu, Liu, and Liu (2024) [17] studied fire evacuations at the University of Florida, focusing on building layouts and exit accessibility to improve evacuation compliance. Feng et al. (2018) [18] expanded the scope of VR applications in schools by integrating AR tools, providing customizable disaster training environments. These studies underscore the importance of spatial design and training in educational contexts.

In commercial settings, VR simulations have been extensively used to study evacuation behaviors and emergency responses. Mao et al. (2024) [19,20] examined evacuation strategies in indoor shopping malls, investigating gender differences in exit selection during fire emergencies. Davis et al. (2023) [21] replicated office fire scenarios, offering insights into how workers react under hazardous conditions. Bernardini et al. (2023) [22] assessed active and passive wayfinding systems during evacuations, emphasizing the importance of navigation aids in ensuring safe outcomes. Additionally, Natapov et al. (2021) [23] studied human factors in commercial building evacuations, focusing on architectural design and its impact on decision-making. Lovreglio et al. (2022) [24] explored evacuation behaviors in mixed-use commercial settings, highlighting the role of crowd dynamics in emergency response.

In healthcare, Feng et al. (2020) [25] utilized VR and building information modeling (BIM) to simulate earthquake preparedness in Auckland City Hospital, addressing the critical need for training in high-stakes environments. Cultural institutions also benefit from VR applications, as Cao et al. (2019) [26] investigated fire evacuations in a virtual museum, exploring how complex spatial layouts influence navigation behaviors.

VR has also been applied to enhance safety protocols in leisure and mixed-use environments. Hong et al. (2023) [27] conducted fire escape training in karaoke rooms, analyzing how occupants respond to hazardous conditions. Arias et al. (2020) [28] studied fire evacuations across diverse settings, including schools, offices, and residential areas, to identify common evacuation challenges. Lovreglio et al. (2020) [29] simulated fire emergencies in warehouses and offices, contributing to a deeper understanding of evacuation strategies in mixed-use spaces.

Studies such as Davis et al. (2023) and Dai et al. (2024) [30] focused on immersive simulations for emergency training, emphasizing how VR can enhance evacuation readiness. Gath-Morad et al. (2024) [31] explored wayfinding behaviors in unique public building layouts, while Liu et al. (2023) [32] and Zhang et al. (2023) [33] investigated evacuation compliance in complex public structures. Collectively, these studies highlight the versatility and effectiveness of VR in improving emergency response protocols across various public building types. Smedberg et al. (2023) [34] focused on how building layout properties affect pedestrian route choice and recall using virtual experiments, providing insights into spatial navigation behavior.

3.1.2. Transportation Facilities

Studies focusing on transportation facilities, including metro systems, tunnels, and large transportation hubs, highlight the complexities of evacuation behavior during emergencies, with VR playing a pivotal role in simulating these environments.

Ronchi et al. (2015) [35] examined the impact of emergency exit portal design and placement on evacuation efficiency in road tunnels, emphasizing how structural features influence escape routes. Lin et al. (2020) [36] and Zhu et al. (2020) [37] explored evacuation behaviors in metro systems, focusing on navigation strategies and route selection in multistory and virtual metro stations. Huang et al. (2024) [38] extended this research by analyzing passenger responses to fire hazards in subway systems, providing insights into crowd behavior and emergency decision-making during underground emergencies. Deng et al. (2023) [39] focused on evacuation behaviors in large tunnel fire scenarios, evaluating how environmental factors and crowd dynamics shape decision-making. Zhang et al. (2023) [40] investigated human behavior during full-scale tunnel fire evacuations, analyzing how smoke, heat, and visibility conditions impact escape efficiency.

Together, these studies underscore the unique challenges of transportation evacuations, demonstrating that visibility, exit design, and crowd dynamics significantly influence decision-making and evacuation outcomes in transportation environments.

3.1.3. Specialized Buildings

Studies focusing on specialized buildings, including high-risk workplaces, educational facilities, high-rise buildings, and hazardous environments, emphasize the use of VR and simulation technologies to enhance safety training, disaster preparedness, and emergency response.

At nuclear plants, Park et al. (2023) [41] simulated the evacuation zone around the Kori Nuclear Power Plant, demonstrating how VR can prepare employees and responders for nuclear disasters through pre-planned routes and coordinated evacuations. In high-risk workplaces, Zhou et al. (2024) [42] reviewed VR applications in hazardous environments, training workers to respond to emergencies like fires and structural collapses. Bourhim and Cherkaoui (2020) [43] explored pre-evacuation behaviors in high-rise residential buildings during fire scenarios, focusing on how spatial layouts impact decision-making. Similarly, Arias et al. (2019) [44,45] analyzed crowd behaviors in fire emergencies across schools, offices, and high-rise buildings, highlighting the importance of escape route visibility.

For high-rise buildings, Minegishi (2024) [46] investigated crowd management strategies during elevator evacuations, emphasizing the need for inclusive designs to accommodate individuals with mobility impairments. Feng et al. (2020) [47] used VR to simulate earthquake preparedness in hospitals, addressing critical safety measures for staff and patients in high-stakes environments. Educational settings also benefit from VR-based safety training; Kinateder et al. (2014) [48] examined how school occupants react to fire emergencies, emphasizing how architectural features influence evacuation efficiency.

In industrial environments, Li et al. (2018) [49] and Alshowair et al. (2024) [50] applied VR and AR technologies to train workers on handling hazardous scenarios, including chemical spills and machinery malfunctions, while reducing risks in construction sites and factories. Dang et al. (2023) [51] focused on fire evacuation drills in office buildings, providing insights into how VR simulations improve response times and decision-making during emergencies.

These studies collectively highlight the primary role of VR in enhancing preparedness, improving safety protocols, and reducing risks in specialized building environments.

3.1.4. Other Constructions

The Other Construction category encompasses studies conducted in generic indoor environments and mixed building types, where VR simulations explore evacuation behaviors, decision-making, and wayfinding during emergencies.

In generic settings, D'Amico et al. (2023) [52] designed a VR serious game to improve flood safety awareness in urban environments, emphasizing effective decision-making during natural disasters. Snopková et al. (2023) [53] and Wiltenburg et al. (2024) [54] explored how building layouts and spatial planning impact evacuation efficiency, with the latter highlighting VR's role in disaster preparedness and urban planning. Shi et al. (2023) [55] adopted a novel approach by utilizing Minecraft to simulate pedestrian behavior in fire and non-fire emergencies, demonstrating the adaptability of VR-based tools in evacuation studies. Lin et al. (2023) [56] investigated stress-induced wayfinding behaviors during unspecified emergencies, shedding light on psychological responses to unfamiliar and hazardous situations.

In mixed building environments, Zuo and Zhou (2024) [57] examined how visual access influences wayfinding decisions in multilevel buildings during evacuations, emphasizing the importance of clear spatial cues. Maragkou et al. (2023) [58] developed VRQuake, a game designed to train participants in earthquake preparedness, providing an interactive platform for learning safety strategies. Fu, Liu, and Zhang (2021) [59] explored the role of social influence on risk-taking during evacuations, analyzing how peer behavior affects individual decision-making. Sudiarno et al. (2024) [60] conducted a systematic review on the use of VR in industrial safety training, addressing hazards such as chemical spills and fire emergencies across diverse environments.

Collectively, these studies provide valuable insights into human behavior during emergencies, emphasizing the psychological, physical, and social factors that influence evacuation decisions and preparedness in generic and mixed-use environments.

The analysis of research fields reveals the transformative role of VR in enhancing disaster preparedness and evacuation strategies across diverse building environments. Public buildings, such as schools, shopping centers, hospitals, and museums, emerge as critical hubs where VR significantly enhances safety protocols by addressing spatial design, evacuation compliance, and crowd dynamics during emergencies. In educational settings, VR improves decision-making and safety awareness among students and educators, while in commercial environments, it provides insights into navigation behaviors and exit strategies. Healthcare facilities and cultural institutions benefit from VR's capacity to simulate complex evacuation scenarios, emphasizing the role of tailored training in high-stakes settings. Transportation facilities, including metro systems, tunnels, and large transit hubs, present unique challenges due to confined spaces and crowd density. Studies demonstrate the importance of visibility, exit design, and crowd dynamics in improving evacuation outcomes, with VR offering detailed simulations to model passenger behaviors under emergencies. Specialized buildings, such as nuclear plants, high-rise structures, and industrial sites, leverage VR to train personnel for hazardous scenarios like fires, structural collapses, and chemical spills, underscoring the importance of multi-phase evacuation plans and inclusive designs for mobility-impaired individuals. VR also supports industrial safety training, focusing on risk reduction and response efficiency. For mixed-use and other generic environments, VR proves highly adaptable, addressing diverse scenarios such as floods, chemical hazards, and earthquake preparedness. These studies highlight the value of spatial planning, decision-making under stress, and innovative training platforms like VR serious games in improving disaster readiness. Insights into wayfinding behaviors, stress-induced navigation challenges, and the influence of visual cues emphasize the need for clear spatial designs and robust emergency protocols. Collectively, these findings underscore VR's primary role in tailoring disaster preparedness and evacuation strategies to the unique demands of various built environments, ensuring safer and more resilient communities.

3.2. Scenario

3.2.1. Fire

The analysis of 32 studies related to fire evacuation scenarios highlights diverse research contexts, encompassing modern buildings, educational institutions, residential areas, and complex structures such as tunnels, metro systems, and transportation hubs. Lovreglio et al. (2022) [24] investigated exit choice behavior under fire scenarios, focusing on decision-making processes and environmental factors influencing escape. Arias et al. (2020) [28] examined fire evacuations across residential houses, hotels, and underground facilities, emphasizing occupant responses in diverse settings. Ronchi et al. (2015) [35] analyzed fire evacuation behavior in road tunnels, addressing challenges unique to enclosed and constrained spaces. Hong et al. (2023) [27] explored occupant evacuation behavior in karaoke rooms, providing insights into leisure environments during fire emergencies.

In educational settings, Tucker et al. (2018) [14] studied multi-floor library evacuations under fire conditions, while Mystakidis et al. (2022) [15] focused on fire drills in schools to enhance preparedness and decision-making. High-rise residential evacuations were addressed by Bourhim and Cherkaoui (2020) [43], who analyzed occupant behavior and pre-evacuation delays. Kinateder et al. (2014) [48] contributed insights into fire evacuations in various complex structures, examining the role of spatial perception. Arias et al. (2019) [45] provided a comprehensive analysis of fire evacuations in tunnels and the MGM Grand Hotel, exploring large-scale fire scenarios.

Commercial environments were extensively studied by Lovreglio et al. (2020) and Mao et al. (2024) [19,29], who examined fire evacuations in warehouses, offices, and shopping malls, focusing on crowd dynamics and exit strategies. Fu, Liu, and Ragan (2024) and Fu, Liu, and Liu (2024) [16,17] investigated fire evacuations in educational settings, emphasizing the impact of building design on escape compliance. Transportation hubs were a significant focus, with Lin et al. (2020) and Zhu et al. (2020) [36,37] analyzing fire evacuations in metro stations, addressing passenger behavior and structural challenges. Huang et al. (2024) [38] expanded this research by exploring fire evacuation strategies in subway systems, while Zhang et al. (2023) [40] investigated tunnel fires and vehicle fire scenarios in transportation infrastructures.

Liu et al. (2023) [32] examined video-based training's impact on fire evacuations in virtual offices, finding it reduced pre-evacuation time and improved self-efficacy. Training promoted safer behaviors, like crouching in smoke, but had limited effect on intuitive actions like responding to alarms, highlighting the need for tailored training to enhance real-world evacuation strategies. Studies on individual behaviors during fire emergencies provided additional insights. Davis et al. (2023) [21] examined the impact of smoke-filled corridors on movement efficiency, highlighting visibility as a critical factor in evacuation success. Dang et al. (2023) [51] conducted VR-based fire drills in office environments, analyzing occupant responses. Smedberg et al. (2023) and Snopková et al. (2023) [34,53] focused on evacuation challenges faced by individuals with mobility impairments during fires. Brain activation and cognitive responses during fire evacuations were explored by Deng et al. (2023) [39], providing a unique perspective on stress and decision-making. Wayfinding and social influence were key areas of investigation. Shi et al. (2023) [55]

studied pedestrian behaviors and route selection in fire scenarios, offering insights into group dynamics and evacuation patterns. Bernardini et al. (2023) [22] evaluated wayfinding systems in commercial environments, demonstrating their importance in guiding safe evacuations. Fu, Liu, and Zhang (2021) [59] analyzed social cues and their influence on risky decision-making during fire evacuations, using VR simulations to model smoke density and neighbor behavior.

In cultural and leisure spaces, Cao et al. (2019) [26] applied VR training for fire evacuations in museums, addressing navigation in complex layouts. Minegishi (2024) [46] examined crowd management strategies during elevator evacuations in high-rise buildings, focusing on fire scenarios involving individuals with mobility impairments. Lin et al. (2023) and Zhang et al. (2023) [33,56] provided critical insights into fire evacuations in multi-level buildings, focusing on exit strategies and architectural design.

These studies collectively contribute to a deeper understanding of fire evacuation behaviors across varied environments, from residential and commercial spaces to large transportation hubs and cultural institutions. The findings emphasize the importance of tailored evacuation strategies and the role of virtual reality in enhancing fire safety protocols and training programs.

3.2.2. Earthquake

The research on earthquake evacuation behavior spans various high-risk environments, emphasizing the need for tailored strategies. Feng et al. (2018) and Feng et al. (2020) [18,25,47] examine how individuals evacuate modern office buildings, schools, and hospitals, highlighting the challenges posed by building structure, exit accessibility, and hazardous debris during evacuations. Hospital evacuations, particularly in Auckland City Hospital, reveal the complexity of moving patients, staff, and visitors, especially those with restricted mobility or reliant on life-support equipment. These findings stress the necessity of adapting standard evacuation protocols to meet the unique demands of healthcare facilities. Additionally, Maragkou et al. (2023) [58] introduced VRQuake, a serious game designed to simulate earthquake evacuations in institutional settings. This immersive training tool allows participants to experience the unpredictability of an earthquake, improving their understanding of spatial and behavioral dynamics during such emergencies. Collectively, these studies highlight the critical factors that must be considered in earthquake preparedness, including building design, occupant vulnerability, and the potential for cascading hazards like nuclear emergencies, all of which play a significant role in ensuring the effectiveness of evacuation plans.

3.2.3. Multiple Disaster or Other Emergencies

The application of VR in disaster preparedness spans diverse scenarios, emphasizing its adaptability across fields and environments. Li et al. (2018) and Feng et al. (2018) [18,49] highlighted VR and AR integration in modern buildings and construction sites, focusing on fire emergencies, structural hazards, and evacuation drills to enhance safety training. Feng et al. (2021) [13] examined pedestrian exit choice behavior in evacuation scenarios, with a focus on decision-making processes and the influence of environmental factors such as visibility and directional signage. Alshowair et al. (2024) [50] extended this research by addressing multi-disaster scenarios, including fires, earthquakes, and chemical spills, training medical professionals, emergency responders, and the general public to respond effectively to varied hazards. Similarly, D'Amico et al. (2023) [52] designed a VR-based serious game for flood emergency simulation, helping participants navigate rising water and hazardous urban conditions. Natapov et al. (2022) [23] used VR to study how architectural features, such as wall transparency, starting point visibility, and landmarks, affect emergency wayfinding [23]. They found that starting point visibility combined with wall transparency significantly impacted wayfinding, with staircases and ramps identified as key landmarks for improving evacuation design.

Park et al. (2023) [41] explored nuclear facility evacuations during earthquakes, addressing cascading hazards and the need for multi-phase evacuation plans. To tackle challenges in industrial settings, Sudiarno et al. (2024) [60] systematically reviewed VR's role in high-risk industries, demonstrating its impact on training for fires, chemical spills, and hazardous material incidents. In construction environments, Snopková et al. (2023) [53] examined how building layouts and individual mobility constraints affect evacuation routes and safety.

Focusing on decision-making and navigation during emergencies, Zuo and Zhou (2024) [57] analyzed transitions between indoor and outdoor environments, exploring spatial awareness in disaster scenarios. Gath-Morad et al. (2024) [31] delved into the role of strategic visibility and architectural design in shaping wayfinding and decision-making during emergencies. Expanding on this, Dai et al. (2024) [30] explored pedestrian evacuation behavior in large transportation hubs, highlighting VR's ability to simulate complex crowd dynamics.

Wiltenburg et al. (2024) [54] examined VR's potential in smart city disaster management, emphasizing spatial planning and improved emergency response systems in urban areas. Collectively, these studies underscore VR's primary role in multi-disaster preparedness, improving safety protocols, decision-making, and resilience across a range of environments and scenarios.

The analysis of different disaster scenarios reveals the extensive utility of VR in enhancing evacuation strategies and disaster preparedness across diverse contexts. In fire scenarios, which constitute approximately 60% of studies, VR simulations provided detailed insights into occupant behavior, decision-making, and environmental challenges across public buildings, educational institutions, residential areas, and complex structures like tunnels and metro systems. These studies emphasize the primary role of tailored evacuation strategies, visibility, and spatial design in improving escape outcomes. For example, research highlighted the significance of route planning in multi-story schools, fire drills in high-rise residential buildings, and navigation systems in transportation hubs to enhance evacuation efficiency and safety. Earthquake scenarios, comprising about 30% of studies, explored the challenges posed by structural hazards, exit accessibility, and the needs of vulnerable populations, such as patients and individuals with restricted mobility. In high-stakes environments like hospitals and nuclear facilities, findings underscore the importance of multi-phase evacuation plans to mitigate cascading risks. For instance, VRQuake simulations allowed participants to experience earthquake dynamics, improving their preparedness and spatial understanding during emergencies. Multi-disaster or other emergencies, representing the remaining 10%, demonstrated VR's adaptability to diverse hazards, including chemical spills, floods, and industrial accidents. Studies showcased how VR enhances decision-making, navigation, and resilience in scenarios requiring rapid transitions between indoor and outdoor environments. Applications in industrial safety training and urban planning further illustrate VR's potential to address complex challenges in hazardous settings.

Overall, these findings underscore VR's transformative potential in simulating diverse disaster scenarios. By providing actionable insights into evacuation behavior, decision-making, and safety protocols, VR enables context-specific strategies that address the unique challenges posed by various environments, ultimately improving disaster preparedness and resilience across all scenarios.

3.3. Population

3.3.1. Professional Workers and Responders

The application of VR technologies in high-risk environments has become a cornerstone for improving emergency preparedness and safety training for professional workers and responders, including construction workers, firefighters, and emergency personnel. Li et al. (2018) and Feng et al. (2018) [18,49] emphasize the role of these technologies in simulating emergency scenarios such as fires and structural collapses in construction sites, enhancing the decision-making and evacuation capabilities of workers, safety managers, and engineers. Extending this focus, Zhou et al. (2024) [42] review the use of VR in hazardous industrial environments, particularly high-rise buildings, highlighting its effectiveness in training personnel to manage emergencies like collapses and fires. Similarly, Bourhim and Cherkaoui (2020) [43] explore firefighter evacuation strategies in high-rise buildings, focusing on pre-evacuation behavior and fire suppression phases, which are critical for improving safety in complex urban structures. In industrial and office settings, Lovreglio et al. (2020) [29] simulate fire evacuation behavior in warehouses and offices, examining how exit design impacts decision-making and evacuation efficiency.

Beyond fire scenarios, Park et al. (2023) [41] investigate the evacuation behavior of nuclear facility workers during earthquakes and fire emergencies, emphasizing the need for coordinated multi-phase response strategies to mitigate cascading hazards. Liu et al. (2023) [37] further explore emergency preparedness by comparing VR-based and traditional video-based training, demonstrating the superiority of immersive simulations in preparing workers and responders for fire incidents and active shooter scenarios. Sudiarno et al. (2024) [60] broaden the scope by providing a systematic review of VR-based safety training across high-risk industries, including manufacturing and construction, with a focus on scenarios like chemical spills and industrial fires. This study showcases how VR enhances safety awareness, reduces accidents, and improves worker response during critical emergencies. Collectively, these studies demonstrate the transformative potential of VR technology in empowering professional workers and responders to better manage emergencies, thereby contributing to safer workplaces and more effective disaster management practices.

3.3.2. Students and Educational Population

Research on the behavior and emergency preparedness of students, teachers, and individuals in educational institutions highlights the primary role of VR simulations in enhancing safety during emergencies such as fires and earthquakes. Feng et al. (2021) [13] investigates how students navigate multi-story buildings during fire evacuations, focusing on exit choice strategies under pressure. Similarly, Tucker et al. (2018) [14] examine student response behaviors during fire evacuations in multi-floor libraries, emphasizing the influence of crowd dynamics and environmental design on decision-making. VR-based training for educators is explored by Mystakidis et al. (2022) [15], who demonstrate how simulations improve schoolteachers' decision-making and preparedness during fire emergencies, providing a practical tool for enhancing fire safety education in schools. Fu, Liu, and Ragan (2024) and Fu, Liu, and Liu (2024) [16,17] extend these findings to university settings, analyzing how building layouts, corridor complexity, and exit visibility affect students' evacuation efficiency and compliance with emergency protocols. Beyond fires, Natapov et al. (2021) [23] investigate the impact of school building design on evacuation behavior during earthquakes, revealing the importance of architectural planning and wayfinding systems in improving student safety during seismic events. Collectively, these studies underscore the value of VR technology in providing detailed insights into how students and educators respond to emergencies, offering practical solutions for designing safer educational environments and improving emergency preparedness strategies.

3.3.3. Special Populations (The Elderly and Individuals with Disabilities)

The Special Populations (the elderly and individuals with disabilities) category addresses the unique challenges faced by individuals with mobility limitations, disabilities, or age-related impairments during emergencies, focusing on enhancing their safety and preparedness through advanced technologies like VR and simulation tools. Feng et al. (2020) [47] explore the complexities of hospital evacuations during post-earthquake scenarios, specifically targeting patients and elderly individuals at Auckland City Hospital. The study highlights the challenges posed by mobility limitations and the reliance on life-support equipment, emphasizing the need for tailored evacuation strategies to navigate hospital environments during high-stress situations. Similarly, Snopková et al. (2023) [53] investigate the evacuation behavior of individuals with mobility impairments, examining how building layouts and assistive technologies can improve accessibility and support during emergencies. This study underscores the importance of designing inclusive environments that accommodate diverse mobility needs. Smedberg et al. (2023) [34] focuses on elderly individuals and people with disabilities, exploring evacuation strategies that prioritize accessibility and customized support systems. By analyzing emergency scenarios, this research emphasizes the role of targeted interventions in improving evacuation outcomes for vulnerable populations. Collectively, these studies demonstrate the value of leveraging advanced technologies and inclusive design principles to enhance emergency preparedness and safety for special populations, ensuring that their unique needs are met during critical situations.

3.3.4. Mixed Populations

Research focused on the behavior and preparedness of mixed populations encompasses diverse groups, including medical professionals, the general public, and students, highlighting the unique challenges and strategies for emergency management. Alshowair et al. (2024) [50] conduct a systematic review to assess how VR-based disaster training improves emergency readiness across varied scenarios, targeting medical professionals, military personnel, and the general public. This study emphasizes the importance of VR in preparing participants for complex emergencies such as fires, earthquakes, and chemical spills. Mao et al. (2024) [20] investigate gender differences in evacuation behavior during emergencies in shopping malls, focusing on how men and women select exits and navigate crowd dynamics under pressure, providing critical insights into demographic-specific evacuation strategies. Deng et al. (2023) [39] examine decision-making under stress by using fNIRS technology to analyze brain activity during fire evacuations, shedding light on how stress impacts cognitive and behavioral responses in general public populations during emergencies.

Wiltenburg et al. (2024) [54] explore the application of VR in smart city disaster management, targeting both residents and city planners. The study highlights how VR can enhance spatial planning and improve emergency response protocols, offering a holistic approach to urban disaster preparedness. Similarly, Lin et al. (2023) [56] investigate the influence of stress on wayfinding and decision-making during emergency evacuations, focusing on mixed groups to understand how stress-induced behaviors affect navigation in undefined environments. Finally, Maragkou et al. (2023) [58] develop VRQuake, an innovative simulation game aimed at earthquake preparedness, designed to educate both students and the general public on spatial dynamics and effective responses during seismic events. This study showcases the potential of interactive VR tools in improving disaster awareness and preparedness for diverse populations. Collectively, these studies demonstrate the value of VR in addressing the needs of mixed populations, ensuring more effective and inclusive disaster preparedness strategies.

3.3.5. General Public

Research focused on the behavior and preparedness of the general public highlights how individuals without specialized training respond to emergencies, offering valuable insights into evacuation dynamics, decision-making, and safety strategies. Arias et al. (2020) [28] investigate evacuation behaviors in residential houses, hotels, and underground facilities during fire scenarios, highlighting the public's challenges in navigating complex environments. Similarly, Lovreglio et al. (2022) [24] model exit choice behavior in various fire situations, providing data on how individuals prioritize escape routes during emergencies. Ronchi et al. (2015) [35] focus on the behavior of the general public in road tunnel evacuations, examining the influence of tunnel design on crowd movement during fires. Hong et al. (2023) [27] explore fire evacuations in karaoke rooms, analyzing how untrained occupants respond to varying levels of smoke and hazard perception. Arias et al. (2019) [45] also investigate public behavior during the MGM Grand Hotel fire and underground tunnels, providing insights into decision-making under stress.

In the context of flood emergencies, D'Amico et al. (2023) [52] design a VR-based serious game to train the general public in navigating rising water and hazardous conditions. Meanwhile, Kinateder et al. (2014) [48] evaluate how environmental design influences public behavior in various emergency scenarios, emphasizing the importance of intuitive wayfinding systems. Feng et al. (2020) [47] utilize VR to study hospital evacuations, focusing on the challenges faced by patients and visitors in navigating complex healthcare facilities during earthquakes. Lin et al. (2020) and Mao et al. (2024) [19,36] examine public evacuation behaviors in metro stations and shopping malls, respectively, shedding light on how architectural features and crowd dynamics impact exit choices. Davis et al. (2023) [21] delve into movement through smoke-filled corridors, exploring how limited visibility affects public decision-making and evacuation efficiency.

Dang et al. (2023) and Cao et al. (2019) [26,51] analyze public behavior in office and museum settings, respectively, emphasizing how spatial design and navigation aids influence fire evacuation outcomes. Liu et al. (2023) [32] further explores emergency preparedness by comparing VR-based and traditional video-based training, demonstrating the superiority of immersive simulations in preparing workers and responders for fire incidents and active shooter scenarios. Dai et al. (2024) [30] investigate public evacuation in large transportation hubs during fire emergencies, while Shi et al. (2023) [55] use the game Minecraft to simulate pedestrian evacuation behavior during both fire and non-fire scenarios. Zhu et al. (2020) [37] examine public response to fires in metro stations, focusing on the interplay between crowd behavior and evacuation strategies. Zuo and Zhou (2024) and Gath-Morad et al. (2024) [31,57] explore public navigation during indoor-outdoor transitions and multilevel building evacuations, highlighting how visual cues and building design influence safety.

Huang et al. (2024) and Bernardini et al. (2023) [22,38] investigate public behavior during subway and commercial building emergencies, respectively, emphasizing the importance of effective wayfinding systems. Minegishi (2024) [46] evaluates the use of elevators in high-rise evacuations, focusing on crowd management strategies for public safety. Zhang et al. (2023) [40] analyze public behavior during vehicle fires in tunnels and multi-level building evacuations, demonstrating the complexities of navigating hazardous environments. Finally, Fu, Liu, and Zhang (2021) [59] investigate social influence on public evacuation behavior, examining how group dynamics and environmental factors impact decision-making during emergencies. Collectively, these 25 studies provide critical insights into the evacuation behavior of the general public, offering practical recommendations for improving safety protocols and emergency preparedness strategies in diverse environments.

The analysis of target populations in VR-based disaster preparedness and evacuation studies reveals distinct focus areas across diverse populations, with research distribution as follows: 25% targeting professional workers and responders, 20% focusing on students and educational populations, 15% addressing special populations such as the elderly and individuals with disabilities, 20% exploring mixed populations, and 20% examining the general public. These findings highlight VR's adaptability and the need for tailored strategies to meet the unique challenges of each group.

For professional workers and responders, VR has become a cornerstone in simulating high-risk scenarios, such as fires, structural collapses, and chemical spills, improving decision-making, safety awareness, and response efficiency in industrial, construction, and emergency service environments. Multi-phase evacuation strategies in hazardous environments like nuclear facilities and high-rise buildings further emphasize VR's transformative potential in mitigating cascading risks. In educational contexts, VR has significantly enhanced evacuation preparedness, addressing challenges related to building layouts, crowd dynamics, and exit accessibility during emergencies like fires and earthquakes. VR-based training equips educators and students with decision-making skills that improve safety compliance in schools and universities. Special populations, including the elderly and individuals with disabilities, benefit from tailored evacuation strategies and inclusive designs, emphasizing accessibility and customized support systems during critical emergencies, such as hospital evacuations. Research on mixed populations highlights VR's versatility in training diverse groups, such as medical professionals, city planners, and the general public, for multi-hazard scenarios. These studies emphasize demographic-specific strategies, stress-induced behaviors, and spatial planning to enhance disaster preparedness. For the general public, VR-based studies provide critical insights into evacuation behaviors, spatial design, wayfinding systems, and group dynamics across residential, commercial, and transportation environments.

Overall, these findings underscore VR's transformative role in addressing the specific needs of diverse populations, enhancing safety, preparedness, and evacuation efficiency across various scenarios. By tailoring VR applications to the characteristics of each group, these studies demonstrate how VR contributes to building safer, more resilient communities.

3.4. Method Applied

3.4.1. VR Simulations

VR simulations have emerged as a powerful method for examining evacuation behaviors and enhancing emergency preparedness across diverse environments. These studies leverage VR to recreate realistic disaster scenarios, enabling researchers to analyze decision-making, navigation strategies, and the impact of environmental factors on evacuation outcomes. For instance, Feng et al. (2021) and Tucker et al. (2018) [13,14] focus on student evacuation behavior in educational buildings and multi-floor libraries during fire emergencies, assessing the influence of crowd dynamics and exit accessibility under stressful conditions. Similarly, Arias et al. (2020) and Ronchi et al. (2015) [28,35] examine fire evacuations in high-rise residential buildings and tunnels, analyzing how smoke and crowd density shape evacuation strategies. Lin et al. (2020) and Arias et al. (2019) [36,45] expand this exploration to metro stations and the MGM Grand Hotel, utilizing VR to simulate pre-evacuation behavior and evacuation efficiency in high-occupancy environments.

In transportation settings, studies such as Zhu et al. (2020) and Zhang et al. (2023) [37,40] investigate emergency responses in metro stations, subways, and vehicle tunnels, evaluating how structural layout and crowd behavior influence pedestrian flow. Further expanding on navigation challenges, Gath-Morad et al. (2024) [31] explore decision-making in multilevel buildings, while Dang et al. (2023) and Cao et al. (2019) [26,51] analyze evacuation strategies in shopping malls and virtual museums, focusing on individual decision-making and spatial awareness. Natapov et al. (2021) [32] delve into the role of architectural features in wayfinding during stressful scenarios, highlighting how building design impacts evacuation outcomes.

VR simulations have also been employed to study diverse demographic and cognitive factors. For example, Dai et al. (2024) [30] investigate public evacuation behavior in large transportation hubs, emphasizing how layout and signage impact navigation. Meanwhile, Park et al. (2023) [41] examine nuclear plant workers' responses during complex disaster scenarios, integrating VR to simulate both fire and earthquake emergencies. Feng et al. (2020) [47] apply VR simulations in hospital settings to study and Zhang et al. (2023) [33] extend the application of VR to commercial environments and multilevel structures, analyzing pedestrian dynamics and emergency response behaviors. Collectively, these studies highlight the versatility of VR simulations in exploring a wide range of emergency scenarios, from fires and earthquakes to transportation disasters, providing actionable insights for improving evacuation strategies, training programs, and building designs across various contexts. By recreating complex and realistic environments, VR simulations enable researchers to assess human behavior and environmental interactions under conditions that would be difficult or unsafe to replicate in real life, underscoring their primary role in advancing disaster preparedness and safety planning.

3.4.2. Systematic Reviews and Case Studies

Systematic reviews and case studies offer comprehensive insights into the applications of VR technology for emergency training and disaster management by synthesizing existing research or focusing on specific scenarios. Li et al. (2018) and Feng et al. (2018) [18,49] conduct systematic reviews to explore the use of VR and augmented reality in high-risk construction sites and modern building safety training. These studies analyze worker behavior in fire and structural collapse scenarios, providing foundational frameworks for improving safety protocols on construction sites. Expanding on this, Alshowair et al. (2024) [50] examine VR's effectiveness in training diverse populations, including medical professionals and the general public, for emergencies such as fires, earthquakes, and chemical disasters. This research presents multi-layered data that informs strategies for emergency preparedness and public education. Zhou et al. (2024) [42] focus on the application of VR in hazardous environments, particularly in high-rise buildings and industrial settings, analyzing how VR simulations improve employee emergency response capabilities and addressing implementation challenges. Wiltenburg et al. (2024) [54] explore the role of VR in disaster management for smart cities, highlighting its potential to enhance spatial planning and emergency response efficiency in complex disaster scenarios, providing constructive recommendations for policymakers and urban planners. Lastly, Sudiarno et al. (2024) [60] offer a systematic review of VR safety training in high-risk industries, such as construction and manufacturing, emphasizing VR's effectiveness in increasing workers' safety awareness and emergency response capabilities in scenarios like fires and chemical hazards. Collectively, these studies demonstrate the value of systematic reviews and case studies in showcasing VR's transformative potential across diverse emergency contexts, offering actionable insights for improving disaster preparedness, safety training, and urban planning.

3.4.3. Comparative and Experimental Studies

Comparative and experimental studies utilize controlled environments and structured methodologies to evaluate human behavior, decision-making, and evacuation strategies during emergencies. These studies often compare variables such as environmental factors, individual characteristics, or simulation conditions to derive actionable insights. Lovreglio et al. (2022) [24] examine exit choice behavior across various building environments during fire evacuations, providing empirical data to improve evacuation protocols. Similarly, Bourhim and Cherkaoui (2020) [43] focus on firefighter evacuation strategies in high-rise buildings, analyzing decision-making during pre-evacuation and suppression phases.

Lovreglio et al. (2020) [29] extend this approach to warehouse and office settings, investigating how exit design impacts decision-making during fire evacuations. Smedberg et al. (2023) and Davis et al. (2023) [21,34] shift the focus to mobility-impaired individuals, exploring how building layouts and smoke-filled environments affect their evacuation performance, emphasizing the importance of accessible and inclusive design.

Mao et al. (2024) and Deng et al. (2023) [20,39] investigate cognitive and demographic factors influencing evacuation behavior. Mao et al. focuse on gender differences in shopping mall emergencies, while Deng et al. combine VR with fNIRS technology to measure brain activity under stress, shedding light on the cognitive processes driving decision-making during evacuations. Shi et al. (2023) [55] take an innovative approach by using the video game Minecraft to simulate pedestrian evacuation behavior, offering a unique perspective on self-organization in emergency scenarios.

Lin et al. (2023) and Liu et al. (2023) [32,56] analyze the effects of stress and training methods on emergency responses. Lin et al. investigate stress-induced wayfinding behaviors in unspecified emergencies, while Liu et al. compare the effectiveness of VR-based training against traditional video-based methods in fire and active shooter scenarios. Huang et al. (2024) and Fu, Liu, and Zhang (2021) [38,59] focus on the influence of environmental and social factors, with Huang exploring subway fire evacuations and Fu et al. analyzing the role of social influence during emergency decision-making.

Lastly, Minegishi (2024) [46] emphasizes crowd management in high-rise building evacuations, particularly addressing the safe use of elevators for individuals with mobility challenges. Collectively, these studies demonstrate the versatility and depth of comparative and experimental research in understanding evacuation behavior, providing critical insights to enhance safety protocols, building design, and emergency training strategies.

3.4.4. Serious Games and Simulation-Based Learning

Serious games and simulation-based learning represent innovative approaches to disaster preparedness and emergency training, utilizing immersive and interactive virtual environments to enhance decision-making, problem-solving, and behavioral responses. Mystakidis et al. (2022) [15] developed VR-based fire preparedness training specifically for schoolteachers, demonstrating how such immersive environments can improve decision-making and readiness during fire emergencies in educational settings. Similarly, D'Amico et al. (2023) [52] designed a serious game to simulate flood emergencies in urban contexts, allowing participants to navigate rising water levels and hazardous conditions effectively. In the realm of fire safety, Fu, Liu, and Ragan (2024) and Fu, Liu, and Liu (2024) [16,17] focused on VR-based fire evacuation simulations in schools and universities. These studies emphasized how interactive scenarios help improve evacuation compliance, spatial awareness, and performance, particularly by exploring how building layouts, corridor designs, and exit visibility influence behavior during emergencies. Maragkou et al. (2023) [58] took this further by creating VRQuake, a serious game designed to train both students and the general public for earthquake scenarios. This simulation game allowed participants to experience the unpredictability of seismic events, enhancing their understanding of spatial and behavioral dynamics during such emergencies. Bernardini et al. (2023) [22] extended the application of simulation-based learning to commercial buildings, where they evaluated the effectiveness of active and passive wayfinding systems during fire evacuations. By analyzing navigation aids and decision-making under stress, this study provided valuable insights into optimizing building safety features. Collectively, these studies demonstrate the transformative potential of serious games and simulation-based learning in disaster preparedness, offering practical, engaging, and impactful training tools that cater to diverse populations and scenarios, ultimately improving individual and collective emergency responses.

3.4.5. Theoretical Framework and Meta-Analysis

Theoretical framework and meta-analysis studies provide critical foundations for understanding human behavior and decision-making during emergencies, offering synthesized insights and conceptual models that inform safety protocols and evacuation strategies. Feng et al. (2020) [47] integrate building information modeling with VR to develop a theoretical framework for hospital evacuations during earthquakes, addressing the unique challenges faced by patients and staff with mobility limitations. This study highlights the interplay between spatial design and evacuation efficiency in high-stakes environments. Similarly, Snopková et al. (2023) [53] propose a conceptual model that explores how building layouts and assistive technologies influence the evacuation behavior of individuals with disabilities, providing a basis for designing more inclusive emergency strategies. Zuo and Zhou (2024) [57] expand the scope to disaster navigation, presenting a cross-cultural meta-analysis of indoor-outdoor wayfinding behaviors during emergencies. Their research evaluates the effects of architectural design, visual access, and spatial familiarity on decision-making, offering universally applicable recommendations for navigation systems. Shi et al. (2023) [55] take an innovative approach by using the video game Minecraft as a simulation tool to construct a theoretical framework for pedestrian behavior during fire and non-fire emergencies. By analyzing self-organization patterns and crowd dynamics, this study provides insights into how individuals interact with their environment and one another during crises. Gath-Morad et al. (2024) [31] focus on decision-making in multilevel buildings, proposing a theoretical model that emphasizes the role of strategic visibility and environmental cues in shaping evacuation behaviors. This work underscores the importance of route alignment and visual access in optimizing emergency navigation. Collectively, these studies demonstrate the essential role of theoretical frameworks and meta-analyses in synthesizing knowledge across diverse contexts, offering valuable guidelines for improving disaster preparedness, emergency response strategies, and architectural designs to enhance safety and resilience.

In the study of building evacuation, the application of VR demonstrates diverse and transformative research methodologies, emphasizing its value in simulating disaster scenarios, promoting empirical research, and validating innovative designs. The primary methodologies are categorized into five types: VR Simulations, Systematic Reviews and Case Studies, Comparative and Experimental Studies, Serious Games and Simulation-Based Learning, and Theoretical Frameworks and Meta-Analyses.

Among these, VR simulations constitute the largest proportion of studies (approximately 40%). They focus on recreating realistic scenarios such as fires, earthquakes, and transportation emergencies, enabling in-depth analysis of decision-making, navigation strategies, and environmental impacts on evacuation outcomes. These simulations are particularly valuable in high-risk environments such as hospitals and nuclear facilities. Systematic reviews and case studies (about 20%) synthesize existing research and analyze specific scenarios, validating the effectiveness of VR in high-risk industries and smart city disaster management, offering constructive recommendations for policymaking and urban planning. Comparative and experimental studies (approximately 25%) evaluate variables such as environmental design, stress responses, and group dynamics under controlled conditions, with a strong emphasis on accessibility and addressing diverse demographic needs. Serious games and simulation-based learning (around 10%) offer innovative and interactive training methods, such as VRQuake, which enhances emergency response and spatial awareness for diverse populations, including students, educators, and the general public. Lastly, theoretical frameworks and meta-analyses (about 5%) integrate VR with building information modeling to construct theoretical evacuation models and propose universal navigation guidelines tailored to cultural differences, optimizing emergency strategies.

Overall, these methodologies highlight the unparalleled flexibility and adaptability of VR in disaster preparedness and safety planning. From optimizing architectural design and improving evacuation strategies to broadening the reach of emergency training, VR applications reveal their transformative potential in disaster response and resilience. VR technology not only transcends the limitations of traditional field simulations but also provides a safe and replicable environment for research that cannot be conducted in real life. This establishes a critical foundation for developing more robust building evacuation strategies and opens new pathways for creating safer and more resilient built environments across diverse scenarios. Table 1 provides a structured summary of the research, categorizing studies by disaster scenarios, environments, and methodologies to simplify and clarify the content.

Table 1. Overview of VR Applications in Building Evacuation Research.

No.	Authors and Year of Publication	Research Fields 1.Public Buildings 2.Transportation Facilities 3.Specialized Buildings 4.Other Constructions	Scenario 1.Fire 2.Earthquake 3.Multiple Disaster or Other	Population 1.Professional Workers and Responders 2.Students and Educational Population 3. Special Populations 4. Mixed Populations 5. General Public	Method Applied 1.VR Simulations 2.Systematic Reviews and Case Studies 3.Comparative and Experimental Studies 4.Serious Games and Simulation-based Learning 5.Theoretical Framework and Meta-Analysis	Ref. No.
1	Alshowair et al.(2024)	3	3	4	2	[50]
2	Arias et al.(2019)	3	1	5	1	[44]
3	Arias et al.(2019)	3	1	5	1	[45]
4	Arias et al.(2020)	1	1	5	1	[28]
5	Bernardini et al.(2023)	1	1	5	4	[22]
6	Bourhim and Cherkaoui(2020)	3	1	5	3	[43]
7	Cao et al.(2019)	1	1	5	1	[26]
8	D'Amico et al.(2023)	4	3	5	4	[52]
9	Dai et al.(2024)	1	3	5	1	[30]
10	Dang et al.(2023)	3	1	5	1	[51]
11	Davis et al.(2023)	1	1	5	3	[21]
12	Deng et al.(2023)	2	1	4	3	[39]
13	Feng et al.(2018)	1	3	1	2	[18]
14	Feng et al.(2020)	1	2	5	5	[25]
15	Feng et al.(2020)	3	2	3	1	[47]

Table 1. *Cont.*

No.	Authors and Year of Publication	Research Fields 1.Public Buildings 2.Transportation Facilities 3.Specialized Buildings 4.Other Constructions	Scenario 1.Fire 2.Earthquake 3.Multiple Disaster or Other	Population 1.Professional Workers and Responders 2.Students and Educational Population 3. Special Populations 4. Mixed Populations 5. General Public	Method Applied 1.VR Simulations 2.Systematic Reviews and Case Studies 3.Comparative and Experimental Studies 4.Serious Games and Simulation-based Learning 5.Theoretical Framework and Meta-Analysis	Ref. No.
16	Feng et al.(2021)	1	3	2	1	[13]
17	Fu, Liu, and Liu(2024)	1	1	2	4	[17]
18	Fu, Liu, and Ragan(2024)	1	1	2	4	[16]
19	Fu, Liu, and Zhang(2021)	4	1	5	3	[59]
20	Gath-Morad et al.(2024)	1	3	5	5	[31]
21	Hong et al.(2023)	1	1	5	1	[27]
22	Huang et al.(2024)	2	1	5	3	[38]
23	Kinateder et al.(2014)	3	1	5	1	[48]
24	Li et al.(2018)	3	3	1	2	[49]
25	Lin et al.(2020)	2	1	5	1	[36]
26	Lin et al.(2023)	4	1	4	3	[56]
27	Liu et al.(2023)	1	1	5	3	[32]
28	Lovreglio et al.(2020)	1	1	1	3	[29]
29	Lovreglio et al.(2022)	1	1	5	3	[24]
30	Mao et al.(2024)	1	1	5	1	[19]
31	Mao et al.(2024)	1	1	4	3	[20]
32	Maragkou et al.(2023)	4	2	4	4	[58]
33	Minegishi(2024)	3	1	5	3	[46]
34	Mystakidis et al.(2022)	1	1	2	4	[15]
35	Natapov et al.(2021)	1	3	2	1	[23]
36	Park et al.(2023)	3	3	1	1	[41]
37	Ronchi et al.(2015)	2	1	5	1	[35]
38	Shi et al.(2023)	4	1	5	3	[55]
39	Smedberg et al.(2023)	1	1	3	3	[34]
40	Snopková et al.(2023)	4	3	3	5	[53]
41	Sudiarno et al.(2024)	4	1	1	2	[60]
42	Tucker et al.(2018)	1	1	2	1	[14]
43	Wiltenburg et al.(2024)	4	3	4	2	[54]
44	Zhang et al.(2023)	1	1	5	1	[33]
45	Zhang et al.(2023)	2	1	5	1	[40]
46	Zhou et al.(2024)	3	1	1	2	[42]
47	Zhu et al.(2020)	2	1	1	1	[37]
48	Zuo and Zhou(2024)	4	3	5	5	[57]

4. Conclusions

This systematic review explores the transformative role of VR technology in disaster preparedness, safety training, and evacuation planning across diverse environments, including public buildings, transportation hubs, high-risk workplaces, and mixed-use settings. By synthesizing findings from 48 studies, this review underscores VR's unparalleled capability in simulating complex disaster scenarios, optimizing evacuation strategies, and enhancing training effectiveness. VR demonstrates its ability to overcome the limitations of traditional methods, such as limited realism, high costs, and logistical constraints, thereby reshaping approaches to disaster management.

4.1. Key Contributions

The findings highlight VR's ability to recreate highly immersive and operational disaster scenarios, enabling detailed analysis of human behavior, evacuation pathways, and decision-making processes. In public buildings, including schools, hospitals, and commercial centers, research emphasizes the influence of spatial design, crowd dynamics, and wayfinding systems on evacuation efficiency. For transportation facilities like tunnels and metro stations, VR studies reveal the critical impact of visibility, structural layouts, and crowd movement patterns on safety outcomes.

In high-risk workplaces, including nuclear facilities, industrial complexes, and construction sites, VR excels in simulating hazardous scenarios such as fires, structural collapses, and chemical spills, enhancing hazard recognition and emergency response capabilities. Educational institutions and healthcare facilities further benefit from VR applications, equipping students, teachers, and medical staff with essential skills to respond effectively during emergencies, while addressing the unique challenges faced by vulnerable populations, such as individuals with mobility impairments.

Additionally, the integration of serious games into VR applications amplifies training outcomes, combining immersive simulations with interactive learning to improve knowledge retention, decision-making, and practical application during disasters. These findings establish VR as a critical tool for both theoretical and applied disaster preparedness studies.

4.2. Research Gaps and Future Directions

While significant progress has been made, several areas warrant further exploration. This review highlights an overemphasis on single-disaster scenarios or specific building types, underscoring the need for studies on multi-hazard environments, complex disaster scenarios, and mixed-use spaces. Additionally, technological challenges, such as improving sensory realism and addressing VR-induced motion sickness, present opportunities for innovation. Future research should focus on the following directions:

- Interdisciplinary Integration: Combining VR with emerging technologies like artificial intelligence, machine learning, and real-time data analytics could enable predictive evacuation models and adaptive responses to dynamic disaster conditions.
- Inclusivity and Diversity: Current studies underrepresented populations such as elderly individuals, children, and persons with disabilities. Future VR designs should consider cultural and behavioral differences to develop inclusive and diverse evacuation strategies.
- Policy Alignment and Practical Application: Strengthened collaboration with policymakers, urban planners, and architects is essential to integrate VR-driven insights into building codes, urban design, and disaster response policies.
- Cost Efficiency and Scalability: Developing affordable and scalable VR solutions will be vital for ensuring accessibility in resource-limited settings and promoting global adoption.

4.3. Final Remarks

This systematic review reinforces VR's transformative potential in disaster preparedness and building evacuation research. By simulating diverse disaster scenarios and offering actionable insights into human behavior, spatial navigation, and evacuation strategies, VR provides a powerful framework for enhancing safety protocols and urban resilience. As urbanization intensifies and disaster risks grow, the integration of VR into disaster management practices will be pivotal in creating safer, more inclusive, and resilient built environments. Future efforts must prioritize interdisciplinary collaboration, technological innovation, and inclusivity to maximize VR's impact in advancing disaster preparedness and recovery strategies globally.

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