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Design and Usability Evaluation of a VR Metaverse-Based Digital Signage Game for Tsunami Evacuation Training

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Abstract

Objectives: This study aims to design, implement, and evaluate a VR Metaverse-Based Digital Signage Game for Tsunami Evacuation as an interactive medium to support disaster mitigation, particularly in improving user understanding and decision-making during evacuation scenarios. **Methods/Analysis:** The system was developed using a prototyping approach, enabling iterative refinement through continuous feedback. The evaluation employed multiple methods, including questionnaire-based assessment for digital signage effectiveness, Cognitive Walkthrough during the prototyping and refinement stages, and usability testing using VRSUQ on the final system. Furthermore, MSSQ was used to assess users' susceptibility to motion sickness in immersive environments. **Findings:** The results indicate that the proposed system effectively supports users in understanding evacuation routes and making appropriate decisions in simulated disaster situations. The usability evaluation indicates that the system achieves an acceptable level of usability, particularly for users with limited prior VR experience. **Novelty/Improvement:** This study introduces a novel integration of digital signage within a VR metaverse environment for disaster mitigation training. It contributes a prototyping-based development framework and provides empirical insights into user interaction in immersive systems. The study also highlights opportunities for improvement, including simplifying interactions, improving navigation support, enhancing user onboarding, and reducing excessive simulation effects to improve the overall user experience.

Keywords: Cognitive Walkthrough; Digital Signage; Disaster Mitigation; Tsunami Evacuation; Usability Evaluation; VR Metaverse Game.

1. Introduction

The Special Region of Yogyakarta (DIY) is one of the most visited provinces in Indonesia. Most of this region is located along the southern coast, making coastal tourism one of the province's leading attractions. Coastal tourism has a positive impact on regional development and economic benefits for the government, industry, and surrounding communities [1]. Despite these positive impacts, coastal areas are vulnerable to natural disasters. Tsunamis and tidal waves are common natural disasters in the Yogyakarta region. This is because of the location of the DIY's coastline, which borders the Indo-Australian and Eurasian plate subduction zones [2]. According to data from the National Disaster Management Agency (BNPB), Yogyakarta has a high tsunami potential, particularly in the coastal areas of Bantul and Gunung Kidul Regencies [3]. The 2006 earthquake, which caused a small tsunami in several coastal areas of Yogyakarta, serves as a reminder of the importance of disaster preparedness for both communities and tourists.

Tourist awareness of beach disaster mitigation, especially in the Yogyakarta Special Region, is relatively low. Most tourists are unfamiliar with the environment around beaches, evacuation routes, emergency procedures, and warning

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signs installed by authorities. Therefore, disaster mitigation efforts must be implemented to reduce the negative impacts of disasters on tourists and communities.

Previous research has shown that conveying information through conventional media, such as static information boards or notice boards, is less effective in attracting the attention of readers or users [4, 5]. Studies indicate that fewer than half of beach tourists pay attention to the available safety signage, and only a small proportion can recall the hazard information conveyed [6]. Matthews et al. [6] discovered that 45.0% of beachgoers saw safety signage, indicating that traditional signage is often ignored. Shibata et al. [7] found that 25% of domestic students and 35% of international students rarely read signage on new beaches, and over 75% of international participants did not comprehend several beach-safety words. This study showed that only 14% of South Koreans recognized red-and-yellow beach safety flags, with most participants struggling to understand important warning terms. In a tsunami-specific situation, Yasufuku et al. found that prototype evacuation route signs were difficult to spot for unfamiliar users, with only one in six supposed tourists reaching the shelter area [8]. Furthermore, various studies have revealed that signage systems in tourism destinations still face several challenges, including limited quantity, suboptimal placement, and inadequate design. Signage is often dominated by textual information, lacks the use of universal symbols, and does not sufficiently consider the diversity of tourist backgrounds, making it difficult to be broadly understood [9].

Moreover, the effectiveness of signage is not solely determined by its presence but also by the quality of its design and user behavioral factors. Research shows that tourists tend to ignore safety signs due to a low-risk perception, a lack of attention, and misunderstandings about the symbols used. In high-risk environments, signage should function as the first line of defense in preventing accidents; however, its effectiveness is highly dependent on factors such as visibility, readability, attractiveness, and universality [10]. This suggests that static and passive signage approaches have not been able to optimally influence tourist behavior. These limitations become increasingly significant in high-risk destinations, such as coastal areas, which require real-time, adaptive, and attention-grabbing information delivery.

In tourism studies, signage serves not only as a directional tool but also as a communication medium that shapes tourists' perceptions, experiences, and behaviors. However, research on signage remains predominantly focused on conventional approaches and has not extensively explored integration with digital technologies [11]. The development of digital technologies such as Quick Response (QR) codes, Augmented Reality (AR), and Virtual Reality (VR) represents a transition from static signage toward dynamic and interactive digital signage systems [12].

In line with these developments, recent studies indicate that the integration of digital technologies in wayfinding and safety communication systems is emerging, although still limited in scope. For instance, AR and QR code technologies are generally used as supplementary media to access information rather than as fully integrated primary signage systems [13, 14]. On the other hand, VR has been widely utilized in evacuation simulation contexts to analyze user behavior and decision-making in emergencies, such as in studies evaluating tourist evacuation route choices within simulated environments [15]. Nevertheless, in these studies, VR is primarily positioned as a simulation or evaluation tool rather than as a core medium within the signage system itself.

Furthermore, studies on wayfinding in tourism contexts indicate that effective navigation systems still largely rely on a combination of physical signage and simple digital media, such as maps or location-based applications [16]. This suggests that although there is a trend toward hybrid systems, immersive and experience-based integration remains underdeveloped. In other words, research that integrates signage, user interaction, spatial navigation, and behavioral learning within a unified digital ecosystem remains very limited.

Based on these conditions, a significant research gap can be identified: the absence of an approach that integrates digital signage, immersive technologies (VR), metaverse environments, and gamification mechanisms into a single, unified system for disaster mitigation education. In fact, experiential learning approaches supported by interactive virtual environments have the potential to be more effective in enhancing users' understanding, engagement, and preparedness compared to conventional passive methods.

Therefore, this study proposes a novel VR metaverse-based digital signage game for tsunami evacuation. The developed system transforms signage from a static information medium into an immersive experience medium, where users can directly interact with signage, the environment, and evacuation scenarios within a virtual space. The integration of VR as the primary platform, the metaverse as the interaction space, and gamification as the learning mechanism enables users not only to understand information but also to experience and practice evacuation processes actively.

This study is developed using a prototyping approach and evaluated using the Virtual Reality System Usability Questionnaire (VRSUQ) to measure usability and user experience. Thus, this study not only contributes to the development of experience-based digital signage concepts but also provides empirical validation of the effectiveness of immersive approaches in disaster mitigation.

2. Related Works

2.1. Digital Signage

A sign is a directional, road, location, or information sign [17]. Signage is used to direct or provide information about locations in built environments [18]. A sign system must connect a place, whether commercial, public, or private, so that it can be navigated in an orderly manner, even during busy times. The series of signs that comprise this wayfinding system must meet applicable international standards and regulations, including requirements for material, visibility, color, and size.

Wayfinding is a term used to describe the process of gathering information and making decisions that people use to navigate from one place to another accurately [19]. Frustration often arises when one becomes lost or disoriented due to illegible or misread signs, a common occurrence for many users of public spaces. Wayfinding is no longer focused solely on transportation facilities; within wayfinding management strategies, it also directs visitors to revenue-generating activities such as retail outlets. Wayfinding is also used to determine and follow paths or routes between starting points and destinations [17]. Thus, it can be concluded that wayfinding is the behavior of moving from one place to another, from a starting point to a destination, driven by motivation and planning, with a goal pursued efficiently and influenced by the environment.

The process of orientation and wayfinding, in addition to being influenced by individual human abilities, is also influenced by cognitive processes and maps, supported by representative environmental information. The overall configuration of the signage system, visual contact, and spatial differentiation related to wayfinding design are closely related to visual contact, which creates user perception [19]. Wayfinding design is an environmental information design system that includes graphics, signage, and sound signals [20].

A literature review on digital signage was conducted to gain a deeper understanding of research developments in this field over recent years. The study focused on articles published between 2021 and 2026, sourced from the ScienceDirect database. The document search was performed using the keywords “Digital Signage” and “Tourism”. Based on these keywords, 58 articles were initially identified. A preliminary screening was then conducted by assessing the relevance of each article based on its abstract. This process resulted in 12 articles deemed relevant to the specified keywords. Table 1 presents the stages and the number of selected papers.

Table 1. Stages and Number of Papers in the Literature Review

Year	Screened Papers	Excluded Papers	Relevant Papers
2021	10	8	2
2022	9	8	1
2023	9	8	1
2024	9	5	4
2025	16	14	2
2026	5	3	2
Total	58	46	12

The analysis of the twelve selected studies highlights a progressive shift in signage systems from conventional static approaches toward hybrid and digital communication systems across tourism, transportation, and urban environments. Despite this transition, existing studies consistently show that signage systems remain non-immersive, minimally interactive, and limited in behavioral engagement, particularly in safety-related contexts.

In the domain of tourism and service systems, Lee et al. [13] proposed a smart exhibition service model that integrates physical and digital services using Customer Experience Journey Mapping (CXJM) and TRIZ-based innovation. The findings demonstrate significant improvements in user experience through the identification of service issues and the development of integrated service platforms. Nevertheless, the system remains limited to a hybrid configuration and does not incorporate immersive technologies such as Virtual Reality (VR) or Metaverse environments. Similarly, studies on coastal tourism management [21, 22] emphasize the critical role of signage within broader safety management frameworks. These studies indicate that although signage is essential for risk communication and accident prevention, its implementation remains dominated by conventional static signage, with limited digital support, such as alert and monitoring systems, and has not yet evolved into an intelligent, adaptive communication system.

Table 2. Overview of Signage Systems and Emerging Technologies (QR, AR, VR, Metaverse) in Tourism and Urban Contexts

No.	Article	Year	Implementation Object	Approach	QR/AR/VR/ Metaverse	Conventional/Hybrid	Key Findings	Relevance
1	[13]	2021	Exhibition center (AEC – Taiwan) and integrated tourism services (hotels, shops, MICE ecosystem)	Service design approach using Customer Experience Journey Mapping (CXJM), TRIZ (innovation problem-solving), service assembly and replacement; empirical case study with KPI validation	Not explicitly using QR / AR / VR / Metaverse (focuses on smart service system integration)	Hybrid (combination of physical services and digital smart systems, such as e-ticketing and integrated service platforms)	(1) Identified 22 customer pain points through CXJM; (2) applied TRIZ principles to redesign the service system; (3) developed Smart Exhibition Service (SES), including tourism linkage, smart venue, and O2O e-ticketing; (4) improved service quality and customer experience	Relevant as an early model of an integrated smart signage/service system, but still limited in immersive technologies (no VR/Metaverse), thus showing a gap toward more interactive and immersive digital signage systems
2	[21]	2021	Beach and coastal tourism areas (insular states, especially Cuba)	Mixed-method (content analysis, expert survey, and case study)	None	Hybrid (predominantly conventional, with limited digital support)	(1) Identified 43 beach management practices and proposed 27 recommendations; (2) Focused on six key variables: facilities, biosafety, spatial reorganization, access, occupancy, and signage; (3) Developed countries apply more digital tools, while developing countries rely on low-cost conventional approaches	Highly relevant as baseline research showing the dominance of conventional signage and the limited integration of advanced digital technologies
3	[23]	2022	Hospitality industry (hotels and restaurants), focusing on operational impact during COVID-19 and technological responses	Exploratory research using literature review, global reports, and statistical data analysis	Mentions AR and AI as part of emerging technologies, but not applied	Hybrid (use of digital technologies such as digital signage, IoT, mobile apps, but still combined with conventional practices)	(1) COVID-19 caused a severe decline in occupancy (~40%), revenue, and employment; (2) The hospitality industry still relies heavily on traditional systems; (3) ICT, AI, IoT, and automation are critical for future resilience; (4) Digital signage is used for communicating health protocols and safety information	Relevant as a baseline study showing that digital signage is used only as a supporting communication tool, not as an integrated or immersive system; highlights the gap for advanced interactive and immersive signage solutions such as VR/Metaverse-based systems
4	[24]	2023	Outdoor advertising (billboards, big boards, banners) along urban road corridors	Quantitative field observation and mapping of advertisements across four road routes	None	Conventional signage	(1) High density of advertisements; (2) the majority are billboards (32.5%) and banners; (3) 87% of advertisements focus on company/brand promotion; (4) complex advertisements increase driver distraction and accident risk; (5) visual pollution negatively affects safety, aesthetics, and the environment	Provides baseline evidence of the limitations of conventional signage; highlights the need for smarter, less intrusive, and more adaptive digital/immersive signage systems
5	[7]	2024	Beach safety signage (flags, textual warnings, and visual icons) in a coastal tourism context	Mixed-method approach (quantitative survey combined with qualitative thematic analysis of user perceptions)	None	Conventional signage	(1) 60% of respondents misinterpreted red–yellow flags as a danger zone; (2) text-based terms (e.g., rip currents, shore break) were poorly understood; (3) visual icons were significantly better understood than textual information; (4) cultural and linguistic differences strongly influenced interpretation	Demonstrates the limitations of conventional signage in cross-cultural communication, and this limitation supports the need for immersive and interactive digital signage (e.g., VR/Metaverse-based systems) for more effective safety education
6	[22]	2024	Beach safety system (tourist beaches, especially in developing regions)	Conceptual and integrative framework (literature synthesis, best practices, and safety management model)	VR	Dominantly Conventional, with limited digital support (alerts, apps)	Safety depends on integrated infrastructure: signage, lifeguards, communication systems, and technology. Digital tools mainly support monitoring and training, not core signage	Highly relevant as a baseline study showing that current signage is still conventional and not yet immersive or integrated with VR/Metaverse systems
7	[25]	2024	Traffic information system using smart street poles (digital signage and road surface holograms)	Quantitative (Conjoint Analysis) based on a user preference survey (220 respondents)	None	Hybrid signage (digital signage and hologram)	(1) Users prefer a combination of digital signage and holograms; (2) the best format is text and graphics; (3) preferences vary by age, gender, and trip purpose; (4) dynamic information requires richer, combined formats; (5) static information tends to favor simpler visuals	Highly relevant to digital signage systems, but lacks immersive and interactive technologies such as VR/Metaverse
8	[14]	2024	Transportation-related communication systems (public information, navigation, signage, mobility systems)	Systematic Literature Review (PRISMA) and Thematic Analysis	AR included; VR/Metaverse not dominant; QR not emphasized	Hybrid (mix of conventional and digital communication technologies)	Emerging technologies (mobile apps, AR, interactive screens, navigation systems) enhance real-time information access, personalization, and navigation efficiency. However, many solutions are still conceptual and require further testing. Inclusion and accessibility remain underexplored.	Highly relevant for digital signage research; shows a shift from static signage to interactive and smart communication systems
9	[16]	2025	Pilgrim tourism routes (St. Olav Ways, Norway), focusing on the wayfinding system and signage	Mixed-methods (triangulation): field observation, document analysis, netnography, interviews, questionnaires	None	Hybrid (physical signage and digital navigation tools such as maps, apps, and online platforms)	Wayfinding is multi-layered, involving social, spatial, and semantic behaviors; users rely on a combination of physical signs, social interaction, and digital tools. Signage alone is insufficient without integration with other information sources.	Highlights the importance of integrating signage systems with digital media; however, it still lacks immersive technologies (VR/Metaverse), indicating a gap for advanced interactive signage systems
10	[26]	2025	Pedestrian route selection in train stations (stairs, platforms, junctions)	Experimental (laboratory-based behavioral study using audiovisual stimuli and ANOVA analysis)	None	Hybrid signage (visual digital signage and auditory cues)	(1) Users tend to choose less crowded routes (avoidance behavior); (2) the ratio of pictograms affects decision strength; (3) audio enhances decision-making in complex visual conditions; (4) icon-based signage is more understandable than animated pictograms	Relevant for designing behavior-based digital signage systems, especially for crowd management and evacuation guidance
11	[15]	2026	Tourists' behavior in selecting evacuation routes under emergency conditions in an outdoor tourism environment	Experimental approach (VR-based Discrete Choice Experiment), Social Cognitive Theory, Random Utility Theory, Binomial Logistic Regression	VR	Conventional (simulated signage)	(1) Crowd density has a nonlinear effect on route choice; (2) evacuation signage moderates herding vs. avoidance behavior; (3) familiarity increases confidence in route selection; (4) crowd density is the most influential factor	Highly relevant for behavioral analysis and VR-based methodology, but limited relevance for advanced signage systems (no digital signage, AR/QR, Metaverse, or gamification elements)
12	[27]	2026	Urban signage systems in smart cities (New York, Barcelona, Tokyo, Stockholm, Seoul)	Comparative case study, literature review, and empirical analysis	Limited use (AR mentioned as potential)	Hybrid (combination of conventional and digital signage)	Signage plays a critical role in promoting social equity, accessibility, and sustainability; digital signage improves engagement but may create digital divide issues; hybrid systems are more inclusive and resilient.	Highly relevant; highlights the gap in immersive and integrated signage systems, supporting the need for VR/Metaverse-based digital signage

The limitations of conventional signage are further reinforced by empirical studies examining user perceptions and interpretations. Shibata et al. [7] show that traditional beach safety signage, including flag systems and text-based warnings, is often misinterpreted by users, particularly across different cultural and linguistic contexts. While visual icons improve comprehension, they are still insufficient to overcome communication barriers fully. Similarly, Madlenak et al. [24] demonstrate that conventional outdoor advertising signage contributes to visual pollution and increased safety risks, especially in urban road environments, where complex visual elements can distract drivers. These findings indicate that conventional signage systems are not only limited in effectiveness but may also negatively affect user behavior and environmental quality.

In response to these limitations, recent studies have explored the implementation of hybrid and digital signage systems. Kim et al. [25] examined user preferences for traffic information delivery using digital signage and road surface holograms, finding that users prefer a combination of visual formats, particularly text and graphics, as well as hybrid systems integrating multiple media. Similarly, Asakawa et al. [26] reported that multimodal signage combining visual and auditory elements significantly enhances decision-making in complex environments. Systematic literature reviews [14, 27] further highlight the increasing adoption of ICT-based solutions, such as mobile applications, interactive displays, and navigation systems, enabling real-time information delivery, personalization, and improved accessibility. However, despite these developments, most digital signage systems remain screen-based and non-immersive, indicating that current innovations are still incremental rather than transformative.

Another important dimension in signage research is the role of user behavior and decision-making, particularly in evacuation and emergency contexts. Hu et al. [15] employed a VR-based experimental approach to analyze tourist evacuation route choices and found that factors such as crowd density, familiarity, and signage significantly influence decision-making. While this study demonstrates the effectiveness of VR as a simulation and analytical tool, it does not integrate VR into the design of signage systems themselves. Furthermore, Wattne et al. [16] emphasize that wayfinding is inherently multi-dimensional, involving not only physical signage but also digital tools and social interactions, highlighting the need for integrated and context-aware communication systems.

Overall, a consistent pattern emerges from the reviewed literature: although technologies such as Artificial Intelligence (AI), Augmented Reality (AR), and the Internet of Things (IoT) are increasingly discussed [14, 23], their application in signage systems remains largely supportive rather than transformative. In particular, immersive technologies such as VR and Metaverse are rarely positioned as core components of signage systems, but rather as auxiliary tools for simulation, training, or visualization. A detailed review is presented in Table 2.

Based on the synthesis of the literature, three major research gaps are identified. First, existing signage systems are still dominated by conventional and hybrid approaches, which lack adaptability, interactivity, and real-time responsiveness. Second, there is a lack of immersive and experience-based signage systems, as VR and Metaverse technologies have not yet been optimally integrated into signage design and implementation. Third, although user behavior has been widely studied, signage systems themselves are not designed to be behavior-driven, interactive, and experiential, limiting their effectiveness in influencing decision-making, particularly in emergencies.

To address these gaps, this study proposes a VR Metaverse-Based Digital Signage Game System for Tsunami Evacuation that reconceptualizes signage as an immersive, interactive communication platform. Unlike existing passive systems, the proposed approach integrates virtual environments, behavioral simulation, and gamified interactions to enhance user engagement, situational awareness, and decision-making in evacuation scenarios. This contribution shifts the paradigm from information-centric to experience-centric systems and offers both theoretical and practical implications for the development of next-generation intelligent signage.

This study reconceptualizes signage from a passive information-delivery medium into an interactive, experience-driven system by integrating VR and Metaverse as core components. Furthermore, it links signage design to user behavior and decision-making, positioning signage as a behavioral interface in evacuation contexts.

This study also proposes a VR Metaverse-Based Digital Signage Game System as an innovative solution to enhance preparedness and decision-making for tsunami evacuation through immersive, interactive experiences. The system provides a foundation for developing more adaptive, user-centered, and simulation-based signage systems, with potential applications in disaster mitigation, crowd management, and smart navigation systems.

2.2. Virtual Reality (VR) and Metaverse for Disaster Mitigation

Disaster mitigation is an effort to reduce disaster risk. This field has received extensive research attention in recent decades. In the past decade, disaster mitigation has increasingly used immersive technologies such as VR, augmented/mixed reality (AR/MR), and metaverse platforms to improve risk communication, preparedness training, evacuation planning, and stakeholder coordination. In addition, recent studies highlight the emergence of data-driven and integrated technologies such as digital twins and metaverse ecosystems, which combine immersive simulation with real-time data and collaborative environments [28-30].

VR technology is more effective than traditional media for emergency training and disaster evaluations. Several studies have shown that VR-based training can improve disaster preparedness, response times, and route selection decisions during disaster evacuations [31, 32]. VR can increase learning retention and reduce decision-making errors during disaster evacuations [33, 34]. Simulation and feedback experiments have shown that VR can improve learning retention and reduce decision-making errors [35, 36]. Visual, audio, and haptic feedback, combined with real-time performance metrics, accelerate learning [35]. Earthquake preparedness training in residential areas has been shown to reduce decision-making errors during stressful situations [37]. Disaster preparedness training using VR technology also implies significant cost savings [38, 39]. From a technological perspective, VR primarily functions as an immersive simulation tool that enhances spatial awareness and experiential learning [40, 41]. However, most implementations remain standalone and individual-based, with limited integration into broader systems. Although VR applications are effective for disaster evacuation training, testing with more varied scenarios and more formative feedback is needed, as well as modeling social interactions that better reflect the real world.

Specifically, VR has been used for tsunami preparedness and evacuation, and tsunami VR systems have been developed to test behavioral responses with and without coastal defenses. This system provides information on evacuation times when a tsunami hazard is detected [42, 43]. Tests using an AR-based simulator for tsunami evacuation training demonstrated the application's success for both visitors and staff. Tests have also highlighted the need for contextual markers (signs and landmarks) that are recognizable to non-local tourists [44]. A GIS-based (Geographic Information System) VR application experiment was conducted to collect user preferences for tsunami shelters. Research has shown that tourists tend to choose conspicuous and easily accessible vertical shelters near the coast [45]. Beyond immersive visualization, several studies have introduced digital twin technology to enable real-time modeling and prediction of disaster scenarios. Digital twins enable dynamic simulation environments by integrating sensor data, spatial information, and system behavior, thereby supporting monitoring, prediction, and decision-making processes [46, 47]. In participatory contexts, digital twin systems combined with VR and open data have also been shown to enhance community engagement and improve the accuracy of mitigation strategies [28].

Psychological studies of beach app users have revealed differences in knowledge of tsunami warnings. VR application development should explicitly train users to evacuate under conditions without warnings or natural warnings [48]. Survey results using Protection Motivation Theory (PMT) among tourists and tourism workers showed that VR can strengthen aspects of response affiliation and self-efficacy in threat assessment and evacuation intentions [49].

Research on applying AR to the metaverse was conducted in a smart city simulation study that encompassed coordinated planning and city resilience. AI and digital twin technology support this technological application. Applications include incident command system (ICS) exercises, collaborative planning, and public engagement sandboxes [50, 51]. Experimental studies integrating smart city data, such as assets, sensors, and mobility, into VR evacuation scenarios have shown a positive impact on citizen behavior, although interoperability standards and evaluation protocols remain challenging [52]. Furthermore, the metaverse represents an evolution of VR and digital twin technologies by integrating immersive environments with multi-user interaction and real-time data systems. Studies show that metaverse platforms supported by AI, IoT, and GIS enable collaborative disaster simulation, policy testing, and stakeholder coordination [30, 53, 54]. These platforms allow multiple users to interact simultaneously in shared virtual environments, improving coordination and collective decision-making during disaster scenarios.

Metaverses with digital twin integration are also being used as multi-user spaces for tourism. For beach resorts, the application of this technology allows for cross-agency tabletop exercises using VR and participatory planning training with residents and tourist representatives [54-56]. Despite these advancements, existing studies still tend to implement VR, digital twin, and metaverse technologies in a fragmented manner, with limited integration into a unified system. Moreover, the connection between immersive technologies and interactive communication media, such as digital signage, remains underexplored.

A literature review showed that VR technology has many positive effects on disaster mitigation. Specifically, this study builds a metaverse integrated with VR for tsunami evacuation. The developed application focuses on the placement of digital signage along evacuation routes. This study addressed the need for contextual markers for disaster evacuations [44]. By integrating VR, metaverse, and digital signage into a unified system, this study extends previous studies that largely treated these technologies separately.

Despite the rapid advancement of immersive and data-driven technologies in disaster mitigation, several critical gaps remain. Existing studies predominantly utilize VR as a standalone tool for individual training, while digital

twin applications are often limited to data modeling and system-level analysis, and metaverse platforms are still largely conceptual or applied in general urban contexts [30, 40, 46]. Moreover, these technologies are typically implemented in isolation rather than as an integrated system. In addition, the role of digital signage as an interactive communication medium in immersive environments has received limited attention, despite its importance in guiding real-time evacuation behavior. Furthermore, most prior studies focus on general disaster scenarios, such as floods or urban resilience, with limited emphasis on time-critical, context-specific disasters, particularly in coastal tourism areas, for example, tsunamis.

To address these gaps, this study proposes a VR metaverse-based digital signage game for tsunami evacuation, which integrates immersive simulation, multi-user virtual environments, and interactive communication systems into a unified platform. The novelty of this research lies in three main aspects. First, it introduces an integrated framework that combines VR, metaverse, and digital signage, bridging immersive experiences, collaborative interactions, and real-time guidance. Second, it applies a game-based approach to transform conventional signage into an interactive learning and training medium that enhances user engagement and behavioral response. Third, the system is specifically designed for tsunami evacuation scenarios, incorporating contextual markers and route guidance relevant to coastal environments. This integrated approach not only enhances awareness and preparedness but also supports decision-making during evacuation, thereby contributing both theoretically and practically to the development of next-generation disaster mitigation systems.

3. Research Methodology

The system was developed using a prototype method. This iterative approach is a method for rapidly defining requirements and designing software such that users can immediately interact with the system being developed. After the rapid design, a prototype was developed, and during the iteration cycle, the system was evaluated and tested by users [57].

Prototyping is often used in software development because it makes it easier for users to track the software development process. This method also makes it easier for the development team to build software, even if users cannot determine the detailed features of the required system [58-60]. Furthermore, prototyping is a rapid development method that can reduce software development costs [59, 61].

The prototyping method was implemented in four stages: requirements engineering, rapid system design, prototype development, and testing. The requirements engineering, design, development, and testing stages are iterative. The iteration process continued until the tool satisfied the system's primary requirements. Figure 1 shows the stages of the research methods used.

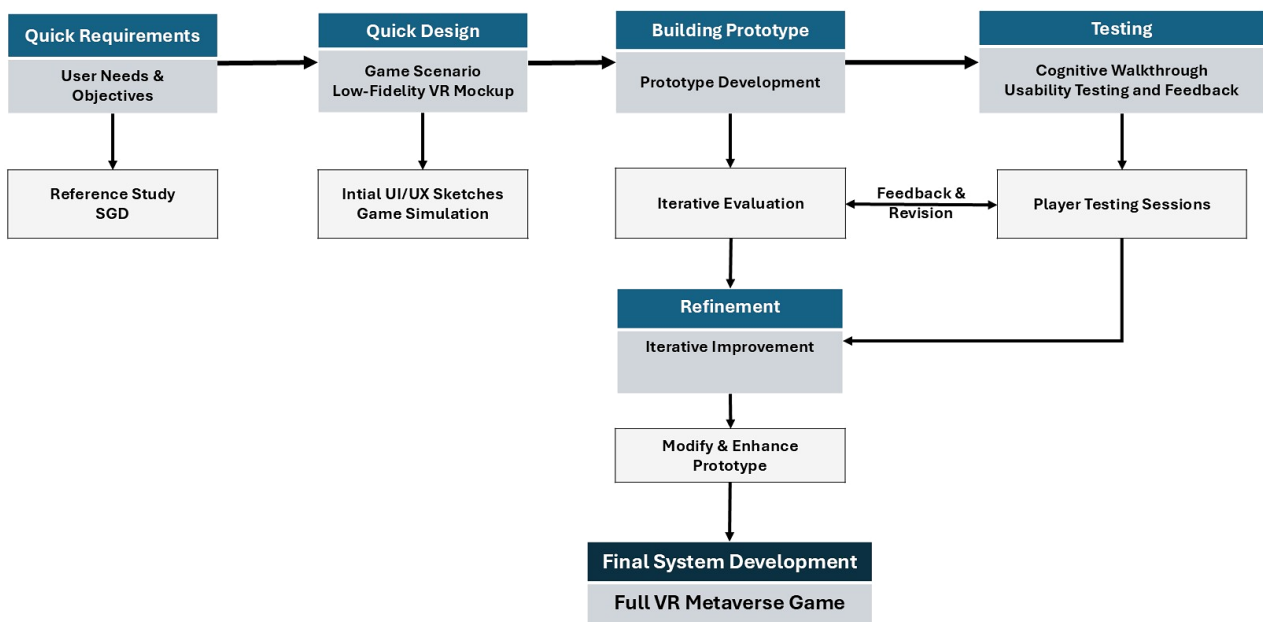


Figure 1. Stages of the employed research methods

Furthermore, Table 3 describes the activities and methods used at each stage.

Table 3. Activities and methods in each research stage

No.	Stage/Phase	Activities	Methods/Tools
1	Quick Requirements	<ul style="list-style-type: none"> • Conducting observations and studies related to digital signage and disaster mitigation in coastal tourism. • Analyzing and defining functional system requirements. 	Reference study Small group discussion
2	Quick Design	<ul style="list-style-type: none"> • Designing digital signage for tsunami disaster mitigation • Designing game scenarios • Designing user interfaces 	Small group discussion Game Simulation
3	Building Prototype	<ul style="list-style-type: none"> • Developing a VR and metaverse-based tsunami evacuation game prototype. • Integrating digital signage into the environment • Implementing core game mechanics (navigation, evacuation scenarios) • Creating alpha version • Conducting iterative evaluations for prototype development 	Prototype development using Unity
4	Testing	<ul style="list-style-type: none"> • Conducting user testing sessions • Evaluating usability and user experience • Collecting feedback and observe user behavior • Analyzing evaluation results 	Simulation Cognitive Walkthrough Usability Testing Questionnaire (VRSUQ)
5	Refinement	<ul style="list-style-type: none"> • Improving UI/UX and signage clarity • Enhancing game mechanics • Optimizing VR performance 	Debugging Optimization
6	Final System Development	<ul style="list-style-type: none"> • Integrating complete system components • Performing final testing (functionality, performance, usability) • Preparing documentation and implementation • Preparing deployment of the VR application 	System testing

4. Results

4.1. Digital Signage for Beach Tourism

Signage is an integral part of urban design that enhances a city's image. Signage comes in various types, functions, and benefits, including evacuation signs for emergencies or natural disasters, such as tsunamis. Tsunami evacuation signs provide directions and evacuation routes in areas prone to tsunamis. These signs serve as public education tools to help identify evacuation zones, routes, and tsunami-safe zones. Tsunami evacuation information boards have also been installed to raise awareness among local communities; therefore, the user experience when viewing and interpreting information on these signs warrants special attention.

This study developed digital signage to support disaster mitigation in coastal tourism. The primary application scenario was the rescue of tourists (players) from a tsunami. The developed digital signage directs players from the starting point to the evacuation building for tsunami rescue. Digital signage, also known as wayfinding, is the primary tool for conveying directional information to players.

The signage design in this study followed the tsunami disaster evacuation route planning guidelines from the Directorate General of Highways of the Ministry of Public Works and Public Housing. Important factors in creating this signage include: a) adjusting the viewing distance to letter and symbol size; b) using a standard for determining the size of symbols based on the observer's viewing distance; c) using a standard for determining letter height based on the observer's distance; d) color theory: the influence of color on emotions; e) topography in writing signage content (font type); and f) pictograms: a graphic communication tool using symbols or symbols that represent an object.

Six signage items were designed for the tsunami evacuation game. The first sign is a tourist area nameplate, also known as an identification sign (Figure 2). The first sign is a tourist area nameplate, also known as an identification sign (Figure 2). This signage serves as an initial cognitive anchor for users.

The second sign shows the evacuation route directions (Figure 3). The second sign was developed with a simple, intuitive user interface. This approach applies color selection and arrows according to [18]. The use of orange or blue conveys guidance and information. Understanding these color symbols is useful for educational purposes, including tsunami awareness, evacuation routes, and assembly points. Signage is placed at road intersections starting from the first zone after the beach, namely, the trade zone [18]. Users must be able to understand the meaning of the message on the sign in less than five seconds [62].



Figure 2. Tourist area signage



Figure 3. Evacuation route direction signage

The third sign used to mark evacuation buildings and assembly points is called a directional sign. This type of signage guides players to safe locations during emergencies, particularly when rapid decision-making is required. The use of green color signifies an emergency condition related to safety and evacuation, and it is internationally recognized as an indicator of safe routes, exits, and assembly areas. Therefore, green is commonly applied in evacuation map symbols and assembly point indicators to enhance visibility, comprehension, and user response under stressful conditions. As shown in Figure 4, the assembly point signage is positioned to effectively communicate the designated safe gathering area for evacuees. The signage was placed in the courtyard of the evacuation building.

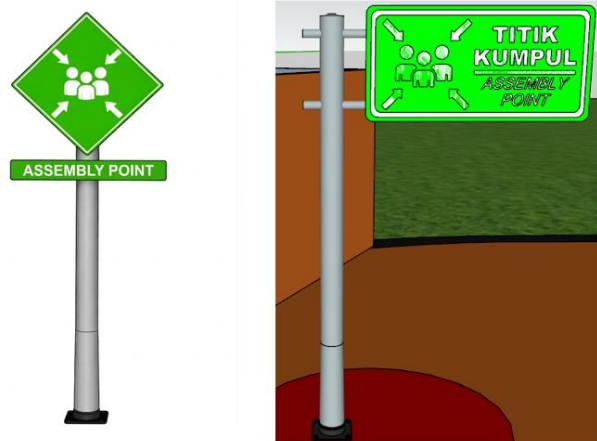


Figure 4. Assembly point signage

The fourth and fifth signs were the distance to the assembly point (orientational sign) and the direct tsunami impact zone (directional sign), respectively [63]. The use of red indicates danger or warning. Usually, this color symbolizes a direct impact zone with no parking allowed. These signs were observed in the most affected areas. The fourth and fifth signs are shown in Figures 5 and 6.



Figure 5. Signage showing the distance to the assembly point



Figure 6. Signage for the direct tsunami impact zone

The sixth and final signage is an elevation indicator (Figure 7). This signage design is similar to the first, providing information about the player's altitude above sea level. The inclusion of elevation information is critical in disaster mitigation contexts, particularly for tsunami evacuation, where higher ground is associated with greater safety. By presenting altitude data, the signage helps users make informed decisions about safe zones and optimal evacuation routes.

Furthermore, the elevation indicator enhances situational awareness by enabling continuous monitoring of vertical position within the environment. This is especially important in immersive virtual environments, where users may have limited perception of real-world geographic cues. The design adopts clear numerical values and intuitive visual elements to ensure readability and quick interpretation, even under time-constrained or high-stress conditions.

Additionally, consistency with the first signage design (Figure 2) for color and the fourth design (Figure 5) for the use of numbers on the signage helps maintain visual coherence and reduces cognitive load, allowing users to easily recognize and interpret information without requiring additional learning. This aligns with the principles of effective signage design such as clarity, consistency, and usability.



Figure 7. Location height indication signage

The digital signage design in this study adopts principles from Gestalt psychology to enhance visual legibility and the effectiveness of the wayfinding system [64]. Gestalt principles emphasize that humans tend to process visual elements as a unified whole, making the organization of these elements crucial for conveying information quickly and accurately [65]. The four main principles applied in signage design are proximity, similarity, closure, and continuity.

The application of Gestalt principles in digital signage design demonstrates that the grouping of visual elements (proximity), consistency in shape and color (similarity), simplification of symbols (closure), and continuity in signage placement (continuity) significantly contribute to creating an intuitive, logical, and unambiguous wayfinding system, particularly in the context of emergency evacuation.

The principle of proximity is applied by grouping related information elements—such as icons and text—in close proximity so that they are perceived as a single unit of information [66]. This allows users to quickly understand the signage message. The principle of similarity is achieved through consistent use of color, shape, and typography throughout the signage system. For example, the color green is used consistently to indicate safe zones or evacuation points, while red is used to mark danger zones. This consistency helps users instantly recognize the function of the signage without requiring a complex interpretation process.

The principle of closure is applied through the use of simplified yet representative pictograms. Simplifying shapes allows users to still recognize the meaning of symbols even when they are not displayed in detail, thereby accelerating the cognitive process, especially in emergency situations. Meanwhile, the principle of continuity is the most dominant aspect in the wayfinding system. Signage placement is designed sequentially and continuously to form a logical navigation flow from the starting point to the evacuation destination. Thus, users can follow the evacuation route intuitively without experiencing confusion in decision-making. Overall, the application of Gestalt principles in digital signage design contributes to reducing users' cognitive load, enhancing information clarity, and accelerating user response during tsunami evacuation situations. Table 4 describes the application of the Gestalt principle in signage design.

The results presented in Table 4 demonstrate that the application of Gestalt principles—proximity, similarity, closure, and continuity—significantly enhances the effectiveness of the digital signage system for tsunami evacuation. The principle of proximity is consistently applied across all signage types by grouping related elements such as text, icons, and directional symbols. This configuration enables users to perceive information as a unified message, thereby accelerating comprehension, particularly in time-critical situations. For instance, directional signage integrates arrows, text, and symbols in close spatial arrangement, allowing users to interpret evacuation routes quickly and accurately.

The similarity principle ensures visual consistency throughout the signage system. Standardized use of colors, typography, and shapes—such as green for safe zones and red for hazard areas—facilitates immediate recognition of signage functions. This consistency reduces cognitive effort and minimizes the need for interpretation, which is essential during emergency evacuations. The application of closure is evident in the use of simplified pictograms across all signage categories. Even with minimal visual detail, these symbols remain recognizable and effective in conveying meaning. This simplification supports rapid cognitive processing and helps users make quick decisions under stress or panic conditions.

Among all principles, continuity emerges as the most dominant in structuring the wayfinding system. The signage is arranged sequentially to form a coherent navigation flow, starting from orientation signage, followed by directional and distance indicators, and ending at evacuation assembly points. Additional signage, such as hazard warnings and elevation indicators, further reinforces this flow by providing contextual and progressive information along the route. Furthermore, the results indicate that each signage type contributes to a specific function within the overall system: orientation (Figure 2), navigation (Figures 3 and 5), destination confirmation (Figure 4), hazard warning (Figure 6), and contextual support (Figure 7). This functional differentiation ensures that users receive the right information at the right stage of the evacuation process. Overall, the integration of Gestalt principles across multiple signage types forms a cohesive visual communication system that enhances clarity, reduces cognitive load, and supports intuitive decision-making during tsunami evacuation.

Table 4. Application of Gestalt Principles in Digital Signage Design for Tsunami Evacuation

No.	Signage	Signage Name	Proximity	Similarity	Closure	Continuity
1	Figure 2	Tourist area nameplate	Area names and visual elements are grouped within a single field, making it easier for users to quickly recognize the location's identity.	Typography and colors are consistent with other signage.	The signage's simple form makes it easily recognizable as a location marker.	It serves as a starting point for orientation before entering the wayfinding system.
2	Figure 3	Evacuation route directions	Arrows, text, and icons are placed close together to speed up the interpretation of directions.	This approach applies color selection and arrows according to [18]. The use of orange or blue conveys guidance and information. Understanding these color symbols is useful for educational purposes, including tsunami awareness, evacuation routes, and assembly points.	The arrow icon is simple yet sufficiently representative. It remains legible even in panic situations.	Signage is placed at road intersections starting from the first zone after the beach, namely, the trade zone [18]. Users must be able to understand the meaning of the message on the sign in less than five seconds [62]. This signage forms a sequential guidance system.
3	Figure 4	Sign for evacuation buildings and assembly points	The gathering point symbol and text are combined.	The green color is consistent with safety standards.	The pictogram of people gathering is quite simple.	It serves as the endpoint of the evacuation signage sequence, providing spatial confirmation to users.
4	Figure 5	The distance to the assembly point	Combines distance and direction information (to aid decision-making).	Consistent formatting with directional signage	Simplification of numbers and symbols	Provides progress feedback along the route. Enhances the sense of progress during evacuation
5	Figure 6	Sign for tsunami impact zone	The hazard symbol and text are placed together.	The symbol's shape matches Figures 2 and 4. The color red is consistently used as a hazard indicator.	The simple icon is easily recognizable as a prohibition	Provides a warning within the flow.
6	Figure 7	Location height indication signage	Elevation information is displayed in a unified manner.	Visual consistency in identification signage (system consistency).	Simple, easy-to-understand forms.	Provides additional context along the route; the information presented is the same as in Figure 5.

4.2. Digital Signage Questionnaire-Based Evaluation

This study evaluates user understanding of the application and digital signage through a questionnaire-based assessment. The respondents consisted of 51 participants. The demographic profile shows that the majority of participants were male (54.90%), followed by female respondents (39.22%), with a small proportion preferring not to disclose their gender (5.88%). In terms of age, most respondents were in the 18–23 age group (64.71%), indicating a strong representation of young adults. Regarding prior experience with Virtual Reality (VR), more than half of the respondents (54.90%) had no prior experience, while 45.10% had previously used VR. This indicates that the evaluation involved a substantial proportion of novice users. These respondents are the same individuals who participated in the system usability testing and completed the VRSUQ questionnaire.

The evaluation results are summarized in Table 5. The table shows that the evaluation was conducted through 15 questions on tsunami warning signs, disaster mitigation understanding, and comprehension of the implemented signage system. The analysis indicates that respondents demonstrate a very high level of understanding of tsunami hazards, warning signs, and appropriate evacuation procedures. Most respondents (approximately 96%) correctly identified undersea earthquakes as the primary cause of tsunamis, while around 92% recognized natural signs, such as sudden seawater recession as early indicators. Furthermore, nearly all respondents (approximately 98%) correctly interpreted repeated long sirens as tsunami warning signals.

From a preparedness perspective, the majority of respondents (approximately 95%) demonstrated a good understanding of mitigation actions prior to visiting coastal areas, particularly in identifying evacuation routes and assembly points. In emergency scenarios, such as earthquakes or sudden seawater recession, approximately 96% of respondents consistently stated that the appropriate action is to immediately move to higher ground or designated evacuation points. This indicates that respondents possess strong conceptual knowledge regarding disaster response.

Furthermore, respondents demonstrated a clear understanding of the function and role of digital signage in emergency situations. Most respondents (approximately 94%) identified digital signage as a tool for providing evacuation routes and emergency information. Additionally, around 85% of respondents recognized that the main advantage of digital signage over conventional signage is its ability to provide real-time information, although a small proportion of respondents have not fully internalized this aspect.

From an information design perspective, respondents showed a strong preference for visual-based communication. Approximately 88% of respondents indicated that icon- and color-based displays are the most helpful forms of information presentation in emergency situations. Color usage was also well understood, with around 95% of respondents recognizing green as indicating safe areas and approximately 94% understanding red as indicating danger requiring immediate evacuation. Moreover, around 90% of respondents stated that the combination of text and color effectively conveys evacuation information quickly and clearly.

Furthermore, spatial information emerged as a primary need identified by respondents. Approximately 92% of respondents stated that the most important information in digital signage is the direction and distance to evacuation points. This indicates that navigation capability and spatial awareness are critical aspects of disaster mitigation systems. In situations where primary evacuation routes were unavailable, approximately 90% of respondents made appropriate decisions by selecting alternative routes based on signage, demonstrating adaptive decision-making.

Overall, these findings indicate that respondents possess a very strong conceptual understanding of tsunami mitigation and evacuation procedures, with response consistency generally exceeding 90%. However, there remains a need to enhance user understanding of digital signage technology as well as their situational experience in emergency conditions. This underscores the importance of developing interactive and immersive technology-based systems that support spatial navigation, dynamic information delivery, and improved decision-making in disaster situations.

Table 5. Question-Based Evaluation Matrix of Tsunami Awareness and Digital Signage Understanding

No.	Questions	Dominant Response Answers	Percentage Dominant Answers
1	What is the main cause of a tsunami?	Undersea earthquake	96%
2	What natural signs commonly appear before a tsunami occurs?	Sudden receding seawater	92%
3	What does a long, repeated siren in a coastal area after an earthquake mean?	Tsunami warning signal	98%
4	Before visiting a beach, what mitigation action should be taken?	Knowing evacuation routes and assembly points	95%
5	If you see the sea suddenly recede drastically, what should you do?	Immediately go to higher ground or evacuation points	96%
6	What is the main function of digital signage in coastal areas during a potential tsunami?	Displaying evacuation routes and emergency information	94%
7	Why is digital signage more effective than conventional signage in tsunami emergencies?	Information can be updated in real-time	85%
8	What does an orange arrow symbol on evacuation signage indicate?	A direction to a safe evacuation point	96%
9	If signage shows a "direct tsunami impact zone," what does it mean?	Area potentially affected by tsunami waves	94%
10	What is the function of text and colors on digital signage?	Delivering evacuation information quickly and clearly	90%
11	What information is most important to display on digital signage during a tsunami?	Direction and distance to evacuation points	92%
12	According to you, what display is most helpful on digital signage?	Icons and colors	88%
13	What does the use of green color on evacuation maps and assembly points indicate?	Safe evacuation location	95%
14	What does the red color on digital signage indicate?	Danger warning and need to evacuate	94%
15	If signage displays "evacuation route closed," what should you do?	Finding an alternative route based on signage instructions	90%

4.3. Tsunami Evacuation Game

This research resulted in a prototype VR-based application for the metaverse. The application was displayed as stereoscopic 3D graphics using a VR device. The currently supported device is the PICO 4 VR. The game environment was set on Parangtritis Beach. The location was chosen based on the most famous beach icon or location in Yogyakarta. The game attempts to mimic the real environment of the location.

The game was set on Parangtritis Beach, with the player on vacation. Upon first entering the application, the player is placed on the beach, experiences an earthquake, and is evacuated during a tsunami scenario. Digital/virtual signage was used to direct the players to the evacuation building. A map of the game simulation is presented in Figure 8.



Figure 8. Game mini-map

The game's theme was to teach players to recognize tsunami sirens and evacuate by consulting a map. The player's task was to follow the evacuation route marked by virtual signage and sirens. The scenarios and gameplay were as follows: The player was located at Parangtritis Beach. Suddenly, an earthquake occurred (represented by a rumbling sound and a screen-shake effect). Five seconds later, the water receded, and 15 s later, a tsunami warning was issued. The player was given a visual and audio notification: "An earthquake has occurred; evacuate immediately to a safe location." Figure 9 shows a simulation of what a tsunami may look like. A map appears for navigation to the temporary tsunami shelters. This map also shows the player's current location and direction toward the shelter building (Figure 10). Players must find and follow the evacuation route using virtual signs (green boards with directional arrows) and an interactive evacuation map (if needed; a map that can be opened and closed) to reach the tsunami shelter (evacuation building). Figure 11 shows the virtual signage in the game.

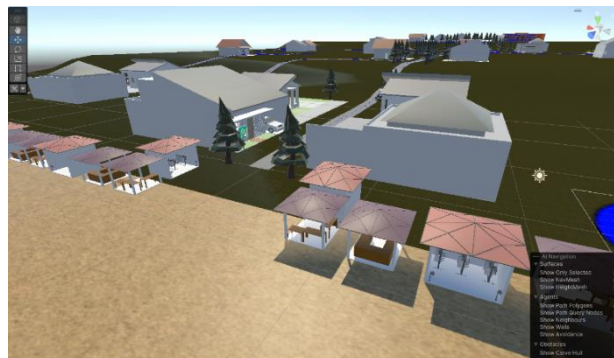


Figure 9. View of the tsunami simulation from the coast

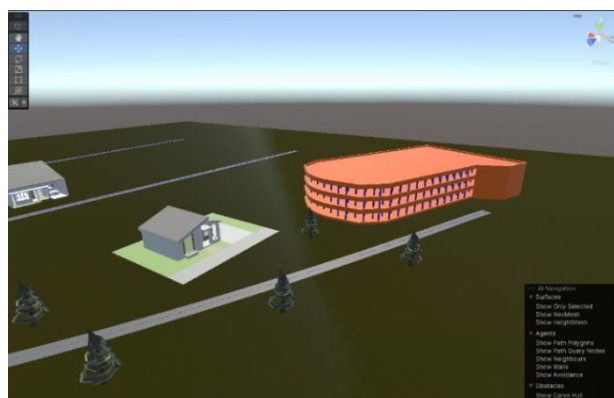


Figure 10. Evacuation building in a virtual environment

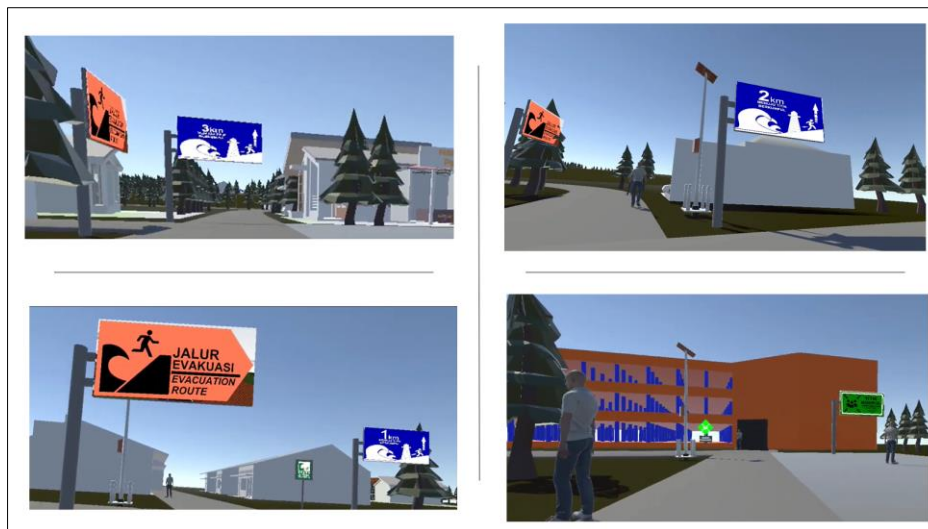


Figure 11. Display virtual signage

The players were given 2–3 min to reach the safe zone. In addition, players may encounter minor obstacles, such as damaged paths, fallen trees, crowds of NPCs (non-Player Characters), or choices of paths, such as a fast but narrow path versus a gentle but longer one.

The players were given 2–3 minutes to reach the tsunami evacuation building. The interactions players can perform include point-to-point teleportation and an autopath system. There are two optional interactions: the player can symbolically “help” other NPCs (e.g., by directing them), and there is an auto-walk mode with special checkpoints for people with disabilities. Several conditions which end the game: (1) reaching the safe zone within the allotted time; (2) triggering an optional cutscene featuring a rescue helicopter and an NPC expressing gratitude; (3) earning the “Tsunami Survivor” badge; or (4) failure, which redirects the player to the learning screen titled “What to Do During a Tsunami.” Game simulation videos for prototypes 1 and 2 can each be accessed at the following address: https://bit.ly/Tsunami_prototype_1 and https://bit.ly/game_simulation.

4.4. Cognitive Walkthrough Testing Result

Testing was conducted using a Cognitive Walkthrough approach. A Cognitive Walkthrough is a usability testing method in which researchers evaluate all the processes respondents use to perform a task. This method was used to identify problems with the device's use. The Cognitive Walkthrough procedure [67] involves three stages: preparation, implementation, and evaluation, as shown in Figure 12.

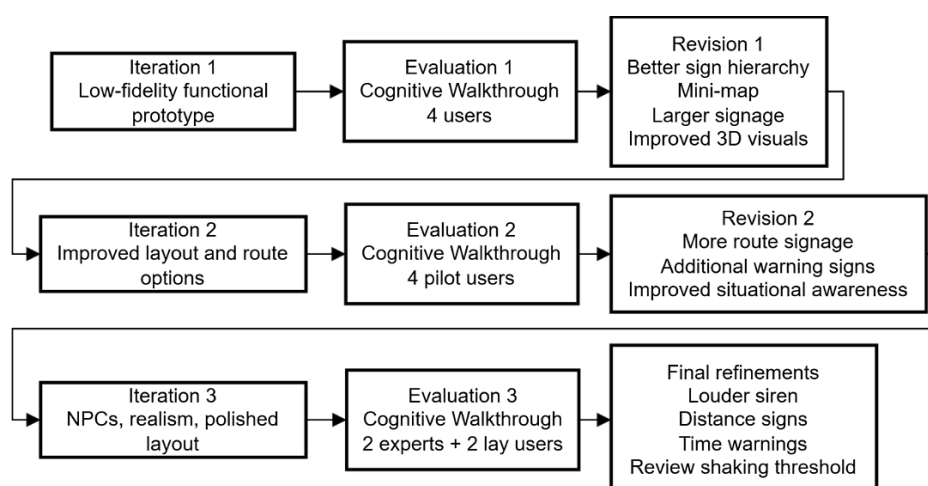


Figure 12. Iterative Evaluation and Revision Process

The preparation step included identifying target users, tasks, task types, testing rules, task sequencing, and the evaluation team. This study's preparation phase included the creation of low-fidelity prototypes. The prototype concentrated on the tsunami event, the countdown timer, key visual elements, and audio effects at this stage. An initial Cognitive Walkthrough with four users assessed whether these main parts were clear and sufficient to guide users through the evacuation scenario. At this stage, customers complained about the visual and 3D design, the difficulty of

finishing the simulation since they couldn't figure out how to reach the safe zone, and the confusion between warning and guidance indicators. Following these observations, various design changes were made. The color coding and icon hierarchy of the signage were revised to better distinguish warning and directional functions. The 3D models and signage graphics were improved, a mini-map was added to help users understand the evacuation building route, and icons and signage were enlarged by 15% for distance visibility.

The implementation phase was the second refinement cycle of the prototype in this project. During implementation, the evaluation team logged all achievements, failures, suggestions, and usability issues while testing each task from the intended product users' perspective. According to feedback from the initial phase, trees and buildings were added to the simulation architecture to make the virtual coastal area more realistic. Two new evacuation roads were added, giving customers three routes to the evacuation building. Joystick-based locomotion and teleportation were included to satisfy VR navigation preferences. A second Cognitive Walkthrough with four pilot testers examined how players understood what to do at the start of the scenario and chose an evacuation path. Two out of four people had a long time choosing a route. Some routes lacked signage, and users were unsure if they had picked the right path. More graphics and directional signage were added along evacuation routes, and more warning signs were placed in the beach area to help users understand the location and emergency scenario upon entering the simulation.

The evaluation phase was conducted through small-group discussions between the testing team and user representatives to jointly review the Cognitive Walkthrough results, discuss the identified problems, and formulate system improvements. This phase was the near-final prototype in this study. NPCs were added, graphics and 3D models were enhanced, the layout was refined, and market items were added to better portray Parangtritis Beach's mood. In this phase, two expert users and two lay users who had never used the application participated in the Cognitive Walkthrough. We used a mixed-methods strategy to gather analytical and experiential perspectives. Expert respondents had at least four years of IT and software development expertise and could identify hidden design and interface flaws [68, 69]. Lay responders represented the application's target audience. Participants had to be 18 years old, have 10 hours of gaming experience per week, and be free of vision or physical limitations. These criteria were chosen to measure system design quality rather than participants' 3D or VR incapacity [70-72]. Gamers with higher digital interaction literacy are more familiar with navigation mechanisms, camera control, visual symbols, and mission-based systems, and they adapt faster to VR interaction techniques like teleportation and joystick movement [71]. Thus, integrating expert and lay respondents has methodological advantages: experts analyze design logic and system consistency, while lay users give ecological validity on how target users utilize the system [69, 73].

The use of four respondents was considered sufficient for the Cognitive Walkthrough because this method is diagnostic rather than statistical in nature. Turner et al. showed that small-sample usability studies can estimate usability problem-discovery rates and that data from the first four participants can be used to estimate sample size in early-stage usability evaluation [74]. The testing purpose is to identify major usability problems through detailed task-based inspection, not to achieve population-level generalization. The combination of two expert users and two lay users provided complementary perspectives: experts examined interface logic, consistency, and design flaws, while lay users reflected how the target audience would naturally interpret and interact with the system. In this context, a small but purposively selected sample was adequate to reveal critical usability issues, especially when recurring patterns of difficulty began to emerge across participants.

Respondents as players should complete three tasks. The first was to identify the initial conditions of a tsunami disaster, including an earthquake, a receding water level, and a siren. The second task required players to follow digital evacuation instructions. The final task was a completion task that required players to reach a shelter or an evacuation building. A list of tasks and their descriptions is presented in Table 6. The design revisions made during each Cognitive Walkthrough phase are summarized in Table 7.

Table 6. List of Testing Tasks

Task	Task Title	Task Description	Task Goal	Task Questions
1	Recognizing the Occurrence of Earthquakes and Tsunami Threats	The users were on Parangtritis Beach when the screen suddenly shook, and a rumbling sound was heard. After a few seconds, the tide receded, and a siren sounded.	Do the users understand that this is a danger signal and the beginning of a tsunami scenario?	a. Did the users realize that an earthquake had occurred? b. Did the users understand the meaning of the siren sounds and the visuals of receding water?
2	Finding an Evacuation Route	The users would see several green signs with directional arrows in the area. Find and follow these signs to reach the shelter.	Can the users recognize evacuation signs and follow them?	a. Did the users know that the green sign is an evacuation sign? b. Could the users follow the correct directions?
3	Reach the Shelter Before Time Runs Out	The users would use the existing navigation markers until you arrive at the evacuation shelter before the simulation time runs out.	Can the users reach the evacuation location within a given time frame by following the existing directions (signage)?	a. Did the users know that time was limited? b. Did the users know the directions to the shelter location?

Table 7. The design revisions made during each Cognitive Walkthrough phase

Phase	Prototype focus	Participants and methods	Main findings	Design changes made
Preparation phase	The first low-fidelity prototype focused on the tsunami event, the countdown timer, the visual effects, and the audio effects.	Cognitive Walkthrough with 4 users	Users noted poor 3D and visual quality. Several users had trouble completing the exercise because the safe zone was unclear. Warning and directional signs were unclear.	Revising color coding and icon hierarchy to distinguish warning and directing signs; upgraded 3D models and signage visuals, including a mini-map for route understanding; and enlarged icons and signage by 15% for distance visibility.
Implementation phase	Realism was improved by adding trees and buildings to the area, two extra evacuation routes, joystick locomotion, and teleportation controls.	Cognitive Walkthrough with 4 pilot users	Two of the four users spent a long time choosing among the three paths. Users were unsure if their path was correct, and some lacked signage.	Adding extra graphics and directional signage along evacuation routes, and warning signs in the beach area, to boost early situational awareness and helping users understand the emergency context from the start of the simulation.
Evaluation phase	Near-final prototype with NPCs, updated graphics, 3D models, layout, and market aspects to depict Parangtritis Beach.	Cognitive Walkthrough with 2 experts and 2 lay users	All users knew the earthquake and evacuation cues, 75% knew the tsunami warning from the retreating sea level, and all knew the evacuation building direction. Some people preferred the mini-map to in-world signs. The earthquake simulation made several individuals uncomfortable with teleportation, uninformed of the time restriction, or dizzy.	Amplifying the siren sound, reviewing the earthquake effect shaking threshold, adding clearer distance signs to the evacuation building, strengthening digital signage support along the route, and adding evacuation site time warnings were the final improvements.

4.5. Usability Testing Result

The Cognitive Walkthrough evaluation was conducted early in software development. For the final version of the application, a usability evaluation was carried out. The evaluation employed the Virtual Reality System Usability Questionnaire (VRSUQ) [75]. VRSUQ is a questionnaire instrument specifically developed to comprehensively assess the usability (usefulness and comfort) of VR systems. The main objectives of VRSUQ development are to address the limitations of general usability questionnaires such as the System Usability Scale (SUS), which do not take into account the unique characteristics of VR, incorporate factors that are distinctive to the VR experience, such as immersion, presence, motion sickness, and workload, and provide a more accurate and efficient evaluation tool for research and development of VR systems [75]. The VRSUQ was developed based on the three main usability dimensions of ISO 9241-11:2018: Effectiveness, Efficiency, and Satisfaction, each with three indicators and a total of nine questions. The VRSUQ questions are shown in Table 8.

Table 8. List of VRSUQ Questions [75]

Num.	Question	Measured Aspects/Dimension
1	The system responded well to my manipulations as expected, with no delays.	Effectiveness — Compatibility
2	I think the virtual reality system provides clear feedback on my manipulations.	Effectiveness — Feedback
3	(-) I kept making errors/mistakes while using the virtual reality system.	Effectiveness — Error prevention
4	I could clearly understand the information presented within the virtual environment.	Efficiency — Understandability
5	I think this system is user-friendly, straightforward to learn, and designed so that most people will find it easy to adapt to.	Efficiency — Learnability
6	I think it is easy to correct errors made during virtual reality experiences.	Efficiency — Error recovery
7	I enjoyed the virtual reality experience.	Satisfaction — Pleasure
8	(-) I felt dizzy, had motion sickness, or had a headache while experiencing virtual reality.	Satisfaction — Physical discomfort (motion sickness)
9	(-) While experiencing virtual reality, I felt mental burdens such as tension, frustration, and time pressure.	Satisfaction — Emotional discomfort

Each item was rated on a 1–5 Likert scale (strongly disagree–strongly agree). Negative items (3, 8, and 9), such as those related to motion sickness and emotional discomfort, were reverse-scored before statistical analysis. The usability evaluation was conducted using the VRSUQ instrument, and the overall score was calculated using the Equation 1. This transformation converts the average Likert-scale responses into a percentage scale ranging from 0 to 100, enabling a more intuitive interpretation of usability performance.

$$VRSUQ\ Score = \left(\left(\frac{\sum all\ questions}{9} \right) - 1 \right) \times 100/4 \tag{1}$$

The evaluation involved 51 respondents, comprising 54.9% males, 39.2% females, and 5.9% who chose not to disclose their gender. The respondents’ ages ranged from 15 to 56 years, with the largest age group being 18–23 years (64.7%). Most respondents (68%) were students, while the rest were employed. Regarding VR device experience, 54.9% of respondents had never used one.

The evaluation results showed a VRSUQ score of 69.66. This score is below the standard average VRSUQ value of 72.88. This outcome is attributed to respondents experiencing issues related to error prevention, physical discomfort (motion sickness), and emotional discomfort. Respondents who achieved scores above the standard accounted for 26 individuals, or 51% of the total respondents. This indicates that the application was well received by a substantial proportion of users, while further improvements are still needed to enhance its overall effectiveness. Based on the

evaluation results, six questionnaire items obtained scores above the VRSUQ standard, while the remaining items were below it. The three negative questions received below-average scores: 3, 8, and 9. Based on observations and interviews, some respondents experienced difficulties completing tasks during application testing. This was mainly due to the respondents' limited experience with VR-based games. Some respondents also felt nervous when interacting with VR devices for the first time. This discomfort was also reflected in the responses to question 9, where most respondents reported experiencing discomfort while using the application. For question 8, some respondents reported experiencing dizziness, motion sickness, or headaches while interacting with the system. This discomfort primarily occurred at the beginning of the game, since the tsunami evacuation game started with an earthquake scenario. This initial condition caused several respondents to feel dizzy at the start of gameplay. Detailed results of the application usability testing are presented in Table 9.

Table 9. VRSUQ Testing Results

Respondents	Questions									VRSUQ Scores
	1	2	3	4	5	6	7	8	9	
1	5	4	4	5	4	4	5	2	1	69.44
2	5	5	4	5	5	5	5	4	4	91.67
3	4	5	3	4	3	4	4	3	3	66.67
4	5	5	2	4	4	4	5	2	2	66.67
5	1	3	2	2	4	3	4	2	2	38.89
6	5	5	0	5	5	5	5	4	3	77.78
7	3	3	2	4	5	5	5	2	3	63.89
8	3	4	4	5	4	5	4	4	4	77.78
9	5	4	1	4	4	4	4	0	4	58.33
10	4	5	3	5	5	5	5	1	4	77.78
11	4	4	4	4	4	4	5	4	4	77.78
12	5	5	0	5	5	5	5	0	0	58.33
13	3	4	3	3	3	2	3	1	4	47.22
14	3	3	2	3	3	3	3	2	2	41.67
15	4	3	3	5	4	5	4	4	4	75.00
16	3	4	4	4	4	4	5	3	2	66.67
17	5	5	4	5	5	5	5	4	4	91.67
18	4	5	3	5	5	5	5	2	4	80.56
19	3	3	1	3	3	4	3	2	2	41.67
20	5	5	3	5	5	4	5	2	4	80.56
21	5	5	4	5	5	5	5	1	4	83.33
22	5	5	2	5	5	4	5	4	4	83.33
23	4	4	3	4	4	4	5	1	3	63.89
24	5	5	4	5	5	5	5	4	3	88.89
25	5	5	3	5	5	5	5	1	3	77.78
26	4	4	2	4	4	4	4	0	2	52.78
27	3	4	2	3	5	4	4	2	2	55.56
28	4	4	2	3	4	4	5	1	3	58.33
29	5	5	4	5	5	5	5	2	4	86.11
30	4	4	3	3	2	1	4	0	2	38.89
31	3	3	0	4	4	3	3	1	2	38.89
32	5	5	1	5	5	5	5	1	2	69.44
33	5	3	0	5	4	5	4	0	1	50.00
34	5	5	0	5	5	5	5	3	1	69.44
35	5	5	3	5	5	5	5	4	4	88.89
36	5	5	4	5	5	5	5	4	4	91.67
37	5	5	4	5	5	5	5	4	4	91.67
38	5	5	4	5	4	5	5	4	4	88.89
39	5	5	1	5	5	5	5	4	4	83.33
40	5	5	0	5	5	5	5	2	4	75.00
41	4	4	3	4	5	5	5	4	4	80.56
42	4	4	0	2	3	3	2	0	2	30.56
43	5	5	0	5	5	3	5	1	2	61.11
44	5	5	3	5	5	4	4	1	3	72.22
45	4	4	4	5	4	5	5	4	4	83.33
46	4	4	3	4	4	4	4	1	1	55.56
47	5	5	4	5	5	5	4	4	4	88.89
48	5	5	3	5	5	5	5	1	4	80.56
49	5	5	4	5	5	5	5	1	1	75.00
50	5	5	0	4	4	4	4	1	1	52.78
51	5	5	3	5	5	5	5	3	4	86.11
Average	4.35	4.43	2.45	4.41	4.41	4.35	4.53	2.20	2.94	69.66
Standard	3.48	3.81	4.06	3.78	3.94	4.28	3.62	3.87	4.4	72.89

The usability evaluation of the VR Metaverse-Based Digital Signage Game for Tsunami Evacuation using the VRSUQ instrument resulted in an average score of 69.66, or 3.715 on a 5-point scale. This result indicates a moderate-to-good level of usability, suggesting that users were generally able to use the system, although several usability issues remain. In VRSUQ, usability is assessed across three main dimensions, namely effectiveness, efficiency, and satisfaction, with negative items specifically capturing issues such as physical discomfort, mental burden, and difficulties during interaction [76, 77].

A more detailed interpretation of the result shows that the lower scores were concentrated in the negative-worded items of the VRSUQ. This pattern suggests that although users perceived the system as generally usable, they still experienced discomfort, confusion, or inefficiency in some parts of the interaction. This interpretation is consistent with prior VR usability studies. In the MUVE PCA study, for example, the average VRSUQ score was 3.52, and the lower ratings were associated with system complexity, inconsistency, and the need for better convenience and clarity of use [78]. The same study also found that some users experienced dizziness and discomfort while using the HMD, indicating that negative items were effective in capturing usability constraints that were not fully reflected in the overall positive score distribution [78].

The result in this study can also be explained by the characteristics of the respondents. Based on the data, the sample was dominated by users aged 18–23 years and, and importantly, more than half had never used VR before. This novice-user context is highly relevant because first-time users typically require an adaptation period to understand immersive navigation, interaction logic, and task flow. In line with this, Radianti et al. [79] highlighted that many VR applications—especially in education and simulation contexts—are still in the early or experimental stage, where usability issues often arise due to interaction complexity and user unfamiliarity with immersive environments. This supports the interpretation that the lower scores on the negative items reflect the respondents' learning curve and adaptation process, rather than a fundamental flaw in the system.

Compared with more mature VR systems, the score of 69.66 can still be considered reasonable. A recent immersive VR training study for industrial assembly reported a much higher average VRSUQ score of 95.12%, but that system was a more focused training application and the study emphasized its high system acceptability after a structured validation process [76]. Likewise, the original VRSUQ development study showed that well-structured VR systems can achieve strong usability performance, and that satisfaction scores often contribute strongly to overall usability, even when some effectiveness and efficiency issues remain [75]. This comparison suggests that the system's lower score is understandable because it is not merely a single-purpose VR application, but a more complex integration of VR, metaverse environment, digital signage, and serious game elements for tsunami evacuation.

This complexity matters because integrated systems place greater demands on users. They must simultaneously understand spatial navigation, interpret signage information, respond to game mechanics, and make decisions in an evacuation scenario. Radianti et al. [79] also emphasized that immersive VR environments can increase cognitive load, particularly when users are required to process multiple types of information and interactions simultaneously. Prior findings from the original VRSUQ study also showed that usability issues often emerge when users face mismatches between expected and actual interactions, unclear feedback, or difficulties in performing navigation and manipulation tasks [75]. Similarly, in the Solar-XR study, usability scores were significantly influenced by the input method, with the touch method rated as more usable than raycast, showing that interaction design and control naturalness can directly affect perceived usability in immersive environments [80].

Therefore, the obtained VRSUQ score should be interpreted as acceptable for a novel and relatively complex VR system tested in a largely novice-user population. The lower scores on the negative items are not contradictory to the overall positive result; instead, they provide more specific diagnostic insight into where users encountered friction. In this case, the findings suggest that the system concept is already feasible and usable, but future improvements are needed in interaction simplification, navigation clarity, user guidance, and onboarding/tutorial support. Thus, the result of 69.66 (3.715) is rational and comparable to prior VR studies, especially those involving novice-user [76, 78].

In summary, the obtained usability score is reasonable and aligned with prior VR studies, particularly those involving early-stage systems and first-time users. The findings confirm that while the system is already usable, further improvements are needed to enhance user experience. This supports the feasibility of the proposed approach while emphasizing the importance of iterative design, usability refinement, and user-centered interaction development for future work.

5. Discussion

The results of testing conducted during the initial stage of system development using a Cognitive Walkthrough approach, as well as usability testing on the final product, indicate that users well recognized the developed digital sign. The digital sign effectively provided clear directional cues, enabling users to complete the game tasks successfully. The Cognitive Walkthrough method proved effective in generating several system improvement recommendations.

The usability test results demonstrated generally positive outcomes, although several indicators related to user comfort still require improvement. This discomfort had already been identified during the preliminary testing phase. The developers implemented several system refinements to mitigate user discomfort. However, respondents' susceptibility

to motion sickness emerged as a determining factor in the game's effectiveness in preventing errors (Question 3 of the VRSUQ) and in user satisfaction regarding physical and emotional discomfort (Questions 8 and 9 of the VRSUQ).

Motion sickness is a physiological discomfort condition that arises from sensory conflict among the visual, vestibular, and proprioceptive systems [81]. In the context of immersive technologies such as VR, sensory conflict frequently arises from discrepancies between visually simulated movement and the lack of corresponding physical motion. Not all individuals exhibit the same level of sensitivity to motion sickness. Factors such as age, prior experience, sensory adaptation, and physiological condition influence an individual's susceptibility [82].

Therefore, to confirm the findings of this study, testing was conducted using the Motion Sickness Susceptibility Questionnaire (MSSQ). Golding developed the MSSQ [83] as a quantitative instrument to measure individual susceptibility to motion sickness. This susceptibility may manifest both in everyday life and during the use of immersive technologies such as VR. Research in VR contexts has shown that MSSQ scores are significantly correlated with cybersickness [84]. Accordingly, the MSSQ helps distinguish whether user discomfort stems from the VR system design or from individual susceptibility.

The MSSQ was designed to address the limitations of momentary subjective measurements by assessing an individual's history of motion sickness experiences across various modes of transportation and movement activities. The instrument comprises two sections: MSSQ-A, which assesses motion sickness experiences during childhood, and MSSQ-B, which assesses motion sickness experiences during adulthood [83]. MSSQ scores were calculated using Golding's correction, which adjusts for transportation modes respondents had never experienced. The raw MSSQ score was obtained by summing MSSQ-A and MSSQ-B scores, and subsequently converted into percentile values using Golding's polynomial function [83].

Based on data from 51 respondents who completed the VRSUQ questionnaire, 37 respondents fully completed both the MSSQ-A and MSSQ-B sections. The calculated MSSQ scores and corresponding Golding percentile values are presented in Table 10.

Table 10. MSSQ Testing Results

No.	Respondents	MSSQ-A	MSSQ-B	MSSQ Scores	Golding's Percentile
1	1	15	18	33	97.1
2	4	18	9	27	90.27
3	5	11.25	9	20.25	77.15
4	6	9	9	18	71.39
5	10	9	9	18	71.39
6	12	9	9	18	71.39
7	14	9	9	18	71.39
8	15	9	9	18	71.39
9	16	9	9	18	71.39
10	18	19.125	16.875	36	99.05
11	19	9	9	18	71.39
12	21	24.75	20.25	45	100
13	22	9	9	18	71.39
14	24	10.8	9	19.8	76.05
15	25	9	9	18	71.39
16	26	9	11.25	20.25	77.15
17	27	24	12	36	99.05
18	28	9	9	18	71.39
19	29	11.25	9	20.25	77.15
20	30	12.6	14.4	27	90.27
21	31	18	18	36	99.05
22	33	13.5	18	31.5	95.78
23	34	9	9	18	71.39
24	35	12.375	14.1429	26.5179	89.3
25	36	12.6	12.6	25.2	86.66
26	37	22.5	23	45.5	100
27	38	9	10	19	73.45
28	39	9	9	18	71.39
29	41	13.5	9	22.5	81.75
30	42	18	21	39	100
31	43	9	9	18	71.39
32	44	12	18	30	93.88
33	45	13.5	11.25	24.75	85.76
34	47	9	10.5	19.5	74.77
35	48	20.25	20.25	40.5	100
36	49	25.5	19.5	45	100
37	50	25.71429	19.5	45.21429	100
Average		13.46525	12.7167	26.1819	88.9998

The MSSQ score reflects motion sickness susceptibility: lower scores indicate greater tolerance to sensory conflict, while higher scores indicate greater susceptibility to motion sickness. Golding [82] states that individuals with high MSSQ scores tend to experience nausea and dizziness more rapidly when exposed to dynamic visual environments, including VR systems and simulators. Furthermore, Golding [82, 83] emphasizes that MSSQ scores converted into percentile values reflect an individual’s relative position in terms of motion sickness susceptibility compared to a normative population. Therefore, interpretation should be based on percentile rankings rather than absolute scores.

Based on the data presented in Table 7, the findings indicate that the majority of respondents fall above the 70th percentile, with an average percentile of 88.9998. This suggests moderate to very high susceptibility to motion sickness. Respondents with percentiles ≥ 90 (e.g., Respondents 1, 18, 27, 31, and others with similar values) are classified as having very high susceptibility, meaning they are more susceptible than 90% of the normative population. Respondents in the 70th–75th percentile (40.5%) fall into the moderate susceptibility category, which remains relatively common in the adult population.

An important observation in this study is the absence of respondents with percentile values ≤ 50 . This indicates that all participants demonstrated at least moderate susceptibility to motion sickness. Figure 13 illustrates the distribution of MSSQ percentiles based on Golding’s approach. It shows that most respondents are positioned above the 75th percentile, with a substantial number exceeding the 90th percentile. These findings further confirm that the sample exhibits moderate to very high susceptibility to motion sickness.

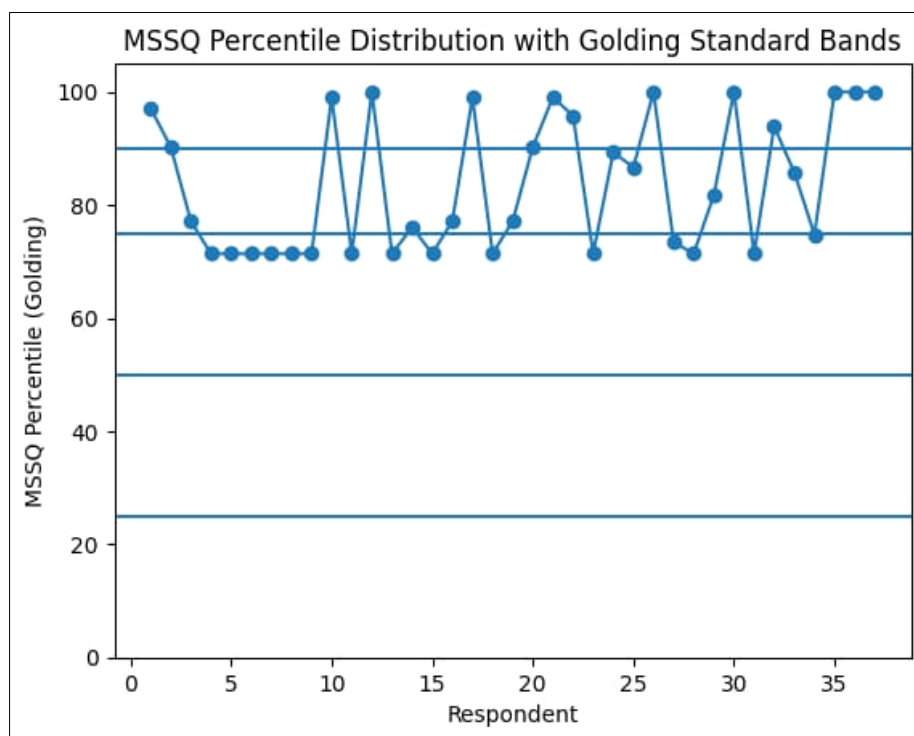


Figure 13. MSSQ Percentile Distribution with Golding’s Standard Bands

The results of the MSSQ assessment provide further clarification of the findings related to physical and emotional discomfort observed in the VRSUQ results that fell below the expected standard. These findings indicate that the reported discomfort was not entirely attributable to the application design but was largely influenced by respondents' individual characteristics and susceptibility levels.

Such discomfort may prompt users to make operational errors while using the application, thereby affecting the system's overall effectiveness (Question 3 of the VRSUQ). This finding strengthens the argument that the initial earthquake simulation in the tsunami educational game can trigger motion sickness, particularly among respondents with high susceptibility levels.

In addition, limited prior experience with VR applications (reported by 70.59% of respondents who had never previously used VR) likely contributed to reduced user comfort. Lack of familiarity with immersive environments may intensify sensory conflict and adaptation challenges, thereby amplifying both physical and emotional discomfort during application use.

6. Conclusion

This study presents the design, implementation, and empirical evaluation of a VR Metaverse-Based Digital Signage Game for Tsunami Evacuation, thereby advancing immersive digital signage and serious games for disaster mitigation. The system was developed using a prototyping approach, enabling iterative refinement through continuous evaluation.

The results show that the proposed digital signage effectively supports decision-making: approximately 90% of respondents can select appropriate evacuation routes, indicating strong adaptive decision-making capabilities. Evaluation using Cognitive Walkthrough during prototyping and refinement successfully identified usability issues early and guided improvements. Furthermore, usability testing with VRSUQ yielded an average score of 69.66 (3.715/5), indicating an acceptable level of usability, particularly among novice users. Lower scores on negatively worded items are mainly associated with interaction complexity and user adaptation to immersive environments. This is supported by MSSQ results, which show that 60% of respondents exhibited high susceptibility, indicating that usability challenges are influenced not only by system design but also by individual characteristics. Despite its strengths, several usability issues remain. Some users experienced motion sickness and emotional discomfort, which affected their interactions and caused operational errors during gameplay.

This research makes the following contributions: (1) introducing a novel integration of digital signage within a VR-based metaverse environment for evacuation training; (2) proposing a prototyping-based development framework; and (3) providing empirical evidence that immersive digital signage enhances user understanding and evacuation decision-making.

Overall, the findings confirm the feasibility and potential of the system. Future work should focus on improving usability by simplifying interaction, enhancing navigation and onboarding, and reducing earthquake simulation effects to minimize motion sickness. Further research may explore adaptive personalization, real-time data integration, multi-user simulations, and large-scale real-world validation to strengthen system effectiveness.

7. Declarations

7.1. Author Contributions

Conceptualization, R.D., I.K.D.S., and M.K.; methodology, R.D. and I.K.D.S.; software, M.K.; validation, I.K.D.S.; formal analysis, R.D. and I.K.D.S.; data curation, R.D. and I.K.D.S.; writing—original draft preparation, R.D., I.K.D.S., and M.K.; writing—review and editing, R.D., I.K.D.S., and M.K. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.5. Institutional Review Board Statement

This study was reviewed and approved by the Health Research Ethics Committee of the Faculty of Medicine, Universitas Kristen Duta Wacana, Yogyakarta, Indonesia. Ethical clearance was granted under approval number 1772/C.16/FK/2025 and is valid for one year from the date of approval (29 July 2025).

7.6. Informed Consent Statement

Not applicable.

7.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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