ARTIGO

VIRTUAL REALITY STUDY ON SIGNAGE IN SUBWAY VENTILATION AND EMERGENCY EXIT STRUCTURES

ESTUDO EM REALIDADE VIRTUAL SOBRE SINALIZAÇÃO EM ESTRUTURAS DE VENTILAÇÃO E SAÍDAS DE EMERGÊNCIA DE METRÔ

ESTUDIO DE REALIDAD VIRTUAL SOBRE LA SEÑALIZACIÓN EN ESTRUCTURAS DE VENTILACIÓN Y SALIDAS DE EMERGENCIA DEL METRO

Ana Regina Mizrahy Cuperschmid[1], Douglas Henrique Dantas Nanni[1]

ABSTRACT:

Though emergencies prompting area evacuation are rare, they can lead to tense and chaotic situations. Considering this, evacuation simulations play a crucial role in comprehending critical points along exit routes and suggesting potential enhancements. In the context of subway lines, there are occasions when it is necessary to plan structures for Ventilation and Emergency Exit (in Portuguese: Ventilação e Saída de Emergência - VSE) between stations. The use of emergency signage is mandatory, and its purpose is to assist people in choosing the fastest and safest route to exit the area. This study aims to assess and compare the effectiveness of two distinct emergency exit signage proposals within a VSE project in São Paulo's subway system, utilizing Virtual Reality (VR). Simulations conducted in a virtual environment involved voluntary participants, divided into two groups, each experiencing different signage proposals. Throughout the simulation, evacuation times were recorded, and participant behavior was observed. Additionally, a questionnaire was administered to evaluate participants' profiles, experiences, well-being, and the perceived effectiveness of the signage. Results indicated that scenarios featuring larger signage facilitated quicker VSE evacuations, suggesting it as the most favorable scenario for user safety.

KEYWORDS: evacuation efficiency; immersive environments; safety assessment; wayfinding.

[1]Universidade Estadual de Campinas (UNICAMP), Departamento de Arquitetura e Construção, Faculdade de Engenharia Civil, Arquitetura e Urbanismo.

Conflito de Interesse: Declaramos não haver conflitos de interesse.

Ética em Pesquisa: CAAE: 60486322.7.0000.8142 CEPUNICAMP: 5.586.240

Submetido em: 11/03/2024
Aceito em: 02/07/2024

How to cite this article:

CUPERSCHMID, Ana Regina Mizrahy; NANNI, Douglas Henrique Dantas. Virtual Reality study on signage in subway ventilation and emergency exit structures. **Gestão & Tecnologia de Projetos**. São Carlos, v19, n2, 2024. https://doi.org/10.11606/222724

RESUMO:

Embora as emergências que exigem a evacuação da área sejam raras, elas podem levar a situações tensas e caóticas. Considerando isso, as simulações de evacuação desempenham um papel crucial para compreender pontos críticos ao longo das rotas de saída e sugerir possíveis melhorias. No contexto das linhas de metrô, há ocasiões em que é necessário planejar estruturas para Ventilação e Saída de Emergência (VSE) entre as estações. O uso de sinalização de emergência é obrigatório, e sua finalidade é ajudar as pessoas a escolherem a rota mais rápida e segura para sair da área. Este estudo tem como objetivo avaliar e comparar a eficácia de duas propostas distintas de sinalização de saída de emergência dentro de um projeto VSE no sistema de metrô de São Paulo, utilizando Realidade Virtual (VR). As simulações realizadas em um ambiente virtual envolveram participantes voluntários, divididos em dois grupos, cada um experimentando propostas de sinalização diferentes. Ao longo da simulação, os tempos de evacuação foram registrados e o comportamento dos participantes foi observado. Além disso, um questionário foi administrado para avaliar o perfil, as experiências, o bem-estar dos participantes e a eficácia percebida da sinalização. Os resultados indicaram que cenários com sinalização de maior dimensão facilitaram evacuações mais rápidas das VSEs, sugerindo ser o cenário mais favorável para a segurança dos usuários.

PALAVRAS-CHAVE: eficiência de evacuação, ambientes imersivos, avaliação de segurança, orientação espacial.

RESUMEN:

Aunque las emergencias que requieren la evacuación del área son raras, pueden llevar a situaciones tensas y caóticas. Considerando esto, las simulaciones de evacuación desempeñan un papel crucial para comprender puntos críticos a lo largo de las rutas de salida y sugerir posibles mejoras. En el contexto de las líneas de metro, hay ocasiones en que es necesario planificar estructuras para Ventilación y Salida de Emergencia (en portugués: VSE - Ventilação e Saída de Emergência) entre las estaciones. El uso de señalización de emergencia es obligatorio, y su finalidad es ayudar a las personas a elegir la ruta más rápida y segura para salir del área. Este estudio tiene como objetivo evaluar y comparar la eficacia de dos propuestas distintas de señalización de salida de emergencia dentro de un proyecto VSE en el sistema de metro de São Paulo, utilizando Realidad Virtual (VR). Las simulaciones realizadas en un ambiente virtual involucraron a participantes voluntarios, divididos en dos grupos, cada uno experimentando propuestas de señalización diferentes. A lo largo de la simulación, se registraron los tiempos de evacuación y se observó el comportamiento de los participantes. Además, se administró un cuestionario para evaluar el perfil, las experiencias, el bienestar de los participantes y la eficacia percibida de la señalización. Los resultados indicaron que los escenarios con señalización de mayor tamaño facilitaron evacuaciones más rápidas de las VSE, sugiriendo que es el escenario más favorable para la seguridad de los usuarios.

PALABRAS CLAVE: eficiencia de evacuación, ambientes inmersivos, evaluación de seguridad, orientación espacial.

INTRODUCTION

Public policy advocates for substantial investments in transportation infrastructure, particularly in the realm of public transit, owing to their potential to enhance urban appeal, foster social equity, alleviate traffic congestion, and mitigate accidents. Notably, metropolitan transit lines have witnessed considerable investment growth, attributed to the significant expansion of subway lines since 1950 (Bono et al., 2022). The surge in investments in subway systems is justified by their capacity to reduce car traffic density, their adaptability for implementation in large urban centers due to their subterranean nature, and the embodiment of a modernity concept.

There has been a noticeable surge in investments within this sector in Brazil. Specifically, in the municipality of São Paulo, the Subway system surpassed its record for expansion and modernization investments in 2023 (ABIFER, 2024). The primary rationale behind the infrastructure investment in São Paulo, which has witnessed annual growth, is the pursuit of ameliorating the chaotic urban mobility stemming from the nearly 11.5 million inhabitants residing in the city (IBGE, 2023). This figure is exacerbated by the pendular migration of individuals living in surrounding cities but working or studying in São Paulo. This demographic constitutes approximately 1.2 million people residing in the São Paulo Metropolitan Region with employment ties in the capital (Lameira and Golgher, 2021), in addition to the student population.

Subway projects are meticulously planned and executed based on standards and guidelines aimed at ensuring user safety. In Brazil, emergency evacuation procedures are primarily supported by Technical Instructions from the Fire Department. These instructions treat fires as critical situations, serving as premises for project development. Due to the high concentration of people, incidents and disasters related to fires tend to cause significant damage and put many lives at risk (Lin et al., 2024). Emergency signage, lighting, escape routes, and emergency exits are considered crucial for efficient evacuation during fire situations (Uliana et al., 2022). However, these elements may be compromised due to visual impediments such as smoke or flames.

Technologies, particularly Virtual Reality (VR), serve as robust allies in the examination of diverse evacuation scenarios. This is because, aside from enabling the simulation of the environment based on the architectural features of the structure, it also allows the incorporation of variables such as obstacles, visual factors, and characteristics of the studied population.

Studies suggest that immersive VR technologies can enhance emergency preparedness, training, and evacuation effectiveness in various disaster scenarios by simulating realistic environments and improving decision-making, signage evaluation, and performance in building evacuations (Lovreglio and Kinateder, 2020; Yu et al., 2022). It has been used in various sectors, including maritime (Vukelic et al., 2023), healthcare (Martin et al., 2020), and industrial settings (Lin et al., 2002).

The use of VR in evacuation scenarios for fire situations in subway environments is a crucial area of study. VR technologies have been shown to complement conventional research approaches, offering promising complementary laboratory tools to improve fire safety (Ghizlane et al., 2022). They provide vivid, interactive, and immersive platforms to practice and optimize evacuation plans, modeling staff behaviors and their implications on passengers' evacuation (Wang et al., 2023).

Some studies highlight the applicability of VR in contexts such as behavioral analysis during emergency evacuations and exit choice. Feng, Duives and Hoogendoorn (2021) used VR to analyze evacuation behavior in emergency situations, focusing on aspects such as cognitive performance, interaction, and system suitability for the design. The assessment employed methods such as questionnaires, Likert scales, and heuristic evaluation. The results indicated satisfactory cognitive performance by participants in the VR immersion, although discomforts were observed, such as a sense of nausea and difficulty in movement with the keyboard.

Mandal, Rao and Tiwari (2022) addressed exit choice in emergency evacuation situations in subways using a partially immersive VR experience. Participants were exposed to various simulated scenarios, varying conditions such as crowd density, queue time, presence of smoke, among others. The results emphasized the participants' agility in the virtual simulation, with a preference for choosing exits with higher people flow. It was also observed that the presence of smoke and the distance to exits influenced participants' choices.

Despite challenges and discomforts reported by participants, the results indicated the effectiveness of VR in providing immersive experiences that contributed to the understanding and analysis of complex situations, fostering valuable insights and improvements in areas such as fire safety and emergency management. Studies have demonstrated the effectiveness of VR-based fire evacuation simulation, offering a new method that overcomes the limitations of traditional approaches, such as low realism, limited interactions, and lack of user study (Liang et al., 2020). It can also incorporate natural user interfaces to simulate realistic movements and interactions within a virtual environment, enhancing the experience (Minegishi; Takahashi; Ikehata, 2022).

Using VR can enhance the assessment and enhancement of emergency signage by offering valuable insights into how individuals detect and respond to signage during evacuations (Sookhanaphibarn et al., 2016). This technology enables the study of human behavior and the testing of evacuation signs in a secure and controlled environment (Occhialini et al., 2016). In essence, emergency signs play a crucial role in wayfinding, effectively reducing the time required for an emergency escape (Tang; Wu; Lin, 2009).

However, there is a need for further research to address the existing gaps and enhance the implementation of VR technology in this context. In this regard, **this study aims to compare the effectiveness of two emergency exit signage proposals in a subway Ventilation and Emergency Exit (in Portuguese: *Ventilação e Saída de Emergência, VSE*) design in the São Paulo subway system, Brazil**. A VSE is designed to provide adequate ventilation in underground facilities, contribute to smoke removal in case of fire, and provide safe evacuation routes in emergency situations. The VSE typically consists of a track tunnel, a connecting tunnel, and a vertical shaft, Figure 1. The proper design of these structures, as well as the signage, is crucial to ensure the safety of passengers and staff in subway systems.

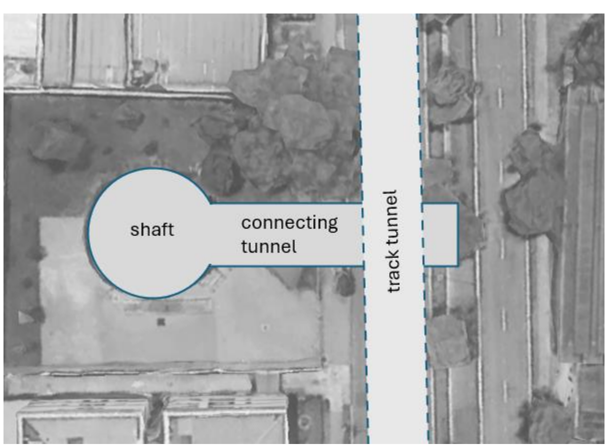

Figure 1. Basic composition of a VSE: track tunnel, a connecting tunnel, and a vertical shaft
.

Source: Authors

In this paper, we simulate two scenarios using different signage dimensions for a VSE. The assumption is that, through this comparison, it would be possible to identify the optimal signage configuration for a quicker exit in emergency situations.

The potential benefits of utilizing VR lie in increased project interaction and decision-making support. This is attributed to the immersive nature of the system, providing more accurate visualizations, higher motivation and interest, and requiring lower cognitive load compared to common flat screen displays (Safikhani et al., 2022). This innovative approach contributes to ongoing efforts to enhance the effectiveness of evacuation procedures and ultimately improve public safety in the face of fire emergencies.

REGULATORY STANDARDS FOR EMERGENCY EXITS

In every civil engineering project, the incorporation of safety parameters and regulations is indispensable to guarantee the well-being and safety of users, be they residents of a locale or patrons of specific developments, such as commercial buildings or public transportation systems. Norms and regulations play a pivotal role in ensuring safety during emergencies and mitigating potential stressful situations. These guidelines are essential for creating an environment that prioritizes user security and establishes a robust foundation for disaster preparedness and response.

In large-scale construction projects, adherence to numerous general and specific standards is imperative for comprehensive project development. When considering VSE, prioritizing accessibility is crucial, as the spatial layout must be meticulously designed for emergency scenarios. The Brazilian Standard NBR 9050 (Associação Brasileira de Normas Técnicas, 2020a) specifically addresses accessibility in buildings, furniture, urban spaces, and equipment. It plays a pivotal role in architectural project planning, contributing significantly to the effective evacuation and protection of all users. Furthermore, NBR 14021 (Associação Brasileira de Normas Técnicas, 2005) provides detailed guidelines for ensuring accessibility in urban and subway railway systems.

Furthermore, there are numerous standards aimed at ensuring the structural safety of constructions, as the paramount concern in civil engineering projects is the preservation of these structures to prevent catastrophes. Noteworthy is NBR 15200 (Associação Brasileira de Normas Técnicas, 2012), extensively employed in projects of this nature, providing procedures for the design of concrete structures in fire situations, a critical aspect for proper dimensioning.

Below, we present some details about Brazilian standards related to fires and signaling, as they have a direct impact on the objectives of this research.

FIRE STANDARDS

In underground construction projects, emergency preparedness revolves around fire scenarios as critical cases. Typically, the primary document followed in the development of VSE projects is Technical Instruction n. 45 (CBPMESP, 2019) which consolidates information from crucial standards on the subject. Notably, among them are the Brazilian Standard NBR 16484 (Associação Brasileira de Normas Técnicas, 2020b) and the international NFPA 130 (National Fire Protection Association, 2020).

The NBR 16484 (Associação Brasileira de Normas Técnicas, 2020b) deals with fire safety for rail transportation systems, focusing on the basic requirements for fire protection and user safety in these types of transportation, including metro-rail systems and their extensions. In a detailed manner, the standard encompasses all necessary components in a VSE project. Notably, items 5.5 and 6.2 of the standard address escape routes and emergency exits, detailing how to propose escape paths, safe distances, quantification of train occupancy loads, maximum evacuation times, as well as specifications for stairs, escalators, elevators, among other components and equipment that may influence escape routes.

NFPA 130 (National Fire Protection Association, 2020) is a Standard for Fixed Guideway Transit and Passenger Rail Systems that addresses the standards to be followed in rail transportation systems. Its primary instructions are outlined in section 7, focusing on the ideal and safe distancing for both mechanical and non-mechanical ventilation, along with other specifications regarding ventilation. Additionally, there are recommended specifications for structural elements to ensure resistance to forces in fire situations.

Technical Instruction n. 45 (CBPMESP, 2019) akin to NBR 16484 (Associação Brasileira de Normas Técnicas, 2020b), also pertains to fire safety for rail transportation systems. It references both NBR 16484 and NFPA 130 but incorporates other standards in an objective manner. This specification encompasses the entire rail passenger transportation system. It aims to ensure that, in emergency and stressful situations, everyone can evacuate from a given structure while safeguarding their physical integrity. Additionally, it ensures practical and secure access for firefighting teams combating the fire. The document presents various parameters to be adopted for enhanced safety and swifter evacuations, listing mandatory elements and alternative adoption options, such as door types. It also includes specifications for elements like dimensions of stairs and platform widths.

It is worth emphasizing item 6.5 of the Technical Instruction n. 45 (CBPMESP, 2019), which specifically addresses escape routes in the underground. This item details the arrangement of stairs and emergency doors, passages between tunnels, as well as trapdoors when necessary. Notably, this instruction makes the construction of VSE facilities between stations mandatory. It stipulates that every 305 meters of distance requires the provision of mechanical ventilation in subway line projects, given that these are enclosed underground pathways. It also mandates that the maximum distance between emergency exits should not exceed 762 meters.

SIGNALING STANDARD

In emergency scenarios, the presence of well-placed and clear signage is paramount to facilitate a seamless evacuation process, minimizing the risk of errors in route selection. To accomplish this, adherence to standards that provide guidance on the proper utilization of such signage is essential.

In Brazil, NBR 16820 (Associação Brasileira de Normas Técnicas, 2022) is the most widely utilized standard for the development of emergency signage projects. It pertains to the emergency signaling system, covering aspects from design to requirements and testing methods. This standard is crucial as it not only provides fundamental definitions but also includes various tables and figures illustrating the correct usage of emergency signage.

Initially, the standard defines basic signage as those indicating prohibition, warning, guidance, and rescue, as well as signage for firefighting equipment and alarms. Additionally, there are complementary signs comprised of color bands indicating obstacles, messages, the indication of extinguishing agents specifying the type of extinguisher and its applications, maximum occupancy indication, continuous route indicating paths to emergency exits, and escape plans aiming to guide people to safely exit the premises.

Among the frequently employed signs in various projects and emergency scenarios are those indicating guidance and rescue, equipment, and extinguishing agents. Specifically, the guidance and rescue signage is a typology commonly utilized for evacuation signs in diverse civil construction contexts. Item 5 of the standard deals with the dimensions of signage and the minimum heights required for installation, dealing with different equations.

Furthermore, the standard includes illustrations of signage for equipment and fire extinguishers, crucial for aiding brigades and firefighters in locating resources during emergencies. Section 6 of the standard is entirely dedicated to project guidelines, with a notable emphasis in item 6.3, detailing the minimum height for installing signage.

According to the standard, it is necessary to ensure a maximum spacing of 15 meters between signage plates. Additionally, a maximum distance of 7.5 meters from the penultimate plate to the last one should be anticipated.

MATERIALS AND METHODS

The study of human behavior in evacuation simulations involves both macroscopic and microscopic models (Cheng et al., 2019; Uliana et al., 2022). Macroscopic models treat human movement as a homogeneous mass with uniform characteristics, whereas microscopic models focus on individual behaviors and interactions. Microscopic models, known for their detailed simulations, are particularly valuable in emergency evacuation studies.

While various software applications computationally simulate individual behaviors during evacuations, the study of signage effectiveness requires simulations using microscopic models. These models do not adhere to a predefined pattern, as each individual may perceive the environment and interactions differently. In this context, VR interaction becomes highly appealing. VR allows for the creation of a first-person scenario and the incorporation of diverse variables to create a realistic simulation, including visual and auditory effects.

With a focus on the microscopic model, this study unfolds in three key phases: (i) designing two signage scenarios for the VSE; (ii) developing a VR simulation system, which includes an environment for users to familiarize themselves with the technology and the VSE using the two signage scenarios; and (iii) conducting user evaluation. The user evaluation comprises five main steps: (1) recruiting participants and scheduling appointments; (2) signing consent forms and administering a questionnaire to gather participants' profiles and assess their knowledge of the technologies used; (3) familiarization and training with the VR system; (4) performing the emergency evacuation simulation, followed by administering questionnaires to collect data; and (5) analyzing the gathered data, Figure 2.

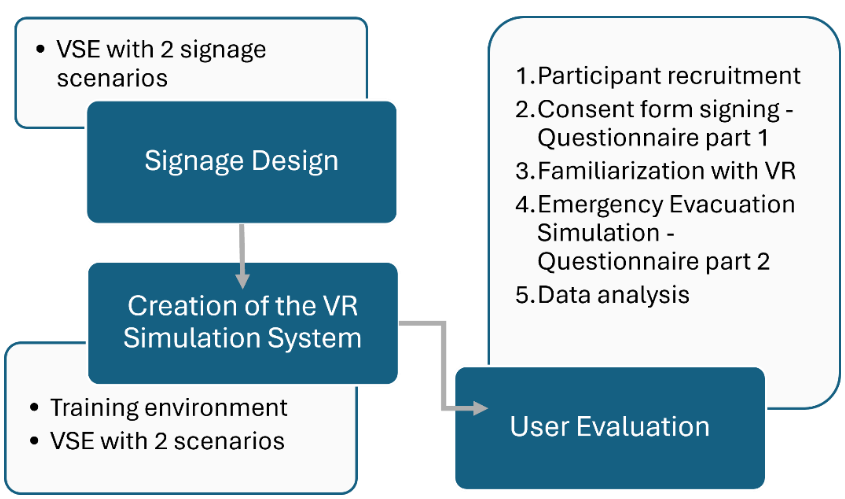

Figure 2. Research process

Source: Authors

Two computers were employed for the project development. The entire system development took place on a PC running a 64-bit Windows operating system, equipped with 8GB of RAM, an Intel Core i5-5200U processor with a 2.20 GHz CPU, Intel HD Graphics 5500 graphics card, and NVIDIA GeForce 910M graphics chip. The computer used for the simulation phase had a 64-bit Windows operating system, 32GB of RAM, and an Intel Xeon W-2133 processor with a 3.60 GHz GPU.

All signage design and modeling tasks were carried out using Autodesk Revit software, version 2021. The simulation aspect was developed using the Unreal Engine game development engine (version 4.26) by Epic Games. The VR simulation utilized the HTC Vive Pro Eye as the Head-Mounted Display (HMD).

SIGNAGE DESIGNS

Derived from a standard VSE model connecting subway lines, two distinct scenarios were crafted, each proposing diverse signage approaches, both meticulously aligned with NBR 16820 (Associação Brasileira de Normas Técnicas, 2022).

In accordance with the standard, the use of minimum dimensions for rectangular signs is permissible within a proximity of up to 6.3 meters from the observer. Examination of all distances in the study model confirms the adherence to the stipulated minimum dimensions. Consequently, to facilitate a comparative analysis, two scenarios were delineated: (1) employing minimum dimensions and (2) utilizing dimensions twice as large for the signs. The signage used for both scenarios is presented in the Figure 3.

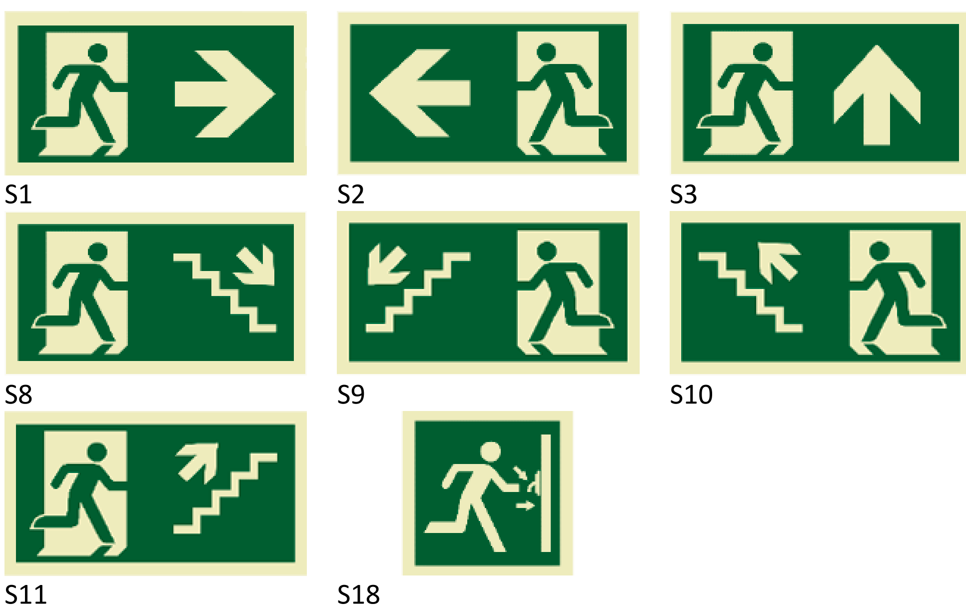

Figure 3. Signage used in the design

Source: NBR 16820 (Associação Brasileira de Normas Técnicas, 2022)

Concerning the installation heights of the signs, measurements were established based on the standard's specifications, supplemented by a model analysis, taking into consideration the visual field of a person with a height of 1.70 meters. This yielded a height of 1.90 meters for linear sections and 1.85 meters for signs positioned in stair areas. The details of both scenarios are elucidated in Table 1 and illustrated in Figure 4.

Table 1. Dimensions of the signs in scenarios 1 and 2

Source: Authors

Signs	Dimensions		Installation Height
	W (mm)	H (mm)	h (m)
Scenario 1			
Orientation and Rescue (S1, S2, S8, S9, S10 e S11)	200	100	1,80
Orientation and Rescue (S3)	200	100	2,20
Orientation and Rescue (S18)	400	120	1,20
Scenario 2			
Orientation and Rescue (S1, S2, S8, S9, S10 e S11)	400	200	1,85-1,90
Orientation and Rescue (S3)	400	200	2,20
Orientation and Rescue (S18)	800	240	1,60

Figure 4. Illustration of the differences between scenarios 1 (left) and 2 (right)

Source: Authors

The model under scrutiny is divided into three main sections: the initial level, intermediate level, and exit, Figure 5. Figure 6 provides an overview of the exit level, corresponding to the ground floor, indicating the point where users will emerge after leaving the VSE. Figure 7 showcases the intermediate level, corresponding to various intermediate floors depending on the depth of the VSE. These floors are classified into levels featuring only evacuation stairs and levels that include additional rooms for ventilation purposes. Figure 8 offers insight into the initial level, the lower floor that provides access to the construction of the VSE. It's important to note that the plans presented in the figures are sketches created by the author, with green highlights indicating the locations of the signage used in this project.

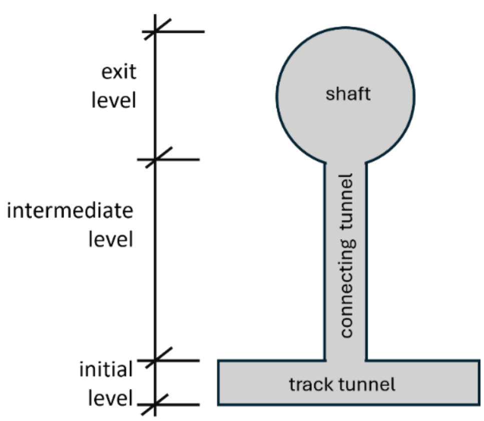

Figure 5. Sketch illustrating the subdivision of levels in a VSE

Source: Authors

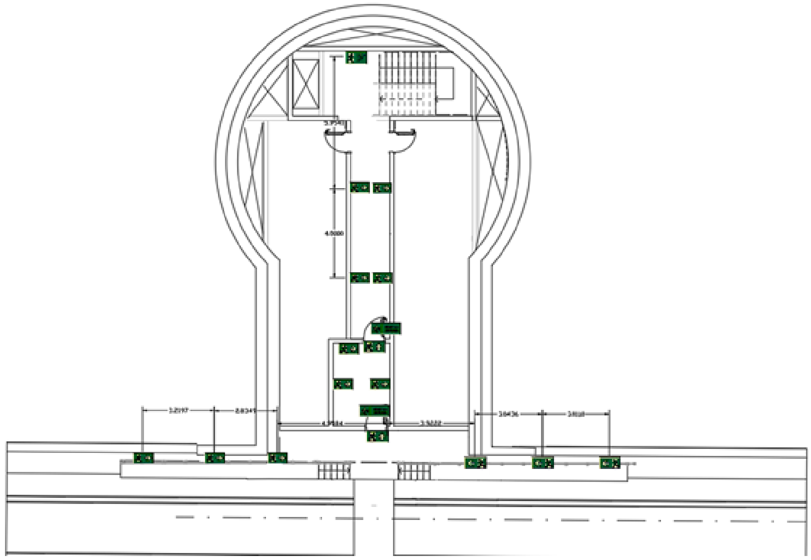

Figure 6. Plan of the initial evacuation level

Source: Authors

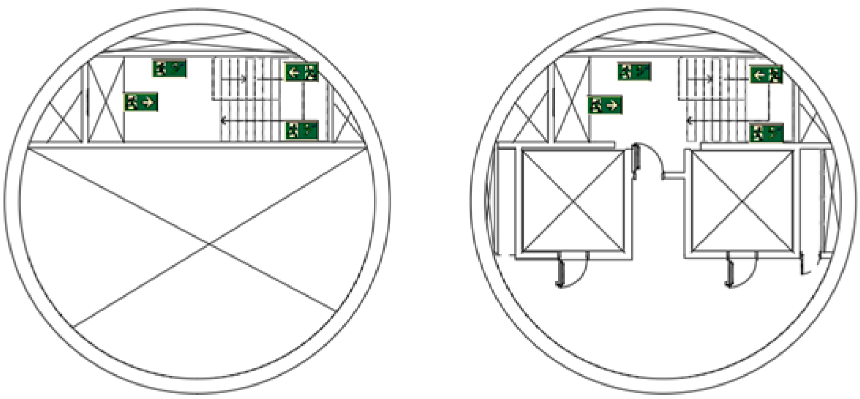

Figure 7. VSE Intermediate levels

Source: Authors

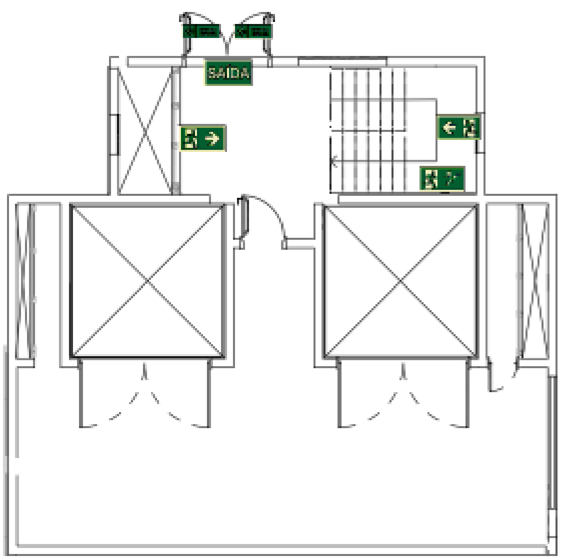

Figure 8. VSE ground floor (exit)

Source: Authors

CREATION OF THE VR SIMULATION SYSTEM

This phase of the project encompasses the development of two VR environments: the first is designed to facilitate user familiarity with the technology and the second presents the VSE through the incorporation of two signage scenarios, employed for evacuation simulations.

VR serves as a communication channel requiring participants to grasp distinctive mental operations, procedures, tools, and techniques (Radoeva et al. 2021, Lin et al. 2002, Bourhim & Cherkaoui 2018). Therefore, participants should be familiarized with the use of VR as a facilitating system for simulations prior to engaging in the proposed simulation (Bourhim and Cherkaoui, 2018; Lin et al., 2002; Radoeva et al., 2021). Therefore, a model was developed to familiarize participants with the VR system, as depicted in Figure 9. The objective was to introduce participants to all the essential technologies and functionalities required for the study. The decision was made to utilize a two-story residence, not only because it is a type of construction familiar to individuals but also because it encompasses all the necessary tools for the evacuation simulation.

Figure 9. Training enviroment

Source: Authors

The architectural model of the VSE was developed in the Revit software and then imported into Unreal Engine using the Datasmith plugin. This plugin is responsible for transforming the geometries, materials, textures, lights, cameras, and animations from these software programs into editable elements compatible with Unreal Engine. The simulation was developed in Unreal Engine using the Blueprints feature, which involves a visual programming language (VPL).

To provide a more comprehensive context for the project, it was essential to integrate a realistic environment around it. Utilizing the Street View Download 360 software, authentic images sourced from Google Street View were acquired. These images, initially in jpg format, underwent conversion to HDR to ensure compatibility with Unreal Engine, Figure 10.

Figure 10. Emergency exit view integrated into an urban environment

Source: Authors

Subsequently, collisions were meticulously incorporated for every element. This is indispensable for an authentic traversal of the environment. Essential structures like floors, walls, and doors were equipped with collisions to emulate real-world dynamics, preventing a "ghost effect" where these elements can be passed through.

To replicate realistic behaviors, a simulation of door opening was implemented to enhance the user experience. The core concept of the programming involved creating a command button that, when pressed, opens the door, facilitating user passage. Upon activation, the button triggers a timeline that rotates the door around its axis by 90° over a 1.5-second period. Pressing the button again closes the door.

Next, a pre-programmed first-person character package was implemented. This package includes various standard programming features commonly used in First Person Shooter (FPS) games. It facilitated the use of typical character movements, enabling walking, running, and hand movements.

A fire was chosen as the emergency evacuation scenario for this simulation. To enhance realism, fire and smoke effects from the Unreal library were implemented. This contributed to creating a lifelike critical situation, signaling danger, and impacting visibility, as depicted in Figure 11.

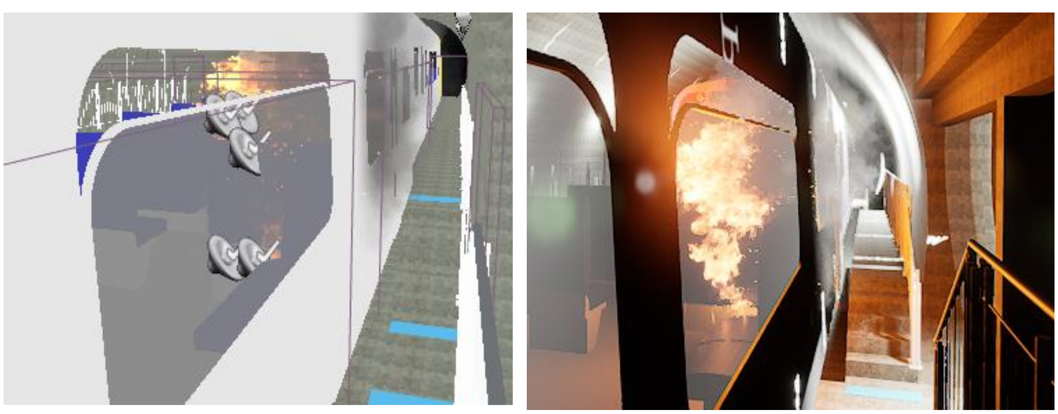

Figure 11. Fire and smoke elements in Unreal Engine (left) with corresponding visualization in the simulation (right)

Source: Authors

Another crucial aspect during evacuations is the ambient audio. In the event of emergency stops, subway systems emit audible alerts instructing people to evacuate the premises.

Leveraging voices similar to those utilized by São Paulo subway systems and featuring a variety of free voice options, the Microsoft Azure software was employed for this purpose.

To simulate ambient sound, chaotic audio clips from real subway events and alarm sounds from publicly available YouTube videos were curated. Using the Shotcut software, the audios were meticulously isolated and merged, resulting in an audio composition that effectively emulates a tumultuous evacuation scenario. This audio element is designed to heighten users' immersion in simulated emergency situation.

Finally, the inclusion of textual elements was necessary to guide the user at the initiation and conclusion of the simulation. The program incorporates "Widgets," enabling the creation of text, insertion of figures, and other functionalities.

Configuring the HTC Vive Pro controller was essential for generating movement and interaction with the model. The VR simulation was realized by utilizing the settings of the existing VR game mode in Unreal.

USER EVALUATION

The VR simulation was designed to be carried out by one participant at a time, allowing for the observation of all participant choices and the genuine assessment of signage effectiveness. This prevents participants from mimicking the decisions of others (Gou et al., 2018; Zia et al., 2021), which could impact the choice of evacuation routes and, consequently, the expected outcomes.

Initially, participant recruitment and selection were conducted through postings in WhatsApp and Facebook groups affiliated with the university. The posts outlined the research's purpose and included a Google Forms questionnaire that provided options for dates and times for individual sessions.

The sessions took place on October 14, 20, and 27, 2022, with the participation of 28 individuals. Although this number of users is insufficient for quantitatively validating the proposals, it enables the analysis of key issues that can aid in the final signaling design.

At the designated dates and times, participants gathered at the research site, where they received and signed the informed consent form (in Portuguese: *Termo de Consentimento Livre e Esclarecido*, TCLE) (CAAE: 60486322.7.0000.8142). Subsequently, they were presented with a questionnaire consisting of three single-choice questions, aimed at profiling the participants, and two matrix-type questions that allowed for multiple responses, intended to assess participants' prior knowledge of the technologies used in the experiment.

After the initial data collection, a roughly five-minute period was allocated for participants to acquaint themselves with the VR navigation system in a training scenario. During this phase, the HMD and controls were calibrated according to each participant's position and height. This approach not only enabled users to learn how to operate the system but also allowed them to familiarize themselves with it before the evacuation simulation. Consequently, participants could focus on the proposed task rather than being preoccupied with the technology employed.

Following this, each participant, while seated, engaged in the evacuation simulation, Figure 12. It is crucial to note that participants were exposed to only one of the scenarios, meaning those who experienced one scenario did not experience the other. This was done to prevent prior knowledge of the environment from influencing the results.

Figure 12. Participant engaging in the simulation

Source: Authors

The simulation commenced from a designated starting point, with a singular task: "you are on a subway train, and an issue has arisen; you must evacuate promptly". Throughout the simulation, the evacuation duration was timed, and the participant's conduct was observed throughout the entire experiment.

After the simulation, participants completed psychometric response questionnaires, aiming to comprehend user behavior and experience. Utilizing a 5-point Likert scale with self-descriptive responses, the questionnaires were divided into three parts: (i) assessing the user experience; (ii) examining the well-being during the simulation, and (iii) understanding the effectiveness of the signage. The 5-point Likert method was employed, with options including "Strongly disagree", "Disagree", "Neither agree nor disagree", "Agree", and "Strongly agree".

In addition, a concluding open-ended question was included in the questionnaire, allowing participants to express any aspects or observations not addressed by the provided questions. This aimed to gather additional insights for a comprehensive interpretation of the data and conclusions.

RESULTS

USER PROFILE

Initially, the aim was to delineate the profile of individuals participating in the simulations by collecting information on age, gender, education level, and familiarity with the used technologies, Figure 13. Given that the experiment was exclusively promoted within the university context, the participant profile mirrors the typical characteristics of undergraduate, postgraduate, and master's students.

The majority of participants, comprising 61%, identify as men (trans or cis), while women (trans or cis) account for 36% of the participants. Additionally, there was the participation of one non-binary individual, representing 3% of the total.

The data revealed that 78% of participants had incomplete higher education, likely representing undergraduate students, while 18% had completed higher education, encompassing postgraduate students, totaling 96% of the sample. Additionally, the majority of participants fell within the 21 to 30 age range, aligning with the average age for undergraduate students, ranging from 23.4 to 29.4 years (INEP, 2023).

It was crucial to assess participants' prior knowledge of the technologies employed in this experiment. While the familiarization model aimed to bring all participants to a similar starting point in terms of technology proficiency, pre-existing familiarity could potentially impact the results, particularly concerning user well-being. It is noteworthy that 22 participants had some familiarity with video game consoles, with 45.5% in Scenario 1 and 54.5% in Scenario 2. This balanced distribution ensures that such familiarity does not unduly influence the outcomes of this study. Notably, only one participant was familiar with VR applications, which has minimal impact on the results. Furthermore, half of the participants simulating Scenario 2 were acquainted with VR headsets, while none in Scenario 1 had such familiarity, potentially influencing the results.

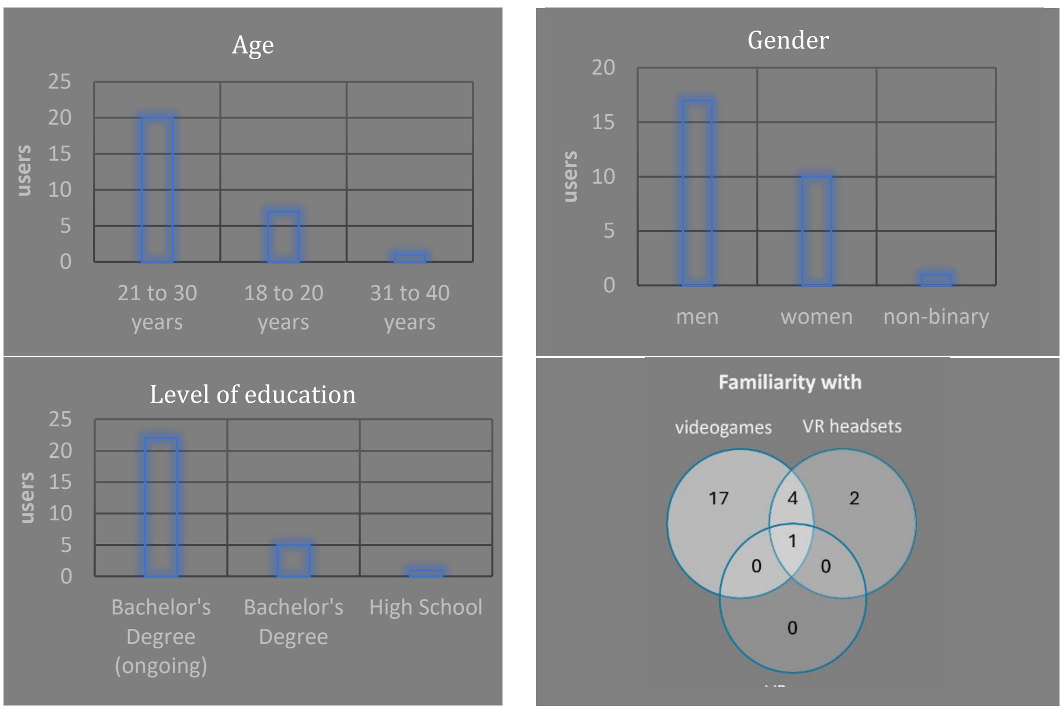

Figure 13. User profile: age, gender, level of education, and familiarity with the used technologies

Source: Authors

Additionally, participants were asked about their familiarity with emergency evacuation situations. Only 25% (7) of the participants had witnessed some form of real (non-virtual) evacuation simulation, and one had experienced an actual evacuation situation. The remaining 75% (21) had never encountered any experience related to emergency evacuations. It is noteworthy that none of the participants had prior knowledge of the specific building, which could influence the results (Shuaib, 2018).

USER EXPERIENCE

With the aim of analyzing the user experience and evaluating all the mechanisms used to represent reality as faithfully as possible, statements were made, and the results from scenarios 1 and 2 are presented, Table 2, Figure 14. The visualization and handling of glasses and controls received a lower score from Scenario 1, Figure 14 (a). This observation aligns with the data gathered, where no participants from Scenario 1 had prior experience with VR.

For most participants, the model accurately represented a real environment, they felt fully immersed in the virtual setting, and they believed that using the Virtual Reality system was appropriate for the proposed simulation, Figure 14 (b), (c) and (f). However, it is not clear why scenario 2 received slightly higher evaluations, despite the only difference being the size of the signage.

The highest rating was achieved for the utilization of sound and visual effects, Figure 14 (d). This indicates that the choice of Unreal Engine development and the incorporation of various effects was appropriate, resulting in an excellent representation of reality.

Regarding any discomfort associated with the use of goggles and controls, most statements indicated a high level of acceptance, Figure 14 (e). The responses indicated that eight participants experienced discomfort, with four in each scenario, representing 28,57% of the users.

	Q1		Q2		Q3		Q4		Q5		Q6		Q7	
Scenario 1	u	%	u	%	u	%	u	%	u	%	u	%	u	%
Strongly agree	4	14,29	4	14,29	8	28,57	6	21,43	0	0,00	8	28,57	6	21,43
Agree	6	21,43	9	32,14	5	17,86	8	28,57	4	14,29	4	14,29	5	17,86
Neither agree, nor disagree	1	3,57	1	3,57	1	3,57	0	0,00	4	14,29	2	7,14	2	7,14
Disagree	3	10,71	0	0,00	0	0,00	0	0,00	4	14,29	0	0,00	1	3,57
Strongly disagree	0	0,00	0	0,00	0	0,00	0	0,00	2	7,14	0	0,00	0	0,00
Scenario 2	u	%	u	%	u	%	u	%	u	%	u	%	u	%
Strongly agree	5	17,86	7	25,00	6	21,43	11	39,29	0	0,00	6	21,43	10	35,71
Agree	8	28,57	7	25,00	8	28,57	3	10,71	4	14,29	8	28,57	4	14,29
Neither agree, nor disagree	1	3,57	0	0,00	0	0,00	0	0,00	3	10,71	0	0,00	0	0,00
Disagree	0	0,00	0	0,00	0	0,00	0	0,00	4	14,29	0	0,00	0	0,00
Strongly disagree	0	0,00	0	0,00	0	0,00	0	0,00	3	10,71	0	0,00	0	0,00

Q1- The way of visualizing and handling the Virtual Reality system felt natural to me

Q2- The model accurately represented a real environment

Q3- I felt fully immersed in the virtual environment

Q4- The mechanisms used (auditory and visual) successfully simulated reality

Q5- I experienced discomfort with the Virtual Reality system (goggles and controller)

Q6- I feel that using the Virtual Reality system is appropriate for the proposed simulation (emergency evacuation)

Q7- Finding the exit was easy

Table 2. Collected data of scenarios 1 and 2 for the user experience statements

Source: Authors

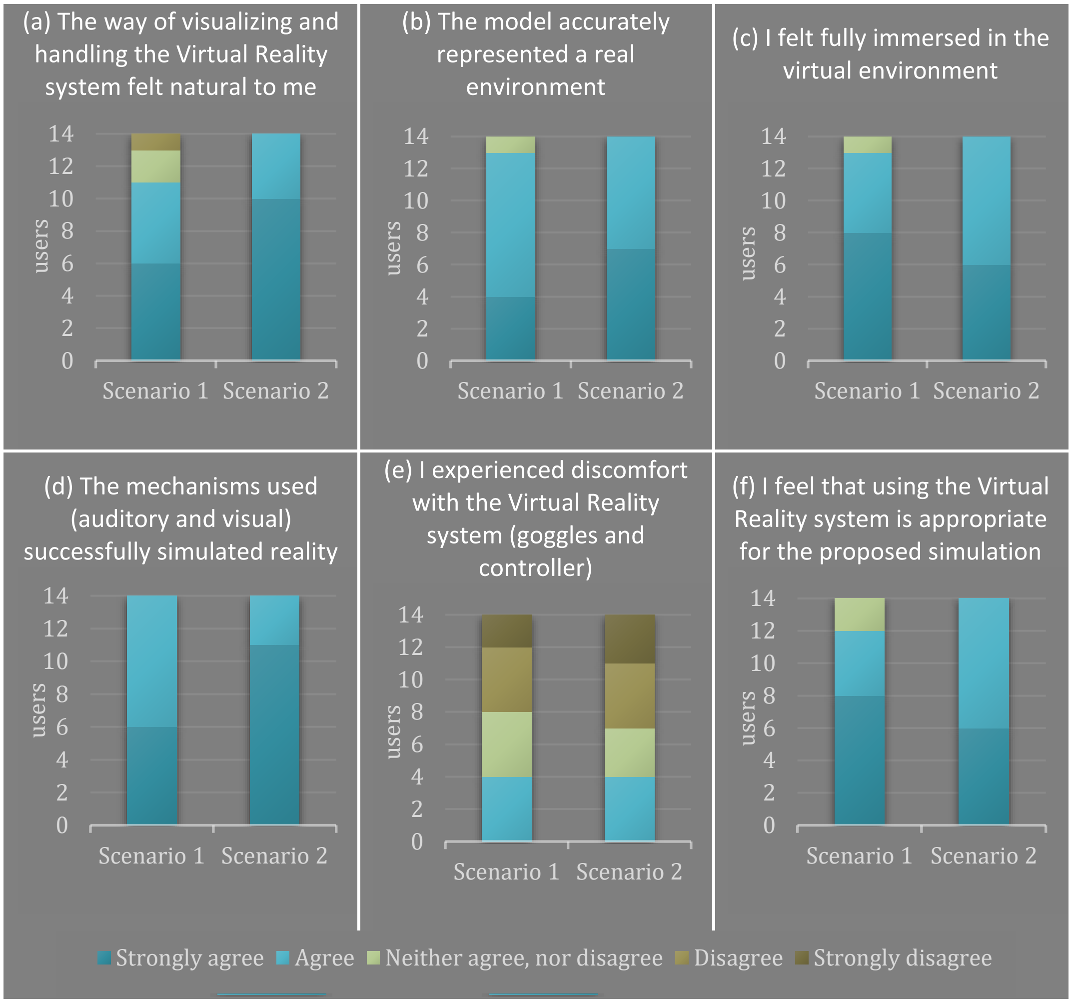

Figure 14. Visual scale of scenarios 1 and 2 for the user experience statements

Source: Authors

One crucial point of analysis is the statement regarding the ease of finding the exit. Despite both scenarios returning relatively close values, this study features an intuitive architectural model with only one possible evacuation route, amplifying the significance of this difference. All participants in scenario 2 agreed that finding the exit was easy, while one participant in scenario 1 disagreed and two had neutral opinions on the matter, Figure 15. The results presented suggest a preference for scenario 2 in the majority of cases.

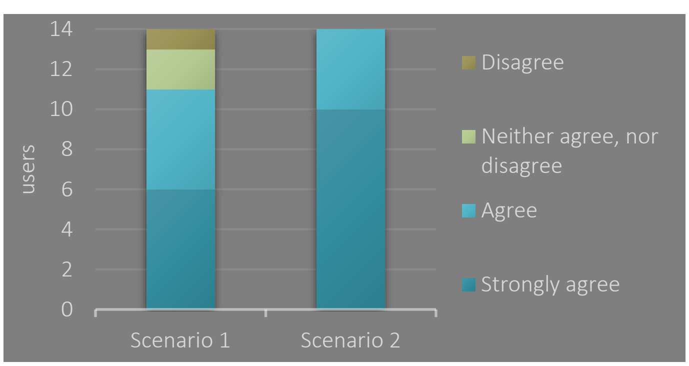

Figure 15. Visual scale of scenarios 1 and 2 for the statement: "Finding the exit was easy"

Source: Authors

WELL-BEING

To assess the feasibility of the simulation, it was necessary to examine how the user's well-being was affected by the use of technology. It is known that the use of VR mechanisms can lead to dizziness and nausea. The obtained data are presented in, Table 3, Figure 16.

In this experiment, there were no significant complaints regarding negative sensations during or after the simulation. All participants successfully completed the study. This is substantiated by the scores obtained in the statements made immediately after the experiment. Concerning the feeling of nausea, among the 28 participants, only four (15,4%) reported this issue, Figure 16 (a). The sensation of anxiety or nervousness was observed by eight users (28,57%), Figure 16 (b). The majority of participants stated that they felt well throughout the entire simulation (71.42%), Figure 16 (c).

Table 3. Collected data obtained from the questionnaire on user well-being

Source: Authors

	Q8		Q9		Q10	
Scenario 1	u	%	u	%	u	%
Strongly agree	0	0,00	0	0,00	2	7,14
Agree	2	7,14	3	10,71	8	28,57
Neither agree, nor disagree	2	7,14	2	7,14	4	14,29
Disagree	5	17,86	2	7,14	0	0,00
Strongly disagree	5	17,86	7	25,00	0	0,00
Scenario 2						
Strongly agree	0	0,00	1	3,57	6	21,43
Agree	2	7,14	4	14,29	4	14,29
Neither agree, nor disagree	0	0,00	0	0,00	1	3,57
Disagree	3	10,71	4	14,29	3	10,71
Strongly disagree	9	32,14	5	17,86	0	0,00

Q8- I felt nauseous during the simulation

Q9- I felt anxious or nervous during the simulation

Q10- I felt well throughout the simulation

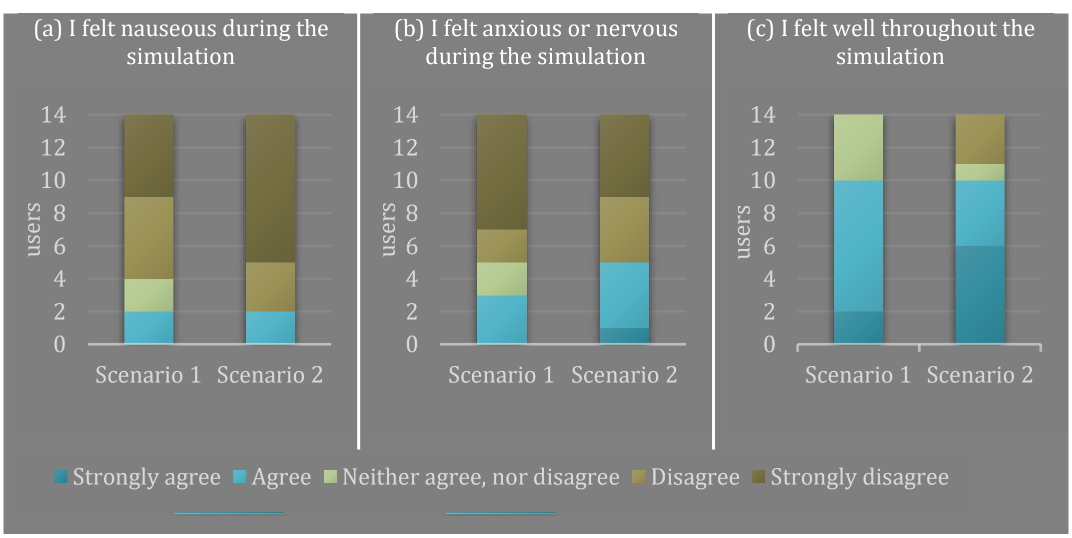

Figure 16. Results obtained from the questionnaire on user well-being

Source: Authors

One of the reasons that may have contributed to the positive well-being results was conducting the experiment while seated, utilizing the rotation of the chair for changes in direction. This choice was made during the adaptation of the project for VR, as the authors observed these sensations when conducting simulations standing and decided to remain seated.

EFFECTIVENESS OF THE SIGNAGE

Initially, it was observed that the evacuation time for Scenario 2, featuring signs with double the dimensions of those in Scenario 1, was approximately 50 seconds shorter, Table 4. It is essential to note that this time should not be regarded as the actual evacuation time since real simulations involve additional variables not considered in this study. In a genuine emergency scenario, analyzing a situation with a crowd of people is intricate, as each individual tends to react differently, impacting the organization of routes and the orderly movement of people (Uliana et al., 2022). Nevertheless, these time variations are significant as they suggest that Scenario 2 may be more efficient in comprehending the evacuation route, thereby potentially leading to a quicker building evacuation.

	Scenario 1	Scenario 2
Average evacuation time (minutes)	3:02:57	2:11:59

Table 4. Evacuation time

Source: Authors

Both scenarios were compared based on three statements, aiming to understand how the signage boards assisted the participants in evacuation, Table 5, Figure 17.

	Q11		Q12		Q13	
Scenario 1	u	%	u	%	u	%
Strongly agree	7	25,00	10	35,71	0	0,00
Agree	6	21,43	4	14,29	3	10,71
Neither agree, nor disagree	1	3,57	0	0,00	5	17,86
Disagree	0	0,00	0	0,00	4	14,29
Strongly disagree	0	0,00	0	0,00	2	7,14
Scenario 2						
Strongly agree	11	39,29	12	42,86	0	0,00
Agree	2	7,14	2	7,14	3	10,71
Neither agree, nor disagree	1	3,57	0	0,00	2	7,14
Disagree	0	0,00	0	0,00	7	25,00
Strongly disagree	0	0,00	0	0,00	2	7,14

Q11- The visualization of the signage boards was clear

Q12- The signage boards assisted me in evacuating the environment

Q13- I felt that there should be more signage boards

Table 5. Collected data about the effectiveness of the signage

Source: Authors

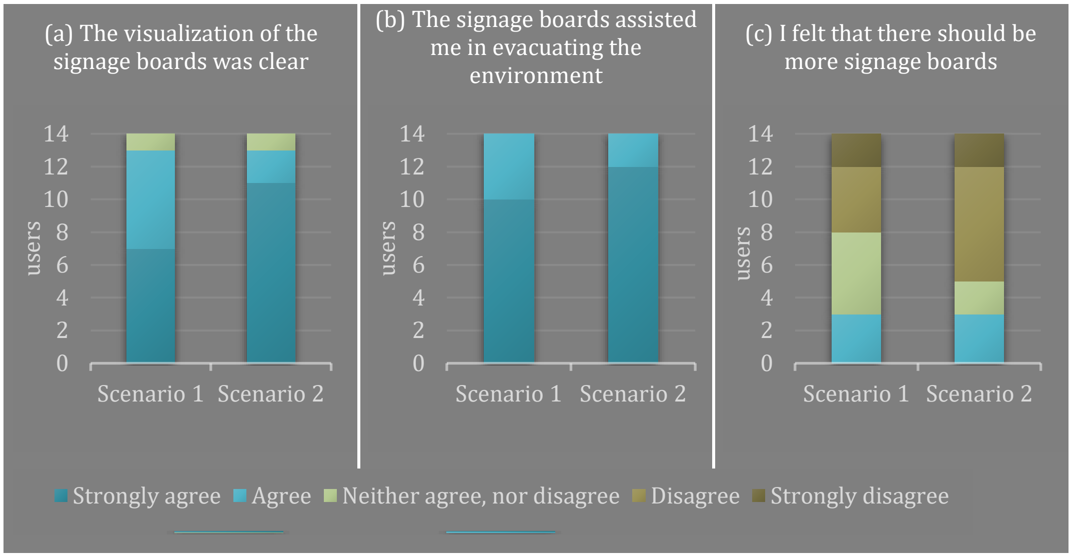

Figure 17. Questionary about the effectiveness of the signage

Source: Authors

In general, Scenario 2 demonstrated greater effectiveness in all aspects. Specifically, the visualization of the signage was clearer, Figure 17 (a). Consequently, the signage boards with double the minimum required dimensions proved to be more easily visible, particularly in environments with obstructed visibility, such as in the presence of smoke.

In terms of the efficacy of the signage in facilitating evacuation, all participants unanimously concurred that the signs substantially aided in the evacuation process, Figure 17 (b). Although there was no substantial variance in the scores, consistent with expectations due to the distinct scenarios, the introduction of evacuation signs aimed to guide individuals in exiting the premises more efficiently. Nonetheless, the slight variation in scores indicates that Scenario 2 demonstrated a higher perceived effectiveness.

The responses revealed that in Scenario 2, participants expressed less need for additional signage compared to Scenario 1, Figure 17 (c). It is important to highlight that the quantity of signage incorporated into the model remained consistent across both scenarios, with only variations in dimensions and insertion height. Consequently, the perception that more signs were required in Scenario 1 suggests increased difficulty in visibility, leading to lower efficiency when contrasted with Scenario 2.

QUALITATIVE RESULTS

In terms of qualitative results, valuable insights emerged from participants' comments during the simulation and the authors' observations. Some participants stated that the feeling of dizziness or vertigo occurred only at the beginning of the simulation, normalizing after a few seconds and without accompanying nausea. Another point is regarding the calibration of the goggles and controls, as each participant has a different height, in some instances, the sensors oscillated when encountering the goggles, causing a sudden change of direction not initiated by the participant, leading to surprises. The familiarization scenario was crucial for addressing these two issues, as it allowed for proper calibration based on each participant's characteristics, and they adapted to the VR system, performing the subsequent simulation without significant sensations that could affect the results.

Another noteworthy aspect praised by some participants was the use of sound and visual effects. Both the smoke and fire, as well as the audio simulating a real situation, contributed to a greater immersion in the simulation for the participants. These effects made users more alert and enhanced the feeling of being lost in the environment and experiencing anxiety, as mentioned by some of them.

Two noteworthy issues were highlighted by two participants. The VR glasses employed did not accommodate prescription glasses, posing a challenge for individuals dependent on them for everyday activities, hindering a comprehensive view of the model. Additionally, the cable attached to the glasses affected the performance of users; one participant reported feeling it on their head, which prevented them from being fully immersed as they were always aware that they were in a simulation.

Some critical points were reported by users and observed by the author. At the beginning of the simulation, there was a pillar near the first door that obstructed participants' view, Figure 18. Five out of fourteen participants in Scenario 1 did not see the door and continued straight, losing a few seconds in the evacuation time because it was impossible to see the door signs. Although the pillar also hindered the visibility of signs in Scenario 2, there were no route errors. This was because the larger signs partially appeared in the participants' view. Observing this critical point is essential because, before construction, it is still possible to alert designers and correct these types of issues.

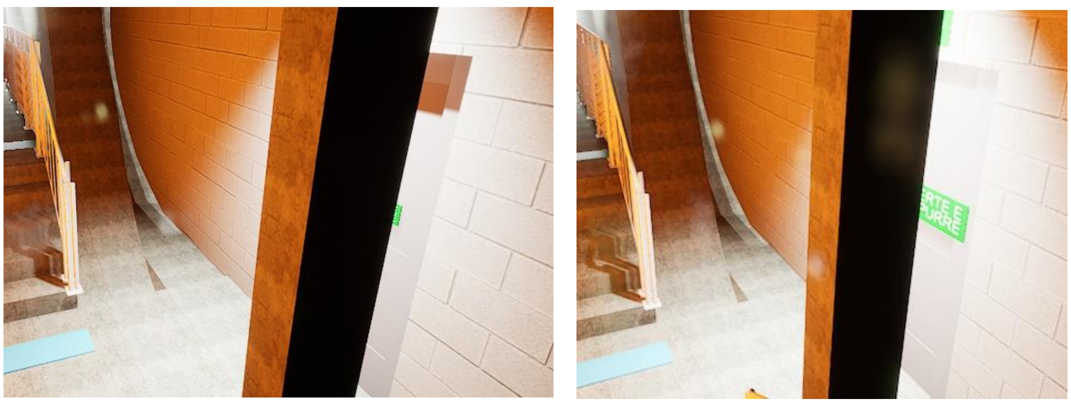

Figure 18. Pillar obstructing the view of the sign: scenario 1 (left) and 2 (right)

Source: Authors

Intentionally, other doors were left with the option to be opened, providing options that led to non-existent paths and lacked corresponding signage. Intentionally, other doors were left with the option to be opened, leading to nowhere and lacking signage. These doors would likely be locked during the actual operation of the VSE; however, to maximize the research results, they were available for opening. Only two individuals made the mistake of opening these doors, both from Scenario 1. The visibility of signs in Scenario 1 was significantly hindered by smoke at certain points. Consequently, one plausible explanation for this error could be the participants' challenge in clearly discerning the signage.

DISCUSSION AND CONCLUSIONS

This study is an integral part of a broader project that encompasses analyses using both macroscopic and microscopic models. The development of macroscopic models for traffic flow analysis, aimed at predicting local traffic in situations of breakdowns or accidents, as well as the necessary dimensioning for this purpose, was conducted separately. This article focuses on constructing a microscopic model that simulates individual behavior during an emergency evacuation in a VSE structure. This study aimed to investigate whether the increase in dimensions of signage placement would impact evacuation times in emergency situations, utilizing VR as a simulation tool within two distinct scenarios. Both scenarios incorporated sound and visual effects, including chaotic evacuation sounds and smoke, to enhance the simulation's realism for participants.

Based on the obtained results, it is possible to conclude that the use of VR to investigate the effectiveness of emergency signage, as well as the mechanisms employed to simulate the model, was satisfactory. The acceptance, adaptation, and immersion of participants to the technologies presented were favorable across all statements in the post-simulation questionnaires. These technologies demonstrate potential for simulating perspectives, exploring models, and, primarily, testing the effectiveness of signage through scenario comparisons.

Although the sample of 14 users for each scenario is insufficient for validating the optimal signaling strategy, the results offer valuable insights into the most promising approaches to pursue. In relation to the effectiveness test of the signage, through comparison, the second scenario, involving signs with double dimensions and heights, proved to be more effective in all responses collected. Participants in the second scenario indicated greater ease in finding the exit, had a better visualization of the signs, and almost achieved the maximum Likert scale rating when considering that the signs assisted in evacuation. Additionally, fewer individuals felt the need for more signage throughout the route.

Furthermore, the evacuation time in the second scenario also proved to be more effective. Although not representing the real evacuation time, participants in scenario 2 were more agile, completing the evacuation approximately 51 seconds faster. As there was better visibility of the signs in this scenario, it likely led to a better understanding of the escape route, avoiding critical points and mitigating errors in choosing the path.

The fact that more people had previous contact with VR may have influenced more favorable results in Scenario 2. However, it is believed that difficulties with VR primarily occurred in the familiarization environment, as complaints and doubts only arose in this model.

The fluidity of the required movements for all participants in the simulated scenarios was similar. No inconsistencies were detected in movements for visualization, nor in the handling of the controller for navigation in the model.

Another factor that may have influenced the results is related to the participants' profile. The participants were a young, university-educated audience (mostly undergraduate students) with access to technology, with approximately 79% of participants being familiar with videogames, and only 14.3% having no familiarity with the technologies used.

The contribution of this work lies in studying the effectiveness of emergency exit signage and understanding people's behavior in evacuation situations and the efficiency of evacuation routes. The simulation of different scenarios was an important tool for analyzing the proposed signaling design. This allowed for a preliminary analysis before construction, ensuring greater safety for users.

Future projects could target a different audience and incorporate other variables that influence emergency evacuation situations, such as crowds or different architectural models with more than one possible exit route. Additionally, the use of VR for emergency evacuation simulation could be compared with real-life simulations to assess its effectiveness.

References

ABIFER. **Metrô de São Paulo bateu recorde de investimento em expansão e modernização em 2023**. Disponível em: https://abifer.org.br/metro-de-sao-paulo-bateu-recorde-de-investimento-em-expansao-e-modernizacao-em-2023/. Acesso em: 6 fev. 2024.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 14021**: Transport - Accessibility on urban or metropolitan train system. Rio de Janeiro: ABNT, 2005.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 15200**: Fire design of concrete structures. Rio de Janeiro: ABNT, 2012. ISBN 978-85-07-03373-8.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 9050**: Accessibility to buildings, equipment and the urban environment. Rio de Janeiro: ABNT, 2020 a. ISBN: 978-65-5659-371-5.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 16484**: Fire safety to rail transport systems - Requirements. Rio de Janeiro: ABNT, 2020 b. ISBN 978-65-5659-689-1

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 16820**: Safety signs systems — Design, requirements and test methods. Rio de Janeiro: ABNT, 2022. ISBN: 978-85-07-09056-4.

BONO, P. H.; DAVID, Q.; DESBORDES, R.; PY, L. Metro infrastructure and metropolitan attractiveness. **Regional Science and Urban Economics**, v. 93, n. November 2021, p. 103757, 2022. ISSN 18792308. DOI 10.1016/j.regsciurbeco.2021.103757.

BOURHIM, E. M.; CHERKAOUI, A. Simulating Pre-Evacuation Behavior in a Virtual Fire Environment. Em: 9th International Conference on Computing, Communication and Networking Technologies, ICCCNT 2018, **Anais**[...]2018. DOI 10.1109/ICCCNT.2018.8493658.

CBPMESP. Segurança contra incêndio para sistemas de transporte sobre trilhos. **INSTRUÇÃO TÉCNICA Nº 45/ 2019**, p. 45, 9 abr. 2019. Disponível em: http://www.ccb.policiamilitar.sp.gov.br/dsci_publicacoes2/_lib/file/doc/IT-45-19.pdf. Acesso em: 3 mar. 2024.

CHENG, Y.; LIU, D.; CHEN, J.; NAMILAE, S.; THROPP, J.; SEONG, Y. Human behavior under emergency and its simulation modeling: A review. Em: Advances in Intelligent Systems and Computing, **Anais**[...]2019. DOI 10.1007/978-3-319-94223-0_30.

FENG, Y.; DUIVES, D. C.; HOOGENDOORN, S. P. Using virtual reality to study pedestrian exit choice behaviour during evacuations. **Safety Science**, v. 137, n. December 2020, p. 105158, 2021. ISSN 18791042. DOI 10.1016/j.ssci.2021.105158.

GHIZLANE, A.; MOHAMMED, S.; TAIBI, S.; ELMOSTAPHA, B. Virtual reality for fire evacuation from passenger train. **Maejo International Journal of Science and Technology**, v. 16, n. 3, p. 238–248, 2022. Disponível em: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85142441594&partnerID=40&md5=2ab8fac74eb47e3d736613e150910d28. Acesso em: 2 jul. 2024.

GOU, C.; YU, H.; XU, Z.; LI, X.; ZHANG, Y. Simulation of Small Social Group Behaviors in Emergency Evacuation Based on Information Asymmetry. **Journal of Computer-Aided Design and Computer Graphics**, v. 30, n. 3, p. 524–530, 2018. DOI 10.3724/SP.J.1089.2018.16566.

IBGE. **População no último censo [2022]**. Disponível em: https://cidades.ibge.gov.br/brasil/sp/sao-paulo/panorama. Acesso em: 6 fev. 2024.

INEP. Censo da educação superior 2022. p. 01–79, 10 out. 2023. Disponível em: https://download.inep.gov.br/educacao_superior/censo_superior/documentos/2022/apresentacao_censo_da_educacao_superior_2022.pdf. Acesso em: 9 mar. 2024.

LAMEIRA, V.; GOLGHER, A. Mobilidade para trabalho na Região Metropolitana de São Paulo a partir dos dados do Censo Demográfico de 2010. **Revista Brasileira de Estudo de População**, p. 1–20, 2021.

LIANG, H.; GE, C.; LIANG, F.; SUN, Y. VR-based training model for enhancing fire evacuee safety. **International Journal of Performability Engineering**, v. 16, n. 1, p. 107–117, 2020. DOI 10.23940/ijpe.20.01.p12.107117.

LIN, D.; ZHOU, Z.; WENG, M.; BROERE, W.; CUI, J. Metro systems: Construction, operation and impacts. **Tunnelling and Underground Space Technology**, v. 143, 2024. DOI 10.1016/j.tust.2023.105373.

LIN, F.; YE, L.; DUFFY, V. G.; SU, C.-J. Developing virtual environments for industrial training. **Information Sciences**, v. 140, n. 1, p. 153–170, 2002. ISSN 0020-0255. DOI 10.1016/S0020-0255(01)00185-2.

LOVREGLIO, R.; KINATEDER, M. Augmented reality for pedestrian evacuation research: Promises and limitations. **Safety Science**, v. 128, p. 104750, 2020. DOI 10.1016/j.ssci.2020.104750.

MANDAL, T.; RAO, K. R.; TIWARI, G. Study of exit choice behaviour in metro station using partial immersive virtual reality. **IATSS Research**, v. 46, n. 2, p. 290–296, 2022. ISSN 0386-1112. DOI 10.1016/j.iatssr.2022.02.002.

MARTIN, V. B. S.; PALMEIRA, E. G. Q.; GONCALVES, V. B.; SANTOS, L. N. C. D.; MELAZZO, J. J. M.; JUNIOR, E. A. L.; CARDOSO, A. Virtual Reality Simulations for Hospital Fire Evacuation: A Systematic Literature Review. Em: Proceedings - 2020 22nd Symposium on Virtual and Augmented Reality, SVR 2020, **Anais**[...]2020. DOI 10.1109/SVR51698.2020.00054.

MINEGISHI, Y.; TAKAHASHI, W.; IKEHATA, Y. Experimental study on the effect of fire alarms on occupants for situational awareness and evacuation decision-making using a mobile Virtual Reality Head-Mounted Display. **Journal of Environmental Engineering (Transactions of AIJ)**, 2022. DOI 10.3130/aije.87.607.

NATIONAL FIRE PROTECTION ASSOCIATION. Standard for Fixed Guideway Transit and Passenger Rail Systems. **NFPA 130**, p. 81, 2020.

OCCHIALINI, M.; BERNARDINI, G.; FERRACUTI, F.; IARLORI, S.; D'ORAZIO, M.; LONGHI, S. Fire exit signs: The use of neurological activity analysis for quantitative evaluations on their perceptiveness in a virtual environment. **Fire Safety Journal**, v. 82, p. 63–75, 2016. DOI 10.1016/J.FIRESAF.2016.03.003.

RADOEVA, R.; PETKOV, E.; KALUSHKOV, T.; SHIPKOVENSKI, G. An Approach to Development of Virtual Reality Training Systems. Em: 2021 5th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), **Anais**[...]2021. DOI 10.1109/ISMSIT52890.2021.9604576.

SAFIKHANI, S.; KELLER, S.; SCHWEIGER, G.; PIRKER, J. Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review. **International Journal of Digital Earth**, v. 15 (1), p. 503-526, 2022. DOI 10.1080/17538947.2022.2038291.

SHUAIB, M. M. Incorporating intelligence for typical evacuation under the threat of fire spreading. **Safety Science**, v. 106, p. 1–9, 2018. DOI 10.1016/j.ssci.2018.02.022.

SOOKHANAPHIBARN, K.; CHOENSAWAT, W.; PALIYAWAN, P.; THAWONMAS, R. Virtual reality system for fire evacuation training in a 3D virtual world. Em: IEEE 5th Global Conference on Consumer Electronics, **Anais**[...]2016. DOI 10.1109/GCCE.2016.7800430.

TANG, C.-H.; WU, W.-T.; LIN, C.-Y. Using virtual reality to determine how emergency signs facilitate way-finding. **Applied ergonomics**, v. 40 4, p. 722–30, 2009. DOI 10.1016/j.apergo.2008.06.009.

ULIANA, R. S.; LIMA, R. C. A. de; RODRIGUEZ, R. Q.; ROMANO, F. V. Simulação computacional na segurança contra incêndio em edificações: revisão de literatura. **Arquitetura Revista**, v. 18, n. 1, p. 43–57, 2022. DOI 10.4013/arq.2022.181.03.

VUKELIC, G.; OGRIZOVIC, D.; BERNECIC, D.; GLUJIC, D.; VIZENTIN, G. Application of VR Technology for Maritime Firefighting and Evacuation Training—A Review. **Journal of Marine Science and Engineering**, v. 11, n. 9, 2023. DOI 10.3390/jmse11091732.

WANG, Z.; MAO, Z.; LI, Y.; YU, L.; ZOU, L. VR-based fire evacuation in underground rail station considering staff's behaviors: model, system development and experiment. **Virtual Reality**, v. 27, n. 2, p. 1145–1155, 2023. DOI 10.1007/s10055-022-00718-3.

YU, X.; YU, P.; WANG, C.; WANG, D.; SHI, W.; SHOU, W.; WANG, J.; WANG, X. Integrating Virtual Reality and Building Information Modeling for Improving Highway Tunnel Emergency Response Training. **Buildings**, 2022. DOI 10.3390/buildings12101523.

ZIA, K.; FAROOQ, U.; SHAFI, M.; FERSCHA, A. On the effectiveness of multi-feature evacuation systems: an agent-based exploratory simulation study. **PeerJ Computer Science**, v. 7, p. 1 – 25, 2021. DOI 10.7717/PEERJ-CS.531.

Ana Regina Mizrahy Cuperschmid
cuper@unicamp.br

Douglas Henrique Dantas Nanni
dhdnanni@gmail.com