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Shafaq Irshad

Exploring the Role of UX Influencing Factors in Virtual Reality for Natural Hazards Preparedness

A Design-Based Approach

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of Philosophiae Doctor
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

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Trondheim, April 2024

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This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in the fulfillment of the requirements for the degree of Doctor of Philosophy. The doctoral work started in January 2019 at the Department of Electronic Systems, NTNU, Trondheim, Norway. The work has been supervised by Andrew Perkis and co-supervised by Oddbjørn Bruland and Christian A. Klöckner.

Abstract

Climate change is one of the major challenges of our time, and its complexity makes finding innovative solutions challenging. One of the ways that climate change poses a challenge is by reshaping the earth's natural ecosystem and increasing the frequency and severity of Natural Hazards (NH), such as floods and landslides, that affect millions of people and cause substantial losses. One potential solution is to leverage digital transformation and explore the use of narratives and immersive media technologies, such as virtual reality (VR), to communicate scientific information about NH and enable change. However, traditional methods of communication, such as reports and maps, may not be sufficient or accessible to a broader audience. Therefore, there is a need to develop transformative and immersive experiences that can facilitate the comprehension and communication of scientific information about NH.

This research project created immersive and engaging Virtual Reality Environments (VRE) that communicated NH using digital transformation technology as part of an interdisciplinary project called World of Wild Waters (WoWW). VR offered a unique opportunity to create digital twins of NH by integrating numerical simulations of geophysical phenomena that users could explore and manipulate. However, to create engaging VR, it was crucial to explore the factors that influenced User Experience (UX) within VR.

To address this challenge, the work adopted a design-based research (DBR) approach, which consisted of three iterative cycles, each addressing a specific objective. DBR Cycle 1 explored the factors that could enhance user-perceived quality in Immersive Media Experiences (IME). A conceptual framework was formulated by integrating Interactive Digital Narratives (IDN) as an important dimension to be investigated in VR. Based on the proposed framework, a case study was designed to explore the role of IDN and its impact on UX in VR.

DBR Cycle 2 evaluated the impact of affordances on user-perceived experiences in VR. It developed a VR that integrated wayfinding cues as affordances for NH preparedness. The VR prototype implemented three VREs with several types of wayfinding cues: no cues, static cues, and dynamic cues, and it evaluated the psychological and psychometric effects of wayfinding cues on UX within the VR.

DBR Cycle 3 designed and evaluated a VR framework for visualizing numerical simulations of geophysical flows (i.e., floods) to enhance risk communication of NH in VR. We implemented a VR prototype that used the VR framework to visualize and interact with simulations of NH. Furthermore, DBR cycle 3 evaluated the influence of emotions and identity on UX in VR. The research demonstrated the novelty and originality of using VR to enhance the understanding and communication of NH and foster risk awareness and resilience among diverse audiences and stakeholders.

The results showed how UX influencing factors such as IDN, affordances, emotions, and identity enhanced the VR experience, thus contributing to the advancement of knowledge and practice in the fields of VR, UX, and NH. Moreover, this research provided insights and guidelines for creating effective and engaging VR for communicating complex and uncertain scientific information about NH.

Abstrakt

Klimaendringer er en av vår tids store utfordringer, og kompleksiteten gjør det utfordrende å finne innovative løsninger. En av måtene klimaendringene utgjør en utfordring på er ved å omforme jordens naturlige økosystem og øke hyppigheten og alvorlighetsgraden av Natural Hazards (NH), som flom og jordskred, som påvirker millioner av mennesker og forårsaker betydelige tap. En potensiell løsning er å utnytte digital transformasjon og utforske bruken av fortellinger og oppslukende medieteknologier, som virtuell virkelighet (VR), for å kommunisere vitenskapelig informasjon om NH og muliggjøre endring. Imidlertid er tradisjonelle kommunikasjonsmetoder, som rapporter og kart, kanskje ikke tilstrekkelige eller tilgjengelige for et bredere publikum. Derfor er det behov for å utvikle transformative og oppslukende opplevelser som kan lette forståelsen og formidlingen av vitenskapelig informasjon om NH.

Dette forskningsprosjektet skapte oppslukende og engasjerende Virtual Reality Environments (VRE) som kommuniserte NH ved hjelp av digital transformasjonsteknologi som en del av et tverrfaglig prosjekt kalt World of Wild Waters (WoWW). VR tilbød en unik mulighet til å skape digitale tvillinger av NH ved å integrere numeriske simuleringer av geofysiske fenomener som brukere kunne ut-

forske og manipulere. For å skape engasjerende VR var det imidlertid avgjørende å utforske faktorene som påvirket User Experience (UX) innen VR.

For å møte denne utfordringen, tok arbeidet i bruk en designbasert forskning (DBR) tilnærming, som besto av tre iterative sykluser, som hver adresserer et spesifikt mål. DBR syklus 1 utforsket faktorene som kan forbedre brukeropplevd kvalitet i Immersive Media Experiences (IME). Et konseptuelt rammeverk ble formulert ved å integrere Interactive Digital Narratives (IDN) som en viktig dimensjon som skal undersøkes i VR. Basert på det foreslåtte rammeverket, ble en casestudie designet for å utforske rollen til IDN og dens innvirkning på UX i VR.

DBR syklus 2 evaluerte virkningen av affordances på brukeropplevde opplevelser i VR. Den utviklet en VR som integrerte veisøkende signaler som muligheter for NH-beredskap. VR-prototypen implementerte tre VRE-er med flere typer veifinningssignaler: ingen signaler, statiske signaler og dynamiske signaler, og den evaluerte de psykologiske og psykometriske effektene av veifinningssignaler på UX i VR.

DBR-syklus 3 designet og evaluerte et VR-rammeverk for å visualisere numeriske simuleringer av geofysiske strømmer (dvs. flom) for å forbedre risikokommunikasjon av NH i VR. Vi implementerte en VR-prototype som brukte VR-rammeverket for å visualisere og samhandle med simuleringer av NH. Videre evaluerte DBR syklus 3 påvirkningen av følelser og identitet på UX i VR. Forskningen demonstrerte nyheten og originaliteten ved å bruke VR for å forbedre forståelsen og kommunikasjonen av NH og fremme risikobevissthet og motstandskraft blant ulike målgrupper og interessenter.

Resultatene viste hvordan UX-påvirkningsfaktorer som IDN, råd, følelser og identitet forbedret VR-opplevelsen, og dermed bidro til å fremme kunnskap og praksis innen VR, UX og NH. Dessuten ga denne forskningen innsikt og retningslinjer for å skape effektiv og engasjerende VR for å kommunisere kompleks og usikker vitenskapelig informasjon om NH.

Preface

This thesis is being submitted to the Norwegian University of Science and Technology as part of the requirements for a Doctoral degree. The research work was conducted at the Department of Electronic Systems in the Faculty of Information Technology and Electrical Engineering under the guidance of Professor Andrew Perkis (main supervisor), Professor Oddbjørn Bruland (co-supervisor) from the Department of Civil and Environmental Engineering in the Faculty of Engineering, and Professor Christian A. Klöckner (co-supervisor), from the Department of psychology, Faculty of Social and Educational Sciences.

Acknowledgments

I express my utmost gratitude to my supervisor, Andrew Perkis, for his exceptional guidance, support, and kindness throughout my Ph.D. journey. Andrew's unwavering commitment to my research was truly remarkable, inspiring me to remain focused and motivated. His discipline and punctuality served as an inspiration to me, and his insights were invaluable throughout my research process. Andrew went above and beyond to assist me in conducting experiments. He taught me how to establish connections with international researchers through networking, which played a significant role in shaping my research. I consider myself incredibly fortunate to have had Andrew as my supervisor, and I am deeply grateful for his invaluable contributions to this research. I would also like to thank my co-supervisors, Oddbjørn and Christian, for providing valuable feedback on my research.

I also appreciate the Department of Electronic Systems at NTNU for providing me the opportunity and resources to contribute to NTNU's Digital Transformation project, World of Wild Waters (WoWW). I am incredibly grateful to the entire WoWW team for conducting regular meetings to overcome the challenges in this multidisciplinary project. I thank Gebray for his remarkable hard work in making the VR visualization framework possible. His dedication was crucial for moving this project forward. Additionally, I would like to thank Amanda and the BreachAS team, especially Adam and Gabriel, whose exceptional attention to detail played a significant role in the success of the final VR prototype. I want to acknowledge the outstanding contributions of Michael, Adina, Silius, Nitesh, and the rest of the WoWW team. The collaborative spirit and lively discussions during the early stages of the project were invaluable, and I am deeply grateful for the opportunity to work with such a talented and dedicated team.

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I am very fortunate to have had the opportunity to become a part of the European COST Action INDCOR. The experience has been truly enriching and has expanded my knowledge and understanding of interactive digital narratives. I want to express my deepest gratitude to the inspiring INDCOR community, especially Hartmut Koenitz, Frank Nack, Lissa Holloway, Jonathan Barbara, Mattia Bellin, and many others. Their stimulating discussions and insights during the summer schools in Malta and Las Palmas were insightful and profoundly impacted my research endeavors.

From the bottom of my heart, I thank my family, whose unwavering love and support have been the wind beneath my wings. My husband's support, particularly in relocating to Norway and putting his scientific endeavors on hold so I can follow my dreams, has filled me with immense gratitude. He has been my rock throughout this journey. My children, Abdullah and Maria, have been constant sources of motivation and joy. Their resilience, patience, and optimism have rubbed off on me in profound ways. Finally, to my parents, sister, and extended family, your unwavering encouragement and beaming pride have been a driving force. This achievement wouldn't be possible without each and every one of you.

List of Publications

Paper 1: Asim Hameed, Shafaq Irshad & Andrew Perkis (2019) **Towards a quality framework for immersive media experiences: a holistic approach.** In Cardona-Rivera, R., Sullivan, A., Young, R. (eds) Interactive Storytelling. ICIDS 2019. Lecture Notes in Computer Science(), vol 11869. Springer

Paper 2: Shafaq Irshad & Andrew Perkis (2020). **Increasing user engagement in virtual reality: the role of interactive digital narratives to trigger emotional responses.** In Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society (pp. 1-4).

Paper 3: Shafaq Irshad & Andrew Perkis (2020). **Serious storytelling in virtual reality: The role of digital narrative to trigger mediated presence and behavioral responses.** In Extended Abstracts of the 2020 Annual Symposium on Computer-Human Interaction in Play (pp. 267-271).

Paper 4: Shafaq Irshad, Andrew Perkis & Waleed Azam (2021). **Wayfinding in virtual reality serious game: An exploratory study in the context of user perceived experiences** Applied Sciences, 11(17), 7822.

Paper 5: Shafaq Irshad (2022). **Investigating the user experience of IDN based virtual reality environments for solving complex issues**. New Review of Hypermedia and Multimedia, 28(3-4), 173-195.

Paper 6: Andrew Perkis, Mattia Bellini, Valentina Nisi,.. Shafaq Irshad...& M. Wardaszko (2023). **Interactive Narrative Design for Representing Complexity** arXiv preprint arXiv:2305.01925.

Paper 7: Gebray H. Alene , Shafaq Irshad, Adina Moraru, Ivan Depina, Oddbjørn Bruland, Andrew Perkis & Vikas Thakur **Virtual Reality Visualization of**

Geophysical Flows: A framework (submitted to Environmental Modelling and Software, Elsevier)

Paper 8: Shafaq Irshad, Amanda Elizabeth Lai, Gebray Habtu Alene, Adina Moraru, Adam Krupicka, Gabriel Kapellmann-Zafra, Andrew Perkis, Oddbjørn Bruland, and Christian A. Kløckner, A. **Beyond Presence: Understanding the Role of Identity and Emotions in Virtual Reality for Natural Hazards Preparedness** (submitted to Virtual Reality, Springer)

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Abbreviations

Abbreviations

ACR Absolute Category Rating

ANOVA Analysis of Variance

C1 Condition 1

C2 Condition 2

CC Control Condition

CFD Computational Fluid Dynamics

CRED Center for Research on the Epidemiology of Disasters

DBR Design Based Research

DEM Digital Elevation Models

DOF Degree of Freedom

DV Dependent Variables

EC1 Experimental Condition 1

EC2 Experimental Condition 2

EM-DAT The Emergency Events Database

GEQ Game Experience Questionnaire

GP General presence

HMD Head Mounted Display

HR Heart Rate

HRV Heart Rate Variability

IDN Interactive Digital Narratives

INV Involvement

ITC-SOPI Independent Television Company Sense of Presence Inventory

M Mean

MANOVA Multivariate analysis of variance

NH Natural Hazards

PQ Presence Questionnaire

RAMMS RApid Mass Movement Simulation

REAL Experienced Real- ism

SD Standard Deviation

SG Serious Games

SOPS Standard Operating Procedures

SP Spatial Presence

URP Universal Render Pipeline

UX User Experience

VR Virtual Reality

VRE Virtual Reality Environments

WoWW World of Wild Waters

WP Work Packages

XR Extended Reality

Chapter 1

Introduction

1.1 Introduction and Problem Statement

Natural hazards (NH), such as floods and landslides, pose a significant threat to human society. The negative impacts of these events can be far-reaching, leading to devastating consequences for individuals, livelihoods, and infrastructure. It is crucial to take proactive measures to mitigate the risks posed by these NH and ensure the safety and well-being of communities in affected areas. According to The Emergency Events Database (EM-DAT) maintained by the Centre for Research on the Epidemiology of Disasters (CRED) [3], floods and landslides accounted for more than 46% of the total natural disasters reported worldwide from 2000 to 2022, affecting more than 2.6 billion people. Moreover, the frequency and intensity of these hazards are expected to increase due to climate change, urbanization, and land degradation [4].

To reduce the risk and vulnerability of communities to floods and landslides, it is essential to have a comprehensive understanding of the physical processes, spatial patterns, and temporal dynamics of these NH, as well as their potential impacts and mitigation measures [5]. However, this is a challenging task, as floods and landslides are complex phenomena that involve multiple factors, interactions, and uncertainties. Advanced geophysical models and large-scale datasets are often required to simulate and analyze these hazards, which are not easily accessible or understandable by the local authorities and stakeholders responsible for disaster preparedness. Moreover, the conventional methods of presenting and communicating the simulation results, such as maps, graphs, and reports, may not be effective or engaging enough to convey complex and uncertain information to the target audiences, especially those unfamiliar with the technical terms and concepts [6].

A possible solution would be to develop digital twins of NH [7], which can offer a more immersive and engaging way to comprehend and analyze such phenomena. By creating digital twins, it becomes easier to simulate and visualize various NH scenarios and to communicate and share findings with stakeholders in a more effective and accessible manner [6].

Recognizing the need for such advancements, the interdisciplinary project World of Wild Waters (WoWW)[1] proposed a comprehensive initiative within NTNU's Digital Transformation Program. WoWW focuses on the gamification of NH and aims to bring together knowledge of NH's physical and statistical behavior with digital storytelling and human behavior to create immersive user experiences (UX) based on real data, realistic scenarios, and simulations. The objective of WoWW was to be the future tool for analyzing and communicating the cause and effect of potential NH, such as floods and landslides. WoWW aimed to illustrate cause and consequence and the physical behavior of NH in a realistic, immersive experience to increase its impact among planners and decision-makers. By using VR and storytelling, the project created transformative and engaging experiences that facilitated the comprehension and communication of scientific information about NH.

The WoWW project had five work packages (WP) where WP1 was responsible for simulating realistic extreme weather events by analyzing spatial and temporal dependencies within extreme weather events (rainfall, temperature, wind, etc). WP2 was responsible for creating realistic flood simulations via hydrological modeling and visualizing flash floods in steep rivers. WP3 was responsible for modeling and visualizing run-out flow landslides of quick clay. This research work presents work centered around WP4, which was aimed at creating VR experiences based on the visualized simulations of floods and landslides provided by WP2 and WP3. The aim was to propose a methodology for designing, modeling, and evaluating immersive virtual reality environments (VRE) for NH [8]. WP5 was responsible for measuring the risk perception of these VR experiences.

To fulfill the objective of WP4, our research proposed designing and developing VR to enhance the understanding and communication of geophysical simulations of floods. We combined VR and flow simulations to create immersive and interactive experiences that can facilitate the comprehension and retention of complex NH data. By investigating the factors influencing the UX of VR, this research aimed to transform the geophysical simulation and data of floods and landslides into engaging and intuitive VRE that can illustrate the causes, consequences, and solutions of these hazards in a realistic manner. The intersection of VR, UX, and NH

[1] https://www.ntnu.edu/digital-transformation/woww

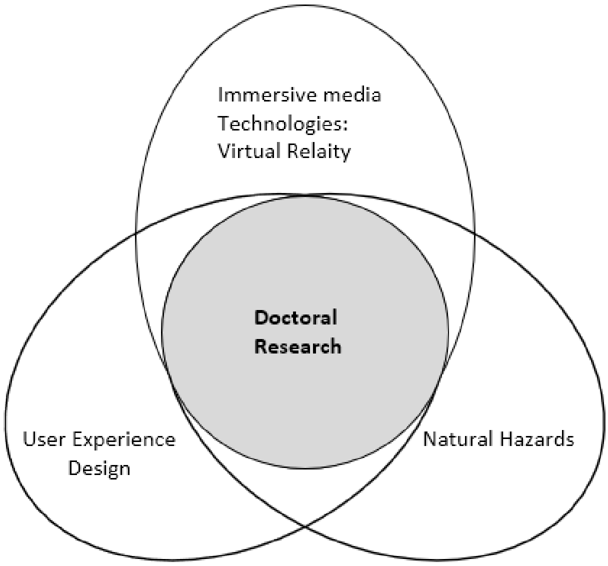

Figure 1.1: The figure illustrates the foundational concepts of this research work by visualizing the intersection of Virtual Reality (VR), User Experience (UX), and Natural Hazards (NH)

framed the scope of this research work. Figure 1.1 illustrates the convergence of these three distinct yet interconnected research domains. The overlapping circles represent the synergy and intersection among these areas, highlighting the shared elements and collaborative aspects crucial in shaping immersive experiences in VR. The intersection signifies the intricate relationship and mutual influence of UX principles, the immersive qualities of VR, and NH, emphasizing their combined impact on shaping user engagement and narrative experiences.

1.2 Goal and Research Questions

This research aimed to create effective and engaging VR for communicating scientific information about NH to a wider audience. To achieve this, we developed digital twins of NH by creating a framework that integrates numerical simulation results of floods in VR. To further enhance the UX, various quality influencing factors were incorporated into VR, and a VR prototype was designed so users could explore and engage with the NH. VR provided a structured approach for users to explore the digital representation of NH and better comprehend the scientific information presented. We formulated the following Research Questions

(RQ) to address the objectives:

- RQ1: what factors can enhance user-perceived quality in Immersive Media Experiences (IME)? (paper1)
- RQ2: What is the impact of IDNs on user experience within Virtual Reality?
  - RQ2a: What is the impact of IDNs on user engagement in VR (Paper 2)
  - RQ2b: What is the impact of IDNs on presence in VR (Paper 3)
- RQ3: What is the impact of affordances on user experience in VR? (Paper 4)
- RQ4: How does incorporating IDNs in VR contribute to addressing complex societal challenges? (Paper 5 and Paper 6)
- RQ5: How can we design and evaluate a VR framework for visualizing numerical simulations of geophysical flows to enhance risk communication among diverse audiences?
  - RQ5a: How can we design a VR framework for visualizing numerical simulations of geophysical flows? (Paper 7)
  - RQ5b: How do emotions and identity impact the user experience in VR? (Paper 8)

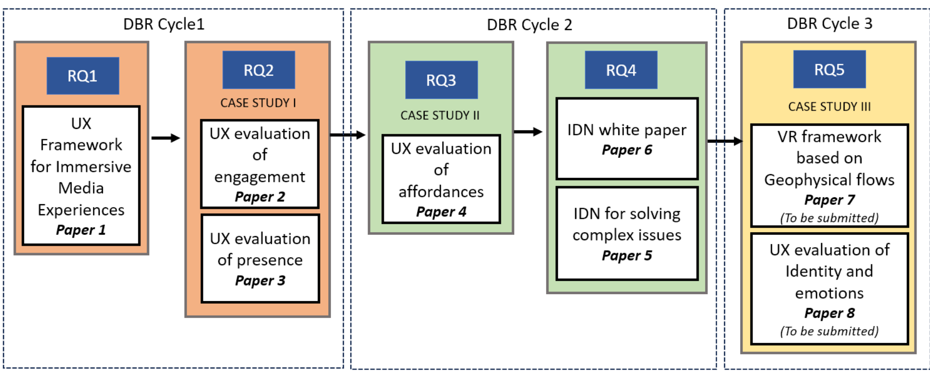

Figure 1.2: The figure illustrates the schematic representation of the research flow. It showcases the research questions (RQ1 to RQ5) and DBR cycles with the corresponding research papers.

1.3 Research Approach

The research work presented in this thesis adopted the Design-Based Research (DBR) approach [9], which is characterized by iterative and flexible monitoring of analysis, design, development, and implementation. An essential first step in DBR is to develop a clear, holistic understanding and univocal definition of the challenge being addressed. In this case, the challenge was to design, implement, and evaluate VR for NH preparedness.

The methodology involved three iterative cycles (DBR Cycle 1, DBR Cycle 2, and DBR Cycle 3), each consisting of four phases: analysis and exploration, design and development, evaluation and results, and reflection and refinement. The detailed methodology is presented in Chapter 3. The three DBR cycles and their respective phases are illustrated in Figure1.3.

Beginning with the design of a conceptual framework for evaluating VR, the study seamlessly transitioned into a series of case studies, each building upon the insights gained from the previous iteration. The design-based approach facilitated an agile and adaptive methodology, allowing for the exploration and assessment of factors contributing to UX, i.e., digital narratives, affordances, emotions, and identity in VR. As an important part of the analysis and exploration phase, we started each

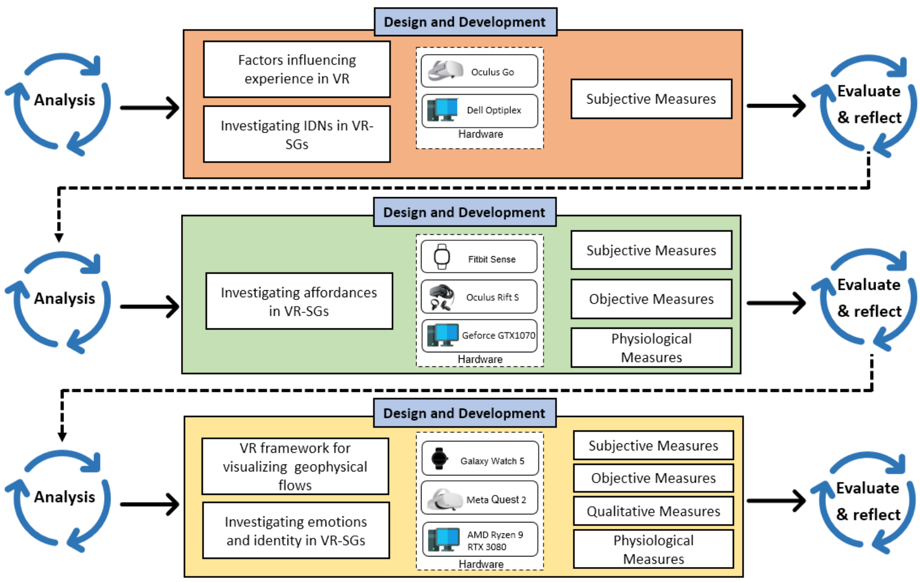

Figure 1.3: The figure illustrates the three cycles of DBR, showing the case studies, equipment, and evaluation measurements used in each cycle.

DBR cycle by reviewing the related work and theory and consulting the research objectives. During the design and development phase, we sought guidance from industry experts and researchers from other WPs to ensure that our interventions were relevant and applicable in real-world scenarios. During the evaluation and results phase, we used various data collection instruments to conduct quantitative, qualitative, and mixed methods research and gain insights into the role of factors influencing UX in VR for NH preparedness from different perspectives. During the reflection and refinement phase, we analyzed the data, identified the strengths and weaknesses of our design, and made suggestions for improvement.

This iterative cycle, grounded in the principles of design-based research, ensured the continual refinement of the VR, ultimately contributing to the advancement of knowledge in the field of natural hazard preparedness and immersive media technologies. This DBR approach enabled us to generate knowledge that enhances the design, implementation, and evaluation of VR user experiences and increases its impact on the adoption and use of VR for NH preparedness.

1.4 Research Contributions and Papers

This research work encompasses eight research papers published in international conference proceedings and peer-reviewed journals. The main contributions (C) are:

- **C1: Conceptual Framework** Development of a robust and comprehensive conceptual framework for evaluating immersive media experiences. This framework serves as a foundational guide for understanding the factors that influence the UX of VR.

- **C2: Evaluation Methods in VR** Advancement of innovative and effective evaluation methods specific to VR. The research introduces and refines evaluation techniques tailored for VR, providing insights into UX influencing factors for enhancing VR experiences.

- **C3: Design Methods in VR** The research work explores and refines design methodologies pertinent to VR, offering valuable insights into creating realistic VR experiences by integrating geophysical flow simulations and IDNs in VR.

- **C4: IDNs for Representing Complexity** Integrating IDNs in VR to understand the role narrative plays on the psychological indicators of human experience for complex representations of NH.

- **C5: Framework for Visualization of Geophysical flows in VR** Development and validation of a design approach for seamlessly integrating and visualizing complex numerical simulations in VR, particularly focused on weather events like floods. The work establishes a framework for importing, visualizing, and interacting with geophysical flows in VR, contributing to the domain of NH.

The following publications were produced as part of the research work:

- **Paper1:** Asim Hameed, Shafaq Irshad, and Andrew Perkis *Towards a Quality Framework for Immersive Media Experiences: A Holistic Approach* 12th International Conference on Interactive Digital Storytelling (ICIDS), LNCS 2019
- **Paper 2:** Shafaq Irshad and Andrew Perkis. *Increasing user engagement in virtual reality: the role of interactive digital narratives to trigger emotional responses.* In Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society, pp. 1-4. 2020.
- **Paper 3:** Shafaq Irshad, and Andrew Perkis *Serious storytelling in virtual reality: The role of digital narrative to trigger mediated presence and behavioral responses.* In Extended Abstracts of the 2020 Annual Symposium on Computer-Human Interaction in Play, pp. 267-271. 2020.
- **Paper 4:** Shafaq Irshad, Andrew Perkis, and Waleed Azam. *Wayfinding in virtual reality serious game: An exploratory study in the context of user perceived experiences*. Applied Sciences 11, no. 17 (2021): 7822.
- **Paper 5:** Shafaq Irshad. *Investigating the user experience of IDN based virtual reality environments for solving complex issues.* New Review of Hypermedia and Multimedia, 28(3-4), 173-195, 2022.
- **Paper 6:** Andrew Perkis, Mattia Bellini, Valentina Nisi, Shafaq Irshad ... & M. Wardaszko (2023). *Interactive Narrative Design for Representing Complexity*. arXiv preprint arXiv:2305.01925.
- **Paper 7:** Gebray H. Alene , Shafaq Irshad, Adina Moraru, Ivan Depina, Oddbjørn Bruland, Andrew Perkis and Vikas Thakur *Virtual Reality Visualization of Geophysical Flows: A framework* submitted to Environmental Modelling and Software , SicenceDirect
- **Paper 8:** Shafaq Irshad, Amanda Elizabeth Lai, Gebray Habtu Alene, Adina Moraru, Adam Krupicka, Gabriel Kapellmann-Zafra, Andrew Perkis, Oddbjørn Bruland, and Christian A. Klöckner *Beyond Presence: Understanding*

the Role of Identity and Emotions in Virtual Reality for Natural Hazards Preparedness submitted to VIRTUAL REALITY Springer Journal.

1.5 Structure of the Thesis

The thesis is structured as follows: Part 1 presents an introduction, related work, employed methodology, results, discussion, and contributions of this thesis. Chapter 2 offers an in-depth overview of the existing literature and theoretical foundations relevant to the research work. Chapter 3 presents the employed research methodology, covering the design, development, and processes implemented in the three DBR cycles constituting this research work. Chapter 4 presents detailed findings derived from the outcomes of the three DBR cycles. Chapter 5 discusses the contributions, implications, and limitations of the research. Chapter 6 summarizes the key findings and insights, concluding with remarks and proposing potential avenues for future research in this domain. Part 2 presents the collection of eight research publications in full length.

Chapter 2

Related Work

2.1 Immersive Media Technologies

Extended Reality (XR) technologies such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) emulate the real world through digital or simulated content, resulting in immersive experiences [10, 11]. Immersive media systems provide different levels of immersion (via AR, VR, and MR technologies [1]), as shown in Figure 2.1. For example, AR superimposes digital content in the real environment, and the users are not fully immersed in the augmented environment but are aware of their surroundings [12]. In MR, the physical and virtual objects coexist and can interact in real-time [13, 14]. However, VR provides a fully immersive experience to the end-user where they are surrounded by a computer-generated simulated world [15].

2.2 Virtual Reality

2.2.1 Definition and Theoretical Concepts

The term "virtual reality" was coined by Jaron Lanier, the founder of VPL Corporation, in 1986 [16]. However, the idea of creating artificial environments that can be experienced by humans dates back to ancient times, when storytellers, artists, and architects used various techniques and media to evoke the senses and imagination of their audiences. One of the pioneers of VR, Ivan Sutherland, defined VR as a display connected to a computer that allows users to manipulate and interact with virtual objects that do not have to obey the laws of physics [17]. This definition implies that VR is not only a visual representation but also a dynamic and interactive system that responds to the user's actions and inputs. There is no

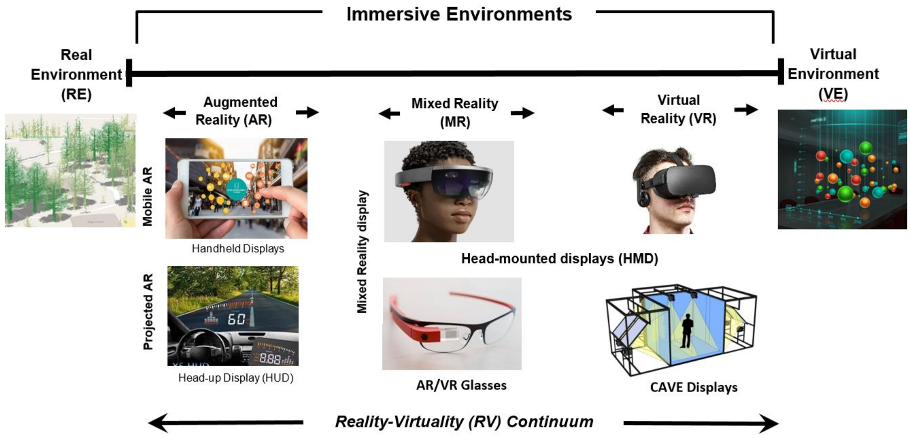

Figure 2.1: Milgram's VR Continuum [1] modified to adapt existing immersive environments [2]

consensus on a single definition of VR, as different authors emphasize different aspects of the phenomenon. For example, Slater (2009) defined VR as "a system that generates an interactive, three-dimensional, computer-generated environment that can be explored by a person through the use of a human-machine interface [18]". In our research, we have adopted Steuer's definition of VR i.e., "a real or simulated environment in which a perceiver experiences telepresence [19] ".

Telepresence is the extent to which a user feels present in a mediated environment rather than the immediate physical environment. Telepresence is defined as an experience of presence in an environment by means of a communication medium [20]. When perception is mediated by communication technology, users perceive two environments at the same time: the environment presented by the medium, telepresence (as explained earlier), and the physical environment in which one is actually present. Telepresence refers to the mediated perception, and presence refers to the natural perception of the environment [18].

Presence is the sense of being in an environment, regardless of whether it is real or simulated [20]. It is a key factor for the success of VR applications, as it affects the user's satisfaction, enjoyment, and involvement [21]. Presence is a subjective and complex phenomenon that involves cognitive, emotional, and perceptual aspects of the user's experience [22, 23]. It is influenced by both the characteristics of the VR system, such as immersion, interactivity, and realism, and the user's personal traits and expectations [24, 25]. It's worth noting that presence and immersion are two distinct concepts, often used interchangeably. Presence refers to the feeling of being in a virtual environment, while immersion refers to the extent to which someone is absorbed in that environment[26]. Immersion is the objective degree to which a VR system can create a realistic and convincing simulation of a natural or artificial world [27]. Immersion depends on the technological capabilities of the VR system, such as the quality of the graphics, sound, and interaction [26, 28]. Immersion is a necessary but not sufficient condition for presence, as presence also requires the user's psychological involvement and acceptance of the virtual environment [29].

VR has the ability to generate immersive and realistic experiences that transcend the boundaries of our physical world. Although it may not be a new concept, it is the result of decades of research and development in different areas [30]. In the next section, we will provide a brief historical overview of how VR has evolved over the years.

2.2.2 Historical background

The history of immersive media technologies can be traced back to the 19th century when stereoscopic devices were invented to create the illusion of depth and immersion [31]. The first head-mounted display (HMD) was patented by Morton Heilig in 1960, who also created the Sensorama, a machine that stimulated multiple senses with 3D video, audio, vibration, smell, and wind [32].

Ivan Sutherland introduced the Sword of Damocles in 1968, which was the first VR realized in hardware, not just in concept. He constructed a device that is considered the first HMD with appropriate head tracking. The device supported a stereo view that was updated accurately based on the user's head position and orientation [30].

In the 1970s and 1980s, VR research and development advanced in the fields of flight simulation, military training, and entertainment [33]. In 1985, Jaron Lanier founded VPL Research, the first company to sell VR products, such as the EyePhone and the DataGlove2 [16].

VR became more accessible and affordable to the general public during the 1990s, with the introduction of consumer products such as the Sega VR, the Nintendo Virtual Boy, and the Sony Glasstron2 [34]. However, VR also faced numerous technical and social challenges in terms of low quality, high cost, health concerns, and ethical issues.

In the 2000s and 2010s, VR experienced a resurgence with the emergence of new technologies, platforms, and applications such as the Oculus Rift, the HTC Vive, the PlayStation VR, and the Samsung Gear VR2. VR also expanded its scope and impact to various domains and industries, including education, healthcare, tourism, gaming, art, and social media platforms [35]. The following section will highlight some of the applications of VR and its use in NH preparedness.

2.2.3 Applications of VR

VR can create realistic and engaging simulations that can enhance learning, training, entertainment, and communication [36, 37] in different fields. VR can also enable users to explore and interact with environments and scenarios that are otherwise inaccessible, dangerous, or costly [38]. VR offers a narrative-rich and cost-effective tool to study and replicate interactions in a controlled environment [39]. VR media creates lifelike environments and simulates complex real-life situations [40], which have significant implications for various domains such as gaming, entertainment [41], education [42], healthcare [43, 44], and NH preparedness [45].

Virtual Reality for NH Preparedness

VR is a powerful technology that can create immersive and interactive learning environments for NH preparedness. VR can be used to design serious games (SG) that aim to educate, train, and motivate various stakeholders, such as professionals, volunteers, and the public, on how to prevent, prepare for, and respond to NH. VR can provide realistic and engaging scenarios that simulate the hazards, risks, and consequences of NH and allow users to practice their skills, learn from feedback, and improve their decision-making and coordination in complex and stressful situations. VR can also foster awareness and behavior change among users by exposing them to the causes and impacts of NH and by providing them with information and guidance on how to protect themselves and others and how to access resources and services in case of emergencies.

Several studies have demonstrated the effectiveness and potential of VR for NH preparedness. For example, Grassini et al. [46] reviewed the literature on the use of VR for procedural training and found empirical evidence that VR can enhance the transfer of skills to real-world scenarios. Breuer et al. [47] explored the impact of game-based learning for flood risk management and reported that VR can support lifelong learning and motivation in users. Sermet et al. [48] proposed a VR framework for disaster awareness and emergency response training, which presented a realistic VR gaming environment to increase public awareness train and evaluate respondents in emergencies using simulated real-time flooding scenarios. Their study showed that participants who experienced a VR simulation of flooding showed increased motivation to evacuate, seek information, and buy flood insurance compared to other NH preparedness methods. Damico et al. [49] developed a VR system that integrated narrative and training objectives to increase knowledge acquisition and self-efficacy in users. Their results showed an increase in the efficacy and safety knowledge of users and suggested that VR can be exploited to increase awareness and NH preparedness in users.

2.3 User Experience Evaluation of VR

User experience (UX) design is the process of creating products or services that provide meaningful and satisfying experiences to the users [50, 51]. UX design encompasses usability, functionality, aesthetics, and emotions [52]. In VR, UX design faces new challenges and opportunities, as VR is an immersive and interactive medium that creates a sense of presence and agency for the users [53]. VR UX design requires a user-centered and iterative approach like other digital platforms [54]. However, VR also introduces some unique features and considerations that need to be addressed by the designers.

For instance, VR allows users to explore and interact with 3D environments, which requires careful attention to the spatial layout, scale, perspective, and lighting of the virtual scenes. Spatial design also involves creating affordances and cues that guide the users' attention and actions, such as physical interfaces, signs, sounds, and haptics [55].

VR can cause discomfort and sickness for some users due to factors such as motion sickness, eye strain, fatigue, and disorientation [56]. To prevent or minimize these issues, VR UX design should follow some guidelines, such as giving users control of their movements, limiting elements that may cause sickness, helping users feel safe, and providing clear feedback and instructions [57, 58]. Another system quality, immersion can be enhanced by creating realistic and consistent environments, building for different types of users and mental models, and designing intuitive and seamless interactions and navigation. similarly, engagement can be influenced by factors such as the content, the narrative, the challenge, and the social aspects of the VR experience.

Evaluating the UX of VR is challenging, as it involves measuring both the objective and subjective aspects of the user's interaction with the VR system [15, 26]. One of the most important outcomes of VR UX is presence, as it can enhance the user's engagement, enjoyment, and learning in the virtual world [29]. Therefore, measuring presence is a crucial part of VR UX evaluation, as it can provide insights into the user's perception and acceptance of the virtual environment [24, 25]. There are different methods and tools for measuring the presence, such as questionnaires, physiological measures, behavioral measures, and performance measures [59, 60]. Each method has its own advantages and limitations, and the choice of the most appropriate one depends on the goals and context of the VR application [59, 60]. Some of the factors that affect the measurement of presence are the realism, interactivity, and social aspects of the VR system, as well as the user's personality, expectations, and motivations [24, 25]. In the following sections, we will review some of the design factors that can contribute to providing a positive UX in VR. By considering and optimizing these factors, developers can create a VR application that provides an exceptional UX.

2.3.1 Interactive Digital Narratives

Interactive Digital Narratives (IDNs) can represent, experience, and comprehend complex issues of everyday life. IDNs are defined as "expressive narrative forms implemented as a computational system and experienced through a participatory process" [61, 62], which can be realized in many ways, including gaming, interactive films, and immersive media technologies [63] (For more information on IDNs, refer to paper 6).

IDN is a form of storytelling that allows users to influence the course and outcome of a narrative through their choices and actions [62]. IDNs in VR leverage the immersive and interactive capabilities of VR technology to create engaging and realistic narrative experiences. IDNs can significantly enhance the UX of VR in various domains, such as education, entertainment, journalism, art, and social media [64].

Narratives and interactive storytelling elements enhance user engagement, emotional responses, and overall experiences within VR in several ways. First, narratives provide a coherent and meaningful structure to the VR experience, guiding the user through a series of events and situations that elicit curiosity, suspense, and satisfaction. Second, interactive storytelling elements empower the user with agency and autonomy, allowing them to explore, manipulate, and influence the VR according to their preferences and goals. Third, narratives and interactive storytelling elements create a sense of presence and immersion, making the user feel as if they are part of the VR world and its story.

IDNs influence user perceptions and interactions in a virtual setting by shaping their cognitive, affective, and behavioral responses [65]. According to the Narrative transportation theory, storytelling can transport the user into a narrative world, where they become absorbed and emotionally involved in the story [66]. This can affect their attitudes, beliefs, and behaviors in relation to the story and its characters, as well as their real-world counterparts [67]. IDNs can create a sense of presence, or the feeling of being in the VRE, by providing spatial, temporal, and social cues that match the user's expectations and actions. This can enhance the user's sense of realism, involvement, and enjoyment in the VR experience. Furthermore, IDNs can enable the users to exercise agency, or the ability to influence the VRE and its story, by providing interactive and responsive elements that acknowledge and reward the user's choices and actions. This can increase the user's sense of control, satisfaction, and empowerment in the VR experience [68].

2.3.2 Affordances in VR

In VR, users perceive the virtual environment in terms of their ability to interact or perform actions. This perceived possibility of performing actions in an environment is called affordance [69]. These affordances can include anything from the ability to pick up and manipulate virtual objects to the ability to move around and explore the virtual space. The design of VR can greatly impact the affordances that are available to users and can have a significant impact on the overall user-perceived experiences [70, 71].

One important aspect of affordances in VR is the ability to interact with virtual objects [72]. In many cases, VR allows users to interact with virtual objects in ways that are not possible in the real world. This can include the ability to manipulate objects in three dimensions or the ability to interact with objects that are otherwise too dangerous or inaccessible in the real world. The design of virtual objects can greatly impact their affordances and significantly impact how users interact with them.

Another important aspect of affordances in VR is the ability to move around and explore the virtual space. VRE can provide users with a wide range of movement options, from free movement to teleportation. The design of the virtual environment can greatly impact these movement options and can have a significant impact on how users navigate and explore the virtual space [73]. VR can implement spatial cues to help users determine the function of objects inside a VRE. These cues should inform the user of their usage and function [74]. The affordances of movement in VR can greatly impact the overall UX. They can be a key factor in determining the success of a VR experience.

Regia et al. [75] evaluated the perception of affordances in VRE. They conducted a study to investigate how the users perceive certain actions in VR as compared to the real environment. Results revealed that users perceive the affordances of everyday actions in VRE as they perceive them in real life, and environmental and user factors influence these perceptions. The study concluded that affordances in VR should be studied further to understand the effects of design on VRE users.

A study was conducted by shin et. al [72] to understand the effects of spatial affordance on narrative experience in an AR game. They compared the factors of narrative experience in an immersive environment for six spatial conditions. They provide guidelines for designing immersive spaces where higher presence and narrative engagement can be achieved. The above-mentioned studies show that VR is a suitable medium to represent complex issues, and integrating narrative in VR can aid in solving complex problems such as natural hazard mitigation.

Overall, the affordances of VR are an important consideration for designers and developers of VR. By carefully considering the affordances that are available to users, designers can create VR that is engaging, intuitive, and easy to use. Additionally, by providing users with a wide range of affordances, designers can ensure that VR experiences are both immersive and informative and can provide users with a deep understanding of the virtual world in which they are immersed.

2.3.3 Identity in VR

One of the factors that can affect UX is the user's identity, which is a cognitive process that becomes an integral component of VR experiences [76]. Identity is considered a subjective understanding of one's characteristics and relationships within the world. Both internal factors, such as personality traits and self-esteem, and external elements, like social roles and norms, shape identity. Many researchers explore how identity priming informs presence [77], focusing mainly on self-referential processing as a significant contributor to spatial presence. Identity priming is a phenomenon in which exposure to a stimulus activates or enhances a particular aspect of one's identity, such as a role, trait, or group membership, and influences one's subsequent cognition, emotion, or behavior [78, 79]. Identity priming can be used to manipulate the cognitive process of identity in VR, as users can adopt different identities or perspectives in the VRE that are congruent or incongruent with their real identities [80].

Identity Priming can affect presence, the subjective sense of being in the VR, and other psychological outcomes [81, 82]. The correlation between the processing of self-related information and enhanced presence in VR is becoming increasingly evident [83]. However, there remains a noteworthy gap in fully understanding the mechanisms involved and the extent of such impact. Advancements in VR technologies continue, leading to immersive and interactive environments, potentially impacting the user's cognitive experience of identity and, therefore, presence [84]. Owing to the substantial cognitive and emotional responses elicited by users within VR, understanding the connection between VR, presence, cognitive feelings, and identity becomes increasingly critical for optimizing user interactions and engagement in various domains. Therefore, comprehensive research and investigation are essential to improving practice and theory in this area [85].

Takac et al. [86], developed a cognitive model for emotional regulation in VR exposure therapy. They suggested that presence arises from constructing a spatial-functional mental model of the VR, which involves two cognitive processes: the representation of bodily actions as possible actions in the VR and the suppression of incompatible sensory input. They used visual cues (such as images) to prime users with different emotional states (such as calm or anxious) before entering a VR and measured their presence using physiological sensors.

Several studies have explored the effects of identity priming in VR using different methods and measures. For example, Weber et al. [87] proposed a two-dimensional construct of presence that consists of being there and perceived realism. They argued that the cognitive feeling of identity influences perceived realism, as users compare their virtual identities to their real identities and judge the level of congruence. They used verbal cues (such as sentences) to prime users with different identities (such as a student or a teacher) before entering a VR classroom and measured their presence using questionnaires.

In a recent study investigating the feeling of presence, researchers explored the impact of priming [77] in VR. Participants were asked to read an article about either a university (a familiar place) or household chores (a neutral topic) before engaging in a virtual classroom discussion. The results showed that those primed with university-related content reported a stronger sense of presence, particularly in their reality judgment. These findings highlight how contextual priming can enhance presence by activating familiarity.

A study by Jicol et al. [88] investigates the effect of imaginative suggestibility, a trait causing people to experience imagination as real, on presence in VR. Through an experiment involving 128 participants within an educational VR experience, it was found that participants with high imaginative suggestibility experienced stronger presence and positive emotions. However, the tested priming cues did not significantly influence VR presence. The priming cues presented during the VR experience consisted of auditory cues (such as sounds or music). The effect of these cues on presence and emotion was measured using questionnaires and behavioral indicators.

Identity priming is an important topic for both theoretical and practical reasons. It can help us understand how we construct our sense of self and relate to others and the world [89]. It can also help us design better VR technologies to enhance our well-being, learning, creativity, and social interaction. However, there are still many challenges and open questions for future research, such as how to measure and manipulate the cognitive feeling of identity in different contexts, how to balance the benefits and risks of using different identities in VR, and how to foster a positive and authentic sense of identity in a diverse and complex society to enhance the overall UX in VR.

2.3.4 Emotions in VR

Another factor that can affect UX is the user's emotion, which is the affective state that arises from their appraisal of a situation [90]. Emotions play an essential role in human experience, affecting cognitive processes, behavior, and well-being [91]. Emotion is a complex psychological phenomenon involving cognitive appraisal, physiological arousal, expressive behavior, and subjective experience[92]. Emotion and presence in VR have a bidirectional relationship that can enhance or impair the VR experience [93].

Emotion can be influenced by the content and context of the VR, such as the level of challenge, feedback, novelty, or threat [92]. Emotion can also be influenced by the user's physiological and behavioral responses in VR, such as their heart rate, facial expression, or gesture. Previous studies have shown that emotions can affect the user's presence by influencing their attention, memory, and motivation in VR [29].

Different methods and paradigms have been used to investigate the effects of emotions in VR [21, 85, 94–96]. Some studies have induced specific emotions, such as fear or joy, in VR and measured their impact on presence [97]. Researchers explored the influence of presence on players' physiological and emotional responses during gameplay in a VR study [98]. Two experiments were conducted where participants played survival horror games and first-person shooters. The results showed that playing games in VR resulted in a heightened sense of presence, lower heart rate variability, and increased subjective fear. The feeling of presence acted as a mediator for the effects of VR on fear responses. However, the impact of playing first-person shooters in VR on hostility was mixed, and overall enjoyment remained similar between VR and TV gaming. Notably, regardless of the game type or display medium, post-play hostility increased. This study demonstrates that commercial VR games can affect players' feelings of presence and their physiological and emotional states.

Studies have also used VR to manipulate the emotional state of the immersive environment [99]. Emotional state refers to the degree to which the VR is perceived as positive or negative. One such study by Hawes et al. [100] used a VR-based priming approach to address anxiety in post-secondary students while enhancing their cognitive bandwidth. The proposed method involved using VR for priming and incorporating games and meditative interventions. The research demonstrated the potential of this VR-based priming approach in reducing anxiety when compared to scenarios with no priming.

Another line of research focused on the bidirectional relationship between emotions and presence in VR. This research suggests that emotions can affect and be affected by presence. For example, Jicol et al. [101] proposed a predictive model for understanding the role of emotions in the formation of presence in VR based on the interoceptive predictive coding theory. They argued that presence is a product of the match between predictions of interoceptive emotional states and the actual states evoked by an experience. They tested their model with two experiments involving high-arousal and low-arousal emotions. They found that user expectations about emotional states in VR impacted presence, moderated by the intensity of an emotion and personality traits.

The studies suggest that emotions play a massive role in creating a sense of presence in VR [102]. They also indicate that VR has the potential to evoke strong emotional responses that can have long-lasting effects on users [90, 92]. However, previous studies have focused on specific emotions or states and used inconsistent definitions and measures of presence, emotion, and VR quality. This limits the comparability and generalizability of their results. Therefore, there is a need for further research on emotion in VR [103, 104] and how they influence the overall UX of VR experiences.

Next, we will briefly present some concepts essential for understanding the VR visualization framework.

2.4 Geophysical flows

2.4.1 Basic concepts in Geophysical flows

Geophysical flows are fluid motions that occur in the Earth and other planets, such as oceans, atmospheres, lava, glaciers, etc. They are influenced by physical factors such as rotation, stratification, buoyancy, gravity, and topography [105]. Geophysical flows are important for understanding the evolution of the Earth's surface, the climate system, the natural hazards, and the distribution of resources [106].

Geophysical flows, including floods, landslides, debris flows, tsunamis, and more, are large-scale natural events that shape landscapes and profoundly impact both human and natural environments. Geophysical flows can be effectively analyzed and predicted through the application of analytical, empirical [107, 108], and numerical methods [109]. Numerical simulation of geophysical flows involves CFD, which uses mathematical models and methods to predict the dynamics of flowing materials [106].

There are different methods to study geophysical flows, depending on the complexity and scale of the problem, the availability of data, and the desired accuracy and efficiency of the solution [110]. Analytical methods are mathematical techniques that provide exact or approximate solutions to geophysical flow problems, often using simplifying assumptions or idealizations [111]. Empirical methods are data-driven approaches that use observations or experiments to derive empirical laws or relationships for geophysical flow phenomena, often using statistical or regression analysis. Numerical methods are computational algorithms that solve geophysical flow problems by discretizing the governing equations and the domain into finite elements or volumes and then iterating to obtain numerical solutions. The VR visualization framework for geophysical flow (Paper 7) uses numerical methods.

One of the most widely used numerical methods for geophysical flows is computational fluid dynamics (CFD) [112], which is a branch of fluid mechanics that uses numerical methods and software tools to analyze and simulate fluid flows, including geophysical flows. CFD involves the development and application of mathematical models and methods to predict the dynamics of flowing materials, such as velocity, pressure, temperature, density, viscosity, turbulence, etc. CFD can handle complex geometries, boundary conditions, and physical processes that are difficult or impossible to model analytically or empirically. CFD can also provide detailed information on the flow field that is not easily accessible by measurements or observations.

CFD has been applied to a wide range of geophysical flow problems, such as floods, landslides, debris flows, tsunamis, and more. For example, CFD can be used to simulate the propagation and inundation of flood waves, the initiation and movement of landslides, the rheology and erosion of debris flows, the generation and impact of tsunamis, and so on. CFD can also be used to assess the effects of different factors, such as topography, vegetation, structures, climate change, etc., on the behavior and consequences of geophysical flows. CFD can thus help to improve the understanding, prediction, and mitigation of geophysical flow hazards [106].

2.4.2 Visualization of Geophysical flows

Geophysical flow numerical simulations produce large volumes of data organized in tables or arrays, comprising numerous numerical values representing various variables. On the other hand, human beings possess an inherent inclination towards processing information visually due to our nature as visual beings [113]. Consequently, employing appropriate visualization techniques becomes essential to effectively comprehend and interpret numerical data. Visualizing numerical simulations of geophysical flows helps to understand the spatial and temporal evolution of the flows, the distribution of the physical variables, and the impact on the surrounding environment. Visualization can also help validate the numerical results with experimental or field data and communicate the findings to stakeholders and decision-makers. In many numerical models, there are two common approaches for visualizing simulation results: utilizing third-party visualization tools (e.g., [114, 115]) or employing a built-in graphical interface within the model itself (e.g., [116, 117] Most of such visualizations might incorporate elements like colored and shaded velocity vectors, contour plots, or even three-dimensional shaded volumes, and speak powerfully to a technical audience. However, achieving a realistic representation of the simulation results within their intended surroundings makes simulation results more inclusive and accessible to non-expert audiences.

2.4.3 Geophysical Flows in VR

In the context of geophysical flows, VR requires incorporating numerical simulation results of the flow dynamics. Some researchers have used VR to raise public awareness of flood events and create an immersive and interactive environment for training and education on flood disaster preparedness, which included flood simulations [48, 118]. However, the sources and methods of these flood simulations are unclear, and the integration process of such simulations into VR environments is hard to reproduce [119, 120]. Some researchers evaluated psychological and psychometric effects on user engagement while experiencing and navigating a flood hazard scenario in a VR environment. However, the flood representations in the VR environment were limited to a hypothetical pre-simulated water level rise mimicking a flood and did not involve physics-based simulations.

On the other hand, Gebray et al. [121] have introduced a framework specifically tailored to incorporate numerical simulation results of debris flows into VR to realistically visualize the spatial and temporal evolution of the debris flow. However, this framework is designed specifically for numerical simulation results generated using the RAMMS (RApid Mass Movement Simulation) modeling software. Moreover, VR technology has exhibited promise in visualizing computational fluid dynamics (CFD) simulations [122, 123] Yet, these studies were predominantly limited to room-scale visualizations of flows in the field of chemical engineering and the visualization of the flows lacks realistic renderings. In any flow simulation, the ability to portray the flowing material in its true form, rather than relying solely on color mapping and rendering the surrounding environment realistically, is crucial for making simulation results meaningful and accessible, especially to non-expert audiences.

Chapter 3

Research Methodology

This chapter presents the methodology used in this research study. We begin by introducing the Design-Based Research (DBR) approach and discuss why it was selected for this research. Next, we provide a detailed description of the design of each case study that constitutes an iteration in the DBR cycle, including the methods used to collect and process the captured data and the various analysis approaches selected to address the RQs.

3.1 Design-Based Research Approach

We employed the DBR approach in this research study because of its primary features, as explained below:

Iterative and Flexible Design Process: DBR approach is characterized by iterative and flexible monitoring of analysis, design, development, and implementation, ensuring continuous refinement of design solutions [124, 125]. We conducted three iterative case studies, where each case study expanded the context and advanced the research direction of the previous study. In DBR cycle 1, we formulated a conceptual framework for evaluating immersive media technologies by integrating IDNs as one important dimension to be investigated. Based on the proposed framework, we designed Case Study 1, which explored the role of IDNs and their impact on User Experience (UX) in VR. VR design was simple (non-positional three degrees of freedom (DOF) tracking and pointer-based locomotion) yet realistic and immersive based on digital representations of real-world terrains using Digital Elevation Models (DEMs) from WP2 and WP3. In DBR cycle 2, we broaden the context of the VR design by implementing realistic environmental elements (terrain meshes, texture maps, and other environmental elements), complex gameplay (immersive environment, realistic physics, interactive objects, advanced graphics, and engaging story-line) and pre-made simulations sourced from the Unity Asset Store to investigating affordances. Furthermore, we leveraged Rift S HMD with high resolution, which provided an in-depth evaluation methodology for measuring the UX of VR. Finally, in DBR cycle 3, we developed a VR framework that could import complex simulations of weather events like floods and landslides into VR. The framework is based on real-time geophysical flows integrated within the VR. After successfully visualizing the weather events in VR, we designed Case Study 3 to explore emotional valence and identity priming in VR.

The three case studies conducted in this research study focused specifically on NH of floods. The reason for this choice was that floods are natural disasters that occur frequently in many parts of the world. As a result, participants are more likely to have realistic and meaningful responses to the simulations. By focusing on floods, we aimed to better understand how people react and respond to this type of NH and how it can be used to improve emergency preparedness and response.

Collaborative and Participative Process: DBR was a suitable approach for our project because it involved the collaboration and participation of different stakeholders, such as researchers, practitioners, and expert professionals. DBR allows us to design, implement, and evaluate immersive VR environments that simulate realistic NH events. For example, in our project, we aim to create a VR system that simulates floods in the scope of the WoWW project (see Chapter 1.1) and measures risk perception. To achieve this goal, we worked together with researchers and practitioners from the Department of Mathematical Sciences, civil and Environmental Engineering, psychology, and Electronics Systems. We also involved the end users who used the VR and provided feedback on their experiences and outcomes. By engaging in long-term collaborations, we benefited from the diverse perspectives and expertise of each stakeholder. We made informed decisions in the different phases of the research process, such as problem analysis, design, development, testing, refinement, and dissemination. DBR enabled us to co-create knowledge and solutions that were relevant, effective, and sustainable for our project.

Use of Mixed-Methods Research: In the field of research, DBR remains neutral to the epistemological challenges that arise due to the choice of methodologies used and adapts to different methodologies based on the requirements and objectives of its various stages. Mixed methods research is a widely used approach that allows the exploration of various factors from multiple perspectives, making it a valuable tool for managing newly emerging research considerations. This approach is commonly employed in user-centered research and within the DBR framework due to its adaptive nature and ability to enhance the credibility of ongoing research. Throughout this research study, we have employed a multi-faceted approach to gain a comprehensive understanding of the research questions. We have used subjective data to capture users' experience, objective data (such as task completion rate and time to complete tasks) to measure their cognitive outcomes, and physiological data (such as heart rate) to monitor their attention and arousal levels during VR experiences. By triangulating these different data sources, we can gain a more accurate and holistic understanding of VR and its effects on users.

Application of Theories on Design and Evaluation : DBR investigates complex immersive environments and their influencing variables to advance related theories and impact practice. This is achieved by realizing and improving the design of VR [126]. The investigation conducted in this research study aims to understand users's experiences with IDNs through VR and to produce knowledge that improves the design, implementation, and evaluation of user experiences in VR. To achieve this aim, contemporary theories, related work, and relevant practice serve as the foundation for this DBR approach. Theoretical concepts such as presence, immersion, UX Design Principles, Agency and interactivity, Narrative Theory, Spatial Storytelling, affordances, emotions, and identity transformation are utilized to understand how VR can be used to deliver complex weather events in VR. The use of these theories enables a deeper understanding of the VR experience and supports the design and implementation of effective VR. By grounding this research in contemporary theories, related work, and relevant practice, the results will have a greater impact on improving the design, implementation, adoption, and ongoing use of VR in NH preparedness.

3.2 Study Design

In this section, we will provide a brief summary of the studies that were conducted as part of this research. The studies were structured as three DBR cycles, and each cycle had specific research objectives answering RQs defined in Chapter 1. We will outline the VRE used, the participants involved, and the data collection and analysis conducted during each cycle of DBR.

3.2.1 DBR Cycle 1

Case Study 1: Investigating the Role of Interactive Digital Narratives

Research Objectives: DBR cycle 1 was initiated by proposing a comprehensive conceptual framework for evaluating immersive media experiences answering RQ1. This led to Case Study 1 where we integrated IDNs (as identified in the framework, paper 1) in VR. The primary purpose of Case Study 1 was to investigate the role of IDNs in VR and how IDNs shape the mediated presence and

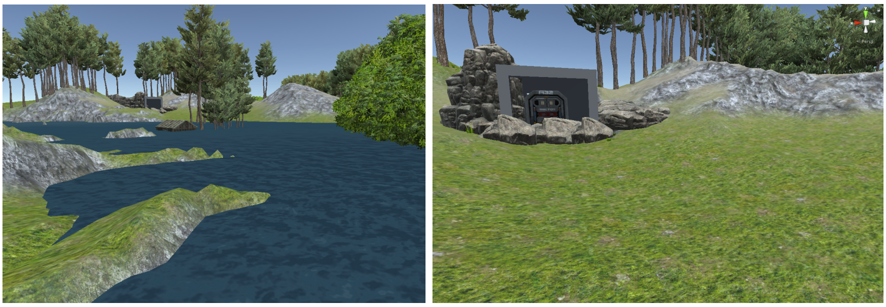

Figure 3.1: VRE for evacuation training

players' behavioral response in VR. This objective answered RQ2a (Paper 2) and RQ2b (Paper 3).

Research Design: The study used a 2x2 within-group experimental design, where participants experienced both a non-narrative and a narrative-based VR in random order.

Comprehensive Overview of the Involved VRE: The fully immersive VRE was designed using the Unity game engine and Oculus software development kit. The system was based on a real-time digital elevation model (DEM) showing part of a small village, Utvik, located in Vestland County, Norway. Two VR conditions were designed as part of the experiment, a non-narrative-based VRE (C1-NN) and a narrative-based VRE (C2-N), adapted to imply IDNs elements to guide the player in the VRE as shown in Figure 3.1.

Recruitment of Participants The study used a convenience sampling method to select 32 participants between the ages of 25 and 44. All participants belonged to several geographical regions and were asked about computer experience, VR, and 3D knowledge.

Employed Procedure: For the experiment, participants were selected through convenience sampling, which involved choosing individuals based on their availability and willingness to participate. Prior to the experiment, their levels of computer, VR, and 3D knowledge were recorded. Participants were given detailed instructions regarding the experiment, and for the training phase, they were made familiar with the Oculus Go HMD and the touch controller. After becoming comfortable with the equipment, they performed a simple task to ensure they were accustomed to the process. Each participant experienced both the narrative and non-narrative conditions in a random order. During the experiment, participants wore the Oculus Go HMD and used the touch controller to navigate and explore the VRE. The sense of presence and behavior of the participants were measured using a questionnaire. The experiment took approximately 30 to 35 minutes for each participant, and the questionnaire took about 5 to 7 minutes to complete.

Data Collection Instruments: We used the Independent Television Company Sense of Presence Inventory, also known as ITC-SOPI, which is a tool used to gauge the level of presence experienced by individuals while engaging with media content, as well as the behavioral outcomes associated with that engagement. The ITC-SOPI consists of measurements for presence, engagement, ecological validity, and negative effects.

Computed Measurements and Statistical Analysis: Multivariate analysis of variance (MANOVA) was computed with narrative immersion (non-narrative (C1-NN) and narrative (C2-N)) as an independent factor and presence, engagement, ecological validity, and negative effects as dependent variables. Results of DBR cycle 1 are presented in Chapter 4.

3.2.2 DBR Cycle 2

Case Study 2: Investigating the Role of Affordances

Research Objectives: Case study 1 aimed to investigate the role of IDNs on presence and behavioral responses in VR. However, the study was limited to the subjective evaluation and within-subject design only. Moreover, using a standalone Oculus Go HMD resulted in a low frame rate and content quality. To overcome these limitations, we designed a consecutive study in DBR cycle 2. The primary objective of case study 2 was to investigate the effects of spatial affordances and understand UX based on the inherent possibilities of actions provided within VR. We addressed RQ3 and RQ4 in DBR Cycle 2.

Research Design: We compared the perceived experiences of participants in an immersive VR depicting a stressful flooding scenario by controlling the experimental conditions with spatial affordances. The research employed a between-group design with three experimental conditions: Control Condition (CC) with no wayfinding cues, Experimental Condition 1 (EC1) with static wayfinding cues, and Experimental Condition 2 (EC2) with dynamic wayfinding cues and visual stimuli.

Comprehensive Overview of the Involved VRE: We extended the VR based on the findings from DBR cycle 1 by incorporating interaction, environmental cues, nonlinear paths, temporal changes (by implementing pre-simulated flooding and dynamic weather), and spatial audio. We used Unity3D[1] together with open-source libraries to design the VR system and deployed it on a computer-powered HMD

[1]https://unity.com/

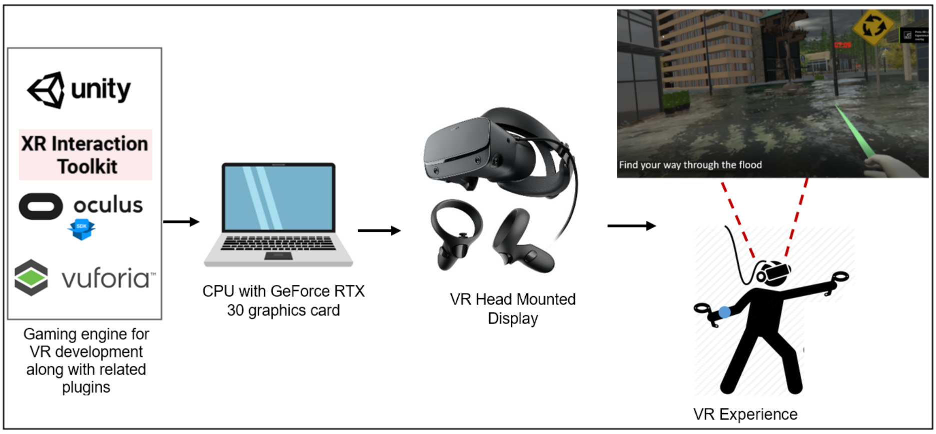

Figure 3.2: The figure illustrates the software and hardware components used in the design and development. A high-performance gaming PC with Oculus Rift S was used to exhibit the VR experience.

called the Oculus Rift S[2] as shown in the Figure 3.2.

We designed and developed a VRE that provided users with an immersive experience of a small city. The VRE allowed users to explore and interact with the virtual space, which consisted of streets, buildings, and landmarks. To achieve this, we used the teleportation technique, which enabled the user to navigate freely with a natural walk and an Oculus Rift Controller. Both locomotion techniques and natural walking were designed to reduce motion sickness.

When the VR experience started, the users were in a parking lot (Figure 3.3), and they could hear sirens and emergency announcements (which were instructions) to evacuate the city and find a safe place where they could be rescued. As the users navigated through the VR environment, the parking lot slowly started to fill with water. This scenario was created to generate a sense of urgency and challenge for the users, as well as to test their spatial awareness and navigation skills. The goal was to reach the designated safe location as shown in Figure 3.4. The aerial view of the VRE shows that the users could navigate from point A to point B by taking any route shown in red dotted lines (Figure 3.5).

Recruitment of Participants: The study involved 39 participants, out of which 13 were females and 26 were males, with an age range between 18 to 54 years. 20.51% of the participants were aged between 18-24 years, while 61.53% were aged between 25-34 years. The majority of the participants had intermediate com-

[2]https://www.oculus.com/rift-s/

(a) (b)

Figure 3.3: Figure (a) shows the 3D rendered parking lot of the VRE. The green line in Figure (b) shows the teleportation beam, which helped the user navigate the VR.

Figure 3.4: Safe zone where the user had to reach to save themselves from the flood

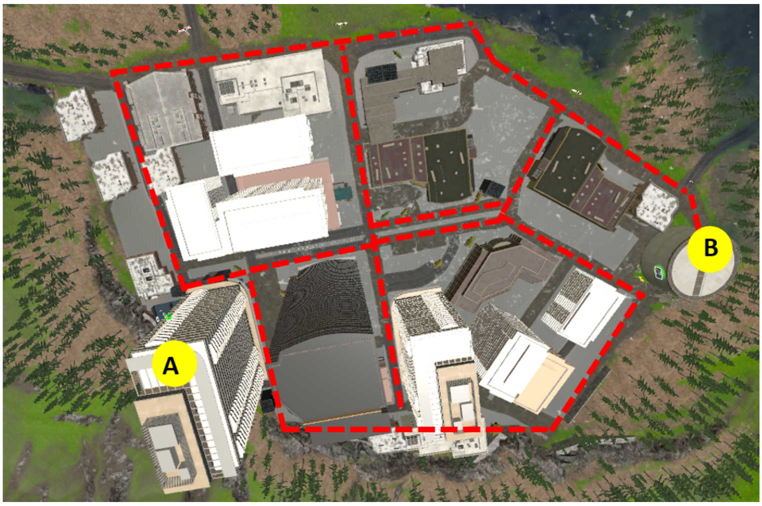

Figure 3.5: Ariel view of the city inside the VRE

puter skills (69.23%), and 69.23% of them had no prior experience with VR. All the participants were given detailed instructions and a comprehensive demonstration before the study. Participants with color vision deficiency were excluded, but those who had farsightedness or nearsightedness were included.

Employed Procedure: Participants signed up for an experiment and provided information about their age, gender, educational background, visual disturbances, and availability. Selected participants were notified via email about the time and venue of the experiment, which was held at the Sense-IT lab, NTNU, in Norway. Before the experiment, participants were briefed about COVID Standard Operating Procedures (SOPs) and signed a consent form. They were then given instructions on using the Oculus Rift S and played a short demo VR game. The Guardian Boundary was set up to ensure safety and help participants stay within the designated play area. After the demo, participants were randomly assigned to one of three experimental conditions (CC, EC1, or EC2). Before starting the task, participants were briefed about the tasks both orally and in written form by the experimenter and were shown the VRE map before and during the VR experiment.

After completing a VR experience, participants had their heart rate (HR) monitored using a Fitbit. They also filled out the Game Experience Questionnaire (GEQ) and received a cinema ticket for their time. The experiment lasted no more than 40 minutes. Results from the study are presented in Chapter 4.

Data Collection Instruments: To gather information, the study used two data collection instruments. The first instrument was the Fitbit Sense, which monitored the participants' HR continuously. The second instrument was a post-test GEQ, which evaluated the participants' psychometric responses. The GEQ assessed various components of the game experience, such as Immersion (the degree of engagement and absorption), Flow (the sense of being fully immersed and losing track of time), Competence (the feeling of capability and effectiveness), Positive and Negative Affect (the positive and negative emotions during gameplay), Tension (the level of stress or anxiety), and Challenge (the level of difficulty and complexity).

Computed Measurements and Statistical Analysis: The study recorded physiological responses, particularly HR, with Fitbit Sense. It also obtained psychometric evaluations from the GEQ, which used an Absolute Category Rating (ACR) System. To assess the impact of different wayfinding cues on user experiences in the VRE, the study conducted statistical analyses, including between-group comparisons.

3.2.3 DBR Cycle 3

Case Study 3: Developing a VR Framework for Geophysical Flows and Investigating the Role of Emotions and Identity

Research Objectives: Case Study 3 aimed to develop a VR prototype that could digitally replicate weather phenomena like floods in real time. The case study had two parts: The first part developed a VR framework that presented numerical simulations of geophysical flows in VR by integrating simulation data. The framework enabled users to experience geophysical flows, such as floods and landslides, through a VRE. The second part designed a VR experience that simulated a flood and examined how identity priming and emotional valence affected user experiences and physiological responses in this VR scenario. The ultimate goal was to create immersive digital twins of natural hazards by combining simulations with VR and evaluating UX. DBR cycle 3 answered RQ 5a and RQ 5b.

Research Design: As a part of fulfilling objective 1 of DBR cycle 3, we developed the VR framework, as explained in the next section. To fulfill objective 2 of DBR cycle 3, we made further enhancements to the VRE and tested it with users. To evaluate the effectiveness of the VRE, we conducted a 2×2 between-group experimental design. In the study, we manipulated emotional state (Fear and NoFear) and priming (Identity and No Identity) in VR. Our main focus was to investigate the effects of these manipulations on presence, cognitive load, and heart rate. We used a mixed-method approach to gain a comprehensive understanding of the subject. The mixed-method approach helped us identify the effects of the manipulations on presence, cognitive load, and heart rate in a more comprehensive manner. The following section gives a detailed explanation of the VR framework and VRE.

Comprehensive Overview of the Involved VRE:

VR framework for geophysical flows: The first stage of the framework development involved selecting the most appropriate numerical simulation model for generating geophysical flow data. The key input parameters for this process included the terrain, which served as the computational domain, parameters controlling the initial conditions, and boundary conditions. We then computed numerical simulations based on these input parameters. The post-processing output result was in CSV format, which we then converted into ESRI ASCII grid format using Python scripts. This grid format is a human-readable representation of the structured grid, containing information about grid dimensions and data values at each grid point.

The integration of geophysical data into the VRE was a crucial step in the framework. To achieve this, we employed three distinct modules: the preprocessing module, the simulation module, and the interaction module, as shown in Figure 3.6. These modules were implemented using C sharp scripts. The VRE was primarily created from the terrain data and flow elevation coordinates derived from the flow depth of the numerical simulation. To imitate the dynamics of the geophysical flow, the velocity vectors obtained from the numerical simulation were incorporated into the shaders to control the direction and speed of flow and add fluid-like behavior to the visual representation. 3D models derived from flow elevation coordinates served as frames to capture the temporal evolution of the geophysical flow.

The last step in the framework was the integration of the VRE with XR devices such as HTC Vive, Oculus Quest, or Rift hardware, which enables users to interact with and immerse themselves in VRE. To achieve this, the XR Interaction Toolkit plugin [3] was integrated with Unity to enable XR device compatibility. Overall, the VR systems consisted of three essential components: the 3D simulated environment, the immersion capability, and the interaction capability. Section 4 of Paper 7 outlines the detailed process for developing and implementing this system. Although the VR framework was designed for different types of natural hazards and case studies were performed on snow avalanches, landslides, and floods (see paper 7), we focused on flood simulations for our user studies. The reasons for this decision are explained in Section 3.1.

The VRE used in DBR cycle 3 was developed in collaboration with Breach AS [4], a gaming development company. The VR prototype was based on numerical flood

[3] https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.5/manual/index.html
[4] https://breachvr.com/project/world-of-wild-waters/

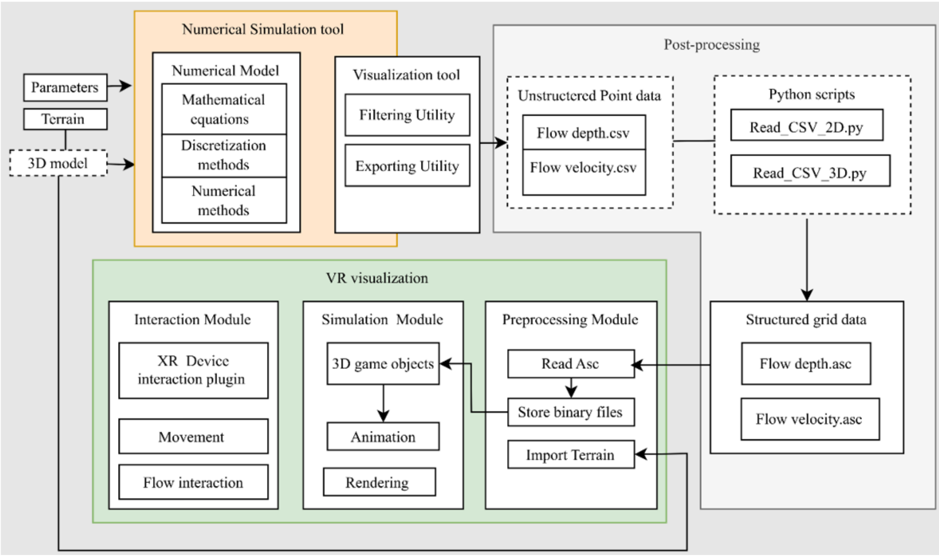

Figure 3.6: General overview of the pipeline of the framework. The proposed framework consists of the parameters that are input for the numerical simulation, the numerical model set-up, visualization, post-processing of simulation results, integration into the VRE, and user interaction within the virtual space.

simulations of geophysical flows in Utvik, a village in Vestland County, Norway. These simulations were computed using Iber [127], a two-dimensional numerical hydraulic model. Iber employs a Roe-type Riemann solver to calculate changes in water levels and velocities along a river, considering the topography and actual discharge. The discharge values were determined based on observed data collected during the event [128] [5]. Breach AS modified the VR environment by implementing a flood scenario in VR (as shown in Figure 3.7). They also implemented game design elements to induce identity, emotional valence, and feedback mechanisms, which were designed to enhance the user experience and learning outcomes in the VR environment. The resulting VRE was developed further to investigate the role that emotions and identity play in a VR setting, as explained below.

Virtual Reality Environment: For this study, four different experiences in the same baseline virtual environment were created. Two of these experiences were designed to elicit participants with a sense of place identity in VRE, with and without inducing fear, while the other two experiences aimed to prevent participants from

[5]information on numerical hydraulic modeling and the technical workflow for immersive VR visualization of geophysical flows is beyond the scope of this research work, and is mentioned here to detail the workflow of VRE development

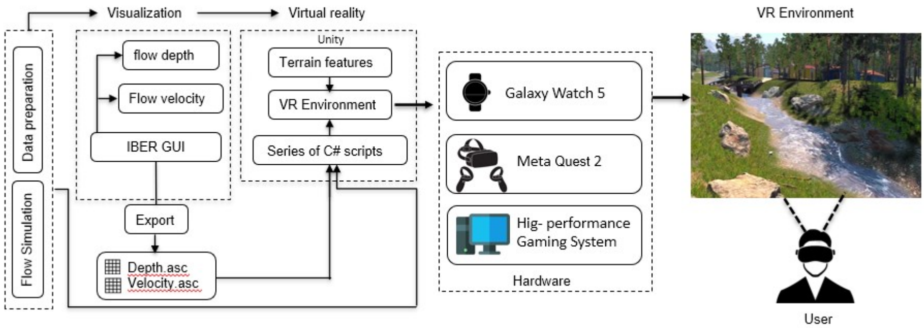

Figure 3.7: The workflow includes data preparation, flood modeling, and the adaptation and import of topographic and flow simulation results into the VRE. The design and development of the VRE, along with the hardware components used, involved a high-performance gaming PC with Meta Quest2 to showcase the VR experience

identifying with the environment, again with and without inducing emotions of fear. To avoid potential confounding variables, participants had only hand representation in the virtual environment with no virtual body [129, 130].

At the beginning of the VR experience, the participants were transported to a VRE. They were presented with an aerial view of the VRE, as shown in Figure 3.8. Participants could look around freely using six degrees of freedom in the environment, allowing them to immerse themselves in the environment entirely. However, they were not yet able to navigate freely through the environment. The VR experience was meticulously designed with a variety of visual and auditory elements that were intended to evoke a strong sense of identity in the user. These elements included Norwegian houses, deer, trampolines, flags, and significant landmarks in the surrounding areas, as depicted in Figure 3.9. A narration guides participants through the environment, assisting them in identifying elements they can relate to and encouraging them to closely examine their surroundings. The participants were primed to develop a profound sense of belonging to the virtual environment.

Participants were then transported to a town near the houses, as shown in Figure 3.10. They were encouraged to interact with the surroundings and given a brief tutorial on using the VRE controller. Later, the participants were taken to a bridge, where they were exposed to either the Fear or NoFear condition.

In the No Identity condition, all participants were given the same aerial view of the VRE as shown in Figure 3.8a. However, they were explicitly informed that they were not part of this environment and that the elements displayed were unfamiliar.

During the Fear condition, participants were exposed to a scenario that was de-

Figure 3.8: Figures show an aerial view of the VRE used in the study. The VR scene depicts a vibrant landscape

Figure 3.9: First person view of the user at the bridge where they are primed for identity. Figures show an aerial view and a closer view of the VRE where the participants were primed for identity or no identity.

Figure 3.10: VRE where participants interacted with the environment and performed the mushroom picking task

signed to instill feelings of fear and urgency. The scenario involved the participants being guided towards a bridge while the weather transitioned into a storm with rising water levels, simulating an impending flood (Figure 3.11). They were given a flood evacuation notice and were exposed to accompanying sounds of thunder, rain, and emergency alarms to increase the sense of urgency. In addition, specific ambient music was played to the participants inside the VRE, with the aim of eliciting a sense of unease and threat. As the scenario unfolded, the weather intensified, creating a threatening environment. Participants were tasked with navigating through rising water, witnessing falling trees, and encountering collapsing structures to reach a designated safe area. The primary goal was to assess the participants' cognitive load levels during this fear-inducing flooding scenario.

As part of the NoFear condition, participants were transported to a beautiful location designed to elicit feelings of happiness and joy. Upon arrival, they discovered a fully prepared picnic set up near the bridge, complete with all the necessary grilling equipment (Figure 3.12). They were then encouraged to take a leisurely walk by the water and cook their selected items on a realistic fire grill, which included various options such as fish, meat, or mushrooms. Using objects like plates and forks, the VR experience allowed for an interactive exploration. The experience thoughtfully integrates serene water sounds and natural ambiance, such as the melodic chirping of birds, to create an atmosphere of tranquility and relaxation, fostering happiness. This transition to the inviting picnic scene on the same

(a) VRE showing the flood scene used in the VRE to induce the emotions of fear and stress

(b) Participants moving through the same bridge shown in Fig 3.9 to find the safe location. This was the second task provided to the participants in the Fear conditions

Figure 3.11: VRE showing the flood scene used in the VRE to induce the emotions of fear and stress

Figure 3.12: In this grilling scenario, participants found themselves at a picnic spot with various grilling options. The participants were subsequently encouraged to participate in grilling activities, constituting the second task for the NoFear condition.

bridge area brought about a surge of positive emotions among participants, who eagerly engaged in the grilling activities at this scenic spot, making the experience unforgettable.

Recruitment of Participants We collected data from 121 participants, and after excluding the missing or incomplete cases, we were left with 102 participants. The age of the participants (N=102) ranged from 19 to 60 years (M =27.73, SD = 9.21). 61.7% of the participants were female, 37.3% were male, and 1.0% were non-binary. The participants had different educational backgrounds, and 52.9% of the participants rated themselves as intermediate in computer skills, 33.4% as basic, and 13.7% as expert. 60.8% of the participants reported previous VR experience.

Employed Procedure: The study aimed to recruit a diverse sample of participants using various methods, including flyers, email invitations, and online ads. If interested, participants signed up for the experiment by scanning a barcode or email link. They completed a questionnaire with demographic information (age, gender, education, visual impairments) and their availability. After signing up, they received notification emails with the location and timing of the experiment. The experiment took place at the Sense-IT lab in the Department of Electronic Systems and the Department of Psychology at NTNU.

The experimenter greeted the participants, obtained their consent, and briefed them on the experiment. They introduced them to a VRE and instructed them on how to navigate it using VR controllers to operate the Meta Quest 2 device and its Guardian Boundary feature. Heart-rate measuring smart watch were attached to monitor participants' physiological responses before the experiment. The participants were randomly assigned to one of four VRE conditions, where they experienced the VR scenarios and performed assigned tasks. After completing the tasks, participants removed the VR HMD. They used Nettskjema[6], a secure data collection tool on a tablet, to provide feedback on their subjective experiences, including presence, cognitive load, and other measures. The test took 45-60 minutes per participant. Participants received cinema tickets as a reward. The following section presents the results of the study. The results of this study will be presented in Chapter 4.

Data Collection Instruments: We employed psychometric measures to evaluate the participants' sense of presence, cognitive load, and simulation sickness during their VR experience. These measures included the NASA Task Load Index, the Presence Questionnaire, and the Virtual Reality Sickness Questionnaire. Additionally, we captured physiological data such as heart rate to gain insight into the participants' emotional state and arousal levels while in VR.

Computed Measurements and Statistical Analysis: Data from questionnaires and physiological measures were collected and analyzed. Presence, cognitive workload, simulation sickness, and physiological responses like heart rate were computed to assess participants' experiences in the VRE. Descriptive statistics and inferential statistics were used to evaluate the impact of emotional state and identity priming on participants' responses.

[6]https://nettskjema.no/

Chapter 4

Results

In this section, we present the results of our research work that aimed to investigate the factors affecting user experiences in VR. We also discuss how IDNs can address the complex challenge of NH preparedness and enhance risk communication through VR visualization of geophysical flows. We present the comprehensive results and key findings from the three DBR cycles and relate them to RQs based on the results obtained in each study.

4.1 Results of DBR Cycle 1

In DBR cycle 1, we proposed a framework by discussing factors that can enhance user-perceived experiences in Immersive Media Experiences (IMEs). Details of the framework are presented in Paper 1, and it answered RQ1 of our research work. The next step was to address RQ2. This was done by exploring the role of digital narratives for user engagement and presence in VR. The following section presents the results obtained from DBR cycle 1.

4.1.1 Comprehensive Results

A controlled experiment was conducted with two independent conditions: non-narrative-based VR (C1) and narrative-based VR (C2). A within-group experimental design was used, and all participants experienced both C1 and C2 in random orders (Chapter 3 Section 3.2.1). Before conducting the data analysis, the data was checked for outliers. Multivariate analysis of variance (MANOVA) was performed for the four dependent variables (DV) using ITC-SOPI: presence, engagement, ecological validity, and negative effects. The results of MANOVA showed a significant difference in the level of immersion between C1 and C2 ($F= 6.423$, $p<0.05$). The sense of presence was significantly higher in C2 ($M=3.94$) than

Table 4.1: A comparison of descriptive statistics, i.e., Mean and Standard Deviation (SD) for C1-NN and C2-N

	Descriptive Statistics			
	Condition	Mean	Std. Deviation	N
Spatial Presence	C1-NN	2.96	0.640	32
	C2-N	3.53	0.602	32
	Total	3.24	0.681	64
Engagement	C1-NN	3.22	0.667	32
	C2-N	3.86	0.635	32
	Total	3.54	0.723	64
Ecological Validity	C1-NN	2.95	0.721	32
	C2-N	3.31	0.778	32
	Total	3.13	0.765	64
Negative Effects	C1-NN	2.06	0.736	32
	C2-N	1.77	0.626	32
	Total	1.91	.694	64

in C1 (M=3.53), indicating that users felt more in control and immersed while interacting with the objects in the narrative condition. The engagement scale (F=15.624, (p<0.05)) also showed a significant increase in C2, indicating that users were more involved and interested in the narrative condition. The ecological validity scale did not show a significant difference between C1 and C2, but users perceived the VR with narrative (C2) to be more natural, real, and believable than the VR without narrative (C1), as shown in Table 4.1 The negative effects scale was not significant (F=3.017 p=0.087), but the level of dizziness and disorientation was higher in C2 than in C1. Figure 4.1 shows the box plot of each DV for the two conditions, and it can be seen that the median values of each DV in C2 are significantly higher than in C1, except for negative effects. From the results, we concluded that the IDN enriched VRE provides a significantly better user experience. The findings confirmed the positive impact of narrative on engagement levels and mediated presence in VR experiences.

4.1.2 Key Findings

We addressed the following research questions: *RQ1: What factors can enhance user-perceived quality in IME?* A framework was proposed to address this RQ, which is presented in Paper 1.

RQ2: What is the impact of IDNs on user-perceived experiences in VR? To an-

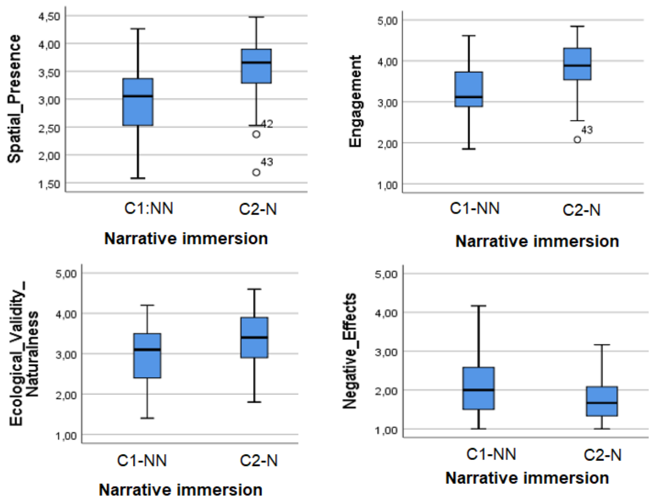

Figure 4.1: Figure shows the box plot with median, lowest, and highest data points of the dependent variables measured through ITC-SOPI

swer this research question, we investigated the role of IDNs in enhancing the user experience of VR. The results of the controlled experiment showed that the narrative-based VRE (C2) had a significant positive effect on the users' sense of presence, engagement, and ecological validity compared to the non-narrative-based VRE (C1). The findings show that users who experienced a VRE with a narrative felt more immersed, involved, and interested than users who experienced a VRE without a narrative. The findings also indicate that the narrative-based VRE was more natural, real, and believable than the non-narrative-based VRE and that it did not cause more negative effects, such as dizziness or disorientation. These findings imply that IDNs can enhance the user experience of VR by providing a more meaningful and enjoyable experience that allows users to interact with the objects and the environment in a natural way. Detailed results can be found in Paper 2 and Paper 3.

4.2 Results of DBR Cycle 2

DBR cycle 2 investigated the impact of affordances on user-perceived experiences in VR and answered RQ3 of our research work. Detailed methodology used to measure the user experience is explained in Section 3.2.2. The subsequent section presents a comprehensive overview of the results obtained.

4.2.1 Comprehensive Results

Physiological Evaluation: We measured heart rate (HR) as an indicator of physiological arousal during the VR experience. Figure 4.2 shows the mean HR values for each group over time. We observed that the control group (CC) without any wayfinding cues had the highest HR (mean = 97.69) throughout the VR experience, especially in the section marked with red dotted lines. This suggests that the CC group experienced more stress and anxiety than the experimental groups (EC1 and EC2) with static and dynamic wayfinding cues, respectively. We performed ANOVA to test the effect of wayfinding cues on HR and found a significant difference among the three groups($p < 0.05$). The CC group had a significantly higher HR than the EC1 and EC2 groups, but there was no significant difference between the EC1 and EC2 groups (paper 5).

Table 4.2: Results from one-way Analysis of Variance (ANOVA) for the HR measurements of the three groups.

		Sum of Squares	df	Mean Square	F	Sig.
	Between Groups	2660.839	2	1330.419	15.81	0
HR	Within Groups	3027.957	36	84.110		
	Total	5688.796	38			

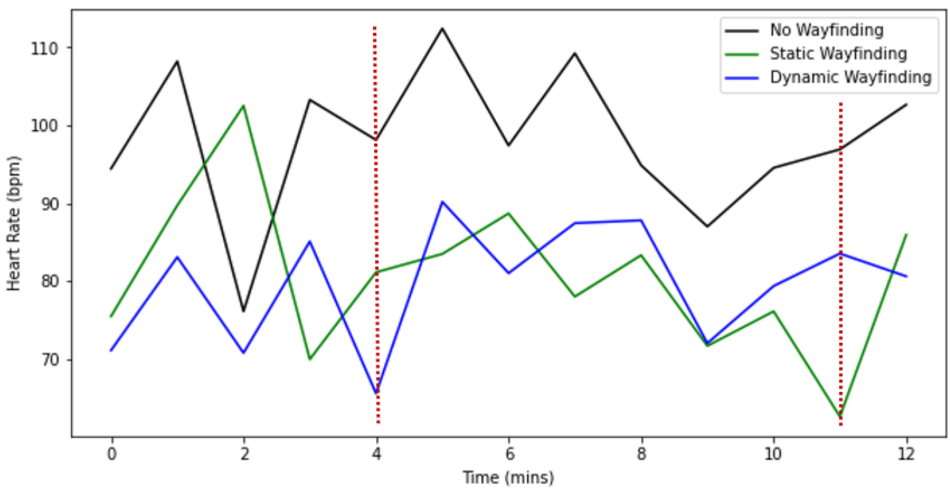

Figure 4.2: The graph illustrates HR data (beats per minute) for the control group (CC) and the experimental groups (EC1 and EC2) with different types of wayfinding cues in a VR environment

Subjective Evaluations: We used ANOVA to measure how wayfinding cues affect the UX in a VR based on seven metrics. We found that the control group (CC) without any wayfinding cues felt more challenged and tense than the experimental groups (EC1 and EC2) with static and dynamic wayfinding cues, respectively. The CC group also had a lower positive effect and higher negative effect than the EC2 group, but there was no difference between the CC and EC1 groups or between the EC1 and EC2 groups in these metrics. The three groups did not differ significantly in their ratings of immersion, flow, and competence in the VRE. See Figure 4.3 for the mean scores of each group.

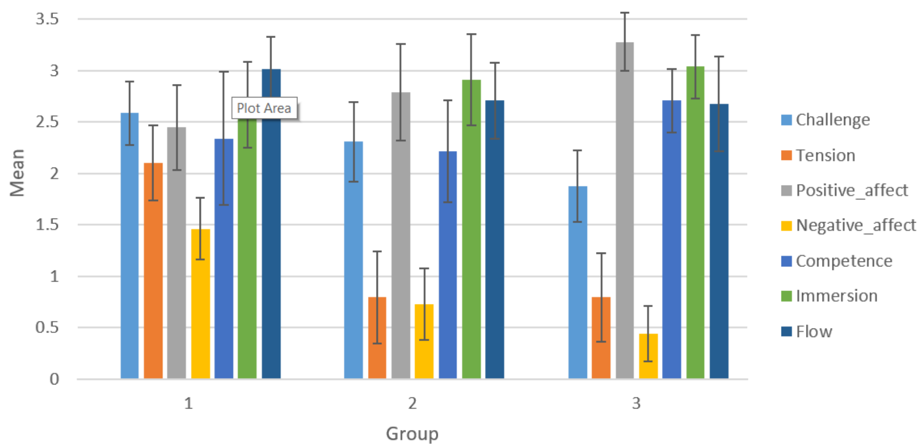

Figure 4.3: Mean scores for the control group (CC) and the experimental groups (EC1 and EC2) with different types of wayfinding cues in a VR.

4.2.2 Key Findings

In DBR Cycle 2, we explored the impact of affordances on user-perceived experiences in VR. We addressed the following research question: *RQ3: What is the impact of affordances on user-perceived experiences in VR?* To answer this question, we compared the effects of different types of wayfinding cues (no cues, static cues, and dynamic cues) on the users' physiological and subjective responses in a VRE. The findings imply that wayfinding cues can enhance the user's perceived experiences in VR by reducing negative and increasing positive emotions. They are important design elements for effective VR training environments. Our study also demonstrates the value of combining physiological and psychometric measures to evaluate user experiences in immersive environments. Details about the study are presented in Part 2, Paper 4.

Table 4.3: Mean scores of GEQ metrics for the three groups.

	Control Condition (n = 13)		**Experimental Condition 1 (n = 13)**		**Experimental Condition 2 (n = 13)**	
	Means	**SD**	**Means**	**SD**	**Means**	**SD**
Challenge	2.58	0.51	2.30	0.64	1.87	0.58
Tension	2.10	0.59	0.79	0.73	0.79	0.71
Positive Affect	2.44	0.68	2.78	0.77	3.27	0.46
Negative Affect	1.46	0.49	0.73	057	0.44	0.44
Competence	2.33	1.06	2.21	0.82	2.70	0.50
Immersion	2.66	0.69	2.91	0.72	3.03	0.51
Flow	3.01	0.51	2.70	0.60	2.67	0.75

Based on the results of DBR cycle 1 and cycle 2, we answered RQ4, which was: *RQ4: How does incorporating IDN in VR contribute to addressing complex societal challenges?* We have addressed RQ4 using the information provided in Paper 5 and Paper 6.

4.3 Results for DBR cycle 3

DBR cycle 3 had two research objectives, as discussed in Chapter 3. To fulfill the first objective, we developed a VR framework that could present numerical simulations of geophysical flows in VR by integrating simulation data and digitally replicating weather phenomena like floods in real time. To fulfill the second objective, we designed a VR experience that simulated a flood and explored how identity priming and emotional valence impacted user experiences and physiological responses in such VRE. The subsequent section presents a comprehensive overview of the results obtained.

4.3.1 Comprehensive Results

Sense of Presence: The data collected on the IPQ scale was analyzed using ANOVA.

We used Tukey's HSD post hoc tests to compare the mean scores of each measure across the four experimental conditions as shown in Figure 4.4. Mean and standard deviation of IPQ scale measures by condition are presented in Table 4.4 For GP, the only significant difference was found between the ID_Fear and ID_NoFear conditions ($p = 0.02$), with ID_Fear having a higher mean score than ID_NoFear. For SP, none of the pairwise comparisons were significant ($p>0.05$). For INV,

Table 4.4: Mean and standard deviation of IPQ scale measures by condition. GP = General Presence, SP = Spatial Presence, INV = Involvement, REAL = Realism.

	ID_Fear		ID_NoFear		NoID_Fear		NoID_NoFear	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
GP	4.32	0.56	3.23	0.26	3.19	0.30	3.23	0.60
SP	3.96	0.79	3.27	0.24	2.87	0.26	2.70	0.83
INV	4.38	0.69	3.32	0.25	3.09	0.40	3.32	0.52
REAL	4.13	0.63	3.26	0.27	2.99	0.42	3.05	0.51

the only significant difference was found between the ID_Fear and ID_NoFear conditions (p = 0.03), with ID_Fear having a higher mean score than ID_NoFear. For REAL, the only significant difference was found between the ID_Fear and ID_NoFear conditions (p = 0.003), with ID_Fear having a higher mean score than ID_NoFear.

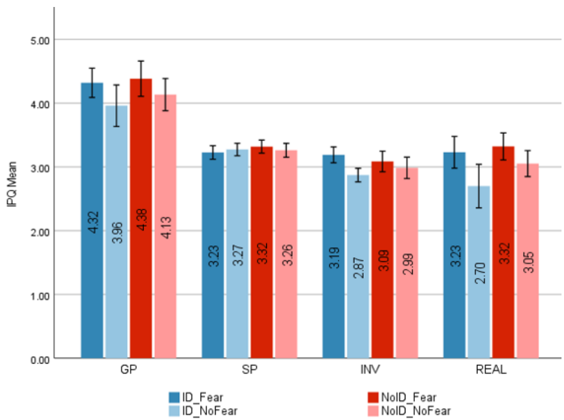

Figure 4.4: Mean aggregated Scores for igroup presence questionnaire (IPQ)

In summary, these findings suggest that both identity level and emotional valence played a significant role in influencing involvement and experienced realism among participants. However, they did not impact general presence and spatial presence measures. Detailed results are presented in Paper 8.

Cognitive load: We used Welch's ANOVA, on the six cognitive workload dimensions measured by NASA-TLX. The aggregated mean scores for the NASA Task Load Index are presented in Figure 4.5. *For mental demand*, findings suggest that when participants were primed with place identity, it increased their mental demand in VRE only when they experienced fear, not when they experienced no fear. Regarding *physical demand*, the study found no significant difference between the groups (F(3, 53.574)=2.702, p=0.055). This means that the emotional state and priming did not impact the amount and intensity of physical activity required to complete the task. Regarding *temporal demand*, the study found a significant difference between the groups (p=0.003). These findings suggest that participants experienced higher temporal demand in VRE when they felt fear and were primed with an identity but not when they experienced no fear conditions. *For performance*, the results showed that there was no significant difference between the groups, indicating that the emotional state and priming did not impact the perceived success or failure in completing the task (see Table 4.5). Results further suggested that priming participants with no identity increases their effort in VRE when they experience fear. Regarding *frustration*, there was a significant difference between the groups (p=0.045). These findings indicate that participants who were primed with no identity experienced more frustration in VRE when they encountered emotions of fear.

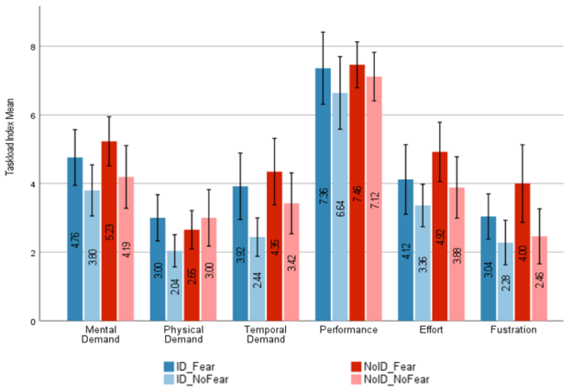

Figure 4.5: Mean aggregated Scores for NASA Task Load Index

Virtual Reality Simulation Sickness An ANOVA was performed to investigate the impact of emotional state (fear vs. no fear) and priming (identity vs no identity) on three measures of simulator sickness: nausea, oculomotor, and disorientation. Mean aggregated scores for VRSQ are presented in Figure 4.6. The results suggest that neither emotional state nor priming had any significant effects on simulator sickness in VR. The only exception was a marginal effect of emotional state on nausea in the identity condition. This finding might indicate that inducing fear in VR users who are primed with their own identity might increase their susceptibility to nausea.

Heart Rate The results pertaining to HR offered valuable insights into the impact

Table 4.5: Mean and standard deviation of six cognitive workload dimensions measured by NASA-TLX.

	ID_Fear		**ID_NoFear**		**NoID_Fear**		**NoID_NoFear**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Mental Demand	4.76	1.964	3.80	1.803	5.23	1.773	4.19	2.263
Physical Demand	3.00	1.633	2.04	1.136	2.65	1.384	3.00	2.040
Temporal Demand	3.92	2.344	2.44	1.356	4.35	2.399	3.42	2.194
Performance	7.36	2.548	6.64	2.564	7.46	1.655	7.12	1.751
Effort	4.12	2.455	3.36	1.497	4.92	2.134	3.88	2.215
Frustration	3.04	1.594	2.28	1.568	4.00	2.800	2.46	1.985

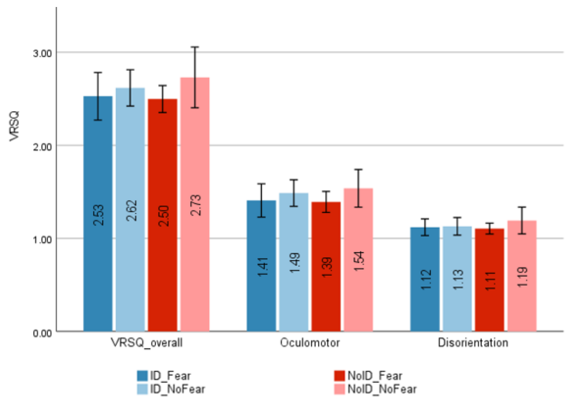

Figure 4.6: Mean aggregated Scores for Virtual Reality Simulation Sickness (VRSQ)

of experimental conditions on physiological responses in VRE, as shown in Table 4.6. The analysis revealed significant main effects of the experimental condition on both average and maximum HR (see Figure 4.7). Specifically, participants in the ID_Fear condition exhibited a significantly higher average HR compared to those in the ID_NoFear condition, suggesting that inducing emotions of fear has an arousal effect, leading to an elevated average HR during VR experiences. This finding aligns with H4 that emotions of fear would increase HR in VR. Additionally, the maximum HR in the ID_Fear condition was significantly higher than in all other conditions, emphasizing the pronounced effect of fear induction on participants' physiological arousal.

Contrary to our expectations, priming participants with a personal identity did not result in a decrease in HR. Instead, the ID_Fear condition, which involved both place identity priming and fear, exhibited the highest HR. This unexpected result prompts a reconsideration of the relationship between identity priming and HR in

Table 4.6: Mean and standard deviation of heart rate measures for VR experiment by condition

	ID_Fear		ID_NoFear		NoID_Fear		NoID_NoFear	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
HR_Avg	88.97	12.52	80.60	7.09	86.17	8.41	83.29	8.41
HR_Max	114.04	16.54	101.12	11.83	103.85	10.60	102.29	9.23
HR_Min	71.72	14.60	67.08	9.84	70.85	10.23	68.96	10.66

the context of VR. The absence of significant differences in minimum HR across conditions indicates that the experimental manipulations did not influence the participants' resting physiological state. The lack of interaction effects between identity priming and emotional state on HR suggests that the effects of these factors on physiological responses operate independently. This finding aligns with our hypothesis and reinforces the notion that the impact of identity priming and emotional state on HR is additive rather than interactive.

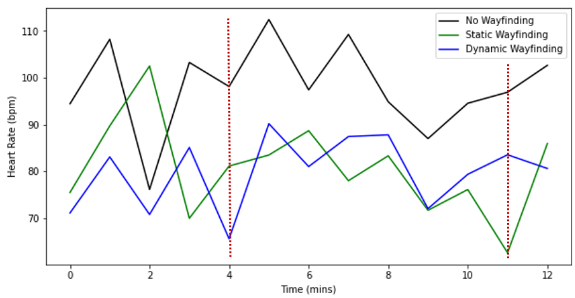

Figure 4.7: Mean aggregated Scores for Virtual Reality HR

The aim of this study was to examine the user experience measures in a virtual reality setting. We used the Pearson Correlation Coefficient analysis to explore the relationships between metrics such as presence, cognitive workload, and physiological responses (Table 4.7). We also tested the effects of identity priming and emotional state on these metrics. The results show that GP was positively correlated with INV and REAL but negatively correlated with SP. This suggests that participants who felt more present in the VRE were more engaged and perceived it as more realistic but less aware of the spatial aspects of the environment. SP was negatively correlated with experienced realism, indicating that participants who felt more present in the spatial dimension of the VRE perceived it as less realistic. INV was positively correlated with REAL, implying that participants who felt more involved in the VRE also perceived it as more realistic.

The results also show that cognitive workload was positively correlated with presence, except for performance and frustration. This suggests that participants who felt more present in the VRE also experienced more mental, physical, and temporal demand, and more effort, but not necessarily more performance or frustration. Performance was negatively correlated with frustration, indicating that participants who performed better in the VRE felt less frustrated. Frustration was positively correlated with simulation sickness, implying that participants who felt more frustrated in the VRE also experienced more nausea, oculomotor, and disorientation symptoms.

The results further show that simulation sickness was negatively correlated with presence, except for nausea. This suggests that participants who felt more present in the VRE experienced less oculomotor and disorientation symptoms but not necessarily less nausea. Nausea was positively correlated with performance, indicating that participants who performed better in the VRE also felt more nauseous. Oculomotor was negatively correlated with experienced realism, implying that participants who perceived the VRE as more realistic experienced fewer oculomotor symptoms. Disorientation was positively correlated with oculomotor, indicating that participants who experienced more oculomotor symptoms also felt more disoriented in the VRE. These correlation results (paper 8) provide valuable insights into the interconnections of different experiences and perceptions users may have in VRE.

4.3.2 Key Findings

In DBR Cycle 3, we explored the potential of VR for visualizing and communicating geophysical flow hazards. We addressed two research questions:

RQ5a: How can we design a VR framework for visualizing numerical simulations of geophysical flows?

To answer RQ5a, we developed a VR framework that can integrate output data from various mesh-based Eulerian numerical models into a VRE, enabling users to interact with and explore the terrain and geophysical flows through the VR experience. We applied our framework to three case studies of different geophysical flow hazards in Norway: a snow avalanche, a quick clay landslide, and a flash flood. We used Python scripts to transform the numerical data into a structured grid format and imported it into Unity, the VR platform.

RQ5b: How do emotions and identity impact user-perceived experiences within Virtual Reality? To answer RQ5b, we conducted an experimental study investigating how identity priming and emotional valence affect users' presence and cognitive workload in VR. We manipulated the emotional state (fear and no fear) and priming (with and without identity) of the participants and measured their pres-

	GP	SP	INV	REAL	TLX1	TLX2	TLX3	TLX4	TLX5	TLX6	VRSQ	O
SP	-.168	–										
INV	.295	-.022	–									
REAL	.526	-.202	.316	–								
TLX1	.176	.044	.007	.292	–							
TLX2	.062	-.088	-.019	.195	.469	–						
TLX3	.179	.020	.190	.248	.356	.128	–					
TLX4	.078	.018	-.130	.166	.122	.099	.060	–				
TLX5	.201	.128	.184	.339	.541	.364	.339	.042	–			
TLX6	.053	.111	.177	.115	.405	.036	.331	-.218	.550	–		
VRSQ	.111	-.070	.156	.158	.086	.020	.102	.227	.074	.025	–	
O	-.243	-.009	.147	-.194	.098	.125	-.062	.020	-.010	.045	.135	–
D	-.151	-.043	.154	-.119	.224	.125	-.001	-.052	.151	.172	.145	.637

Table 4.7: Correlations between different measures of virtual reality experience,GP= general presence, SP=spatial presence, INV=involvement, REAL=experienced realism, TLX1= mental, TLX2=Physical demand, TLX3=Temporal demand, TLX4=Performance, TLX5=effort, TLX6=Frustration, VRSQ=overall, O=Oculomotor, D=Disorientation,

ence, cognitive workload, and physiological responses in VR. We found that identity priming and emotional valence significantly impact the user's involvement and experienced realism but not presence. We also found that identity priming and fear significantly affected mental demand, temporal demand, effort, and frustration, but not physical demand or performance, in VRE.

DBR cycle 3 demonstrates the feasibility and effectiveness of VR for visualizing and communicating flow simulations. It also provides valuable insights into how cognitive experiences such as emotions and identity can affect the user's presence and engagement in VR for NH preparedness. Our findings have significant implications, as explained in the next chapter, and contribute to a better understanding of designing effective and engaging VR experiences.

Chapter 5

Discussion

In this chapter, we will provide a comprehensive overview of the contributions, implications, and limitations of this research work. We will discuss in detail the various ways in which this research has advanced the field and how it has contributed to the existing body of knowledge.

5.1 Contributions

5.1.1 C1: Conceptual Framework

The foundational contribution of this research is the development of a comprehensive conceptual framework for evaluating immersive media experiences. The framework serves as a guiding structure, offering a unified lens through which the impact of UX influencing factors on VR for NH preparedness can be systematically assessed. The conceptual framework synthesizes existing theories related to VR, user experience, and the role of narratives in immersive environments. By establishing a robust theoretical foundation, the research contributes not only to the field of VR but also enriches the broader discourse on the theoretical underpinnings of immersive media.

5.1.2 C2: Evaluation Methods in VR

Advancing the field, this study introduces evaluation methods tailored to VR. A comprehensive methodological approach was employed, integrating quantitative, qualitative, and mixed-methods research strategies. Incorporating established metrics tailored for each DBR cycle provides a standardized basis for assessing VR experiences. Analysis of physiological responses, such as heart rate, added depth to the evaluation process, considering the embodied nature of UX for VRE. The multi-method approach not only ensures a holistic understanding of user experiences but also sets a precedent for rigorous evaluation in the domain of immersive technologies designed for NH preparedness.

5.1.3 C3: Design Methods in VR

Contributing significantly to the field of VR design, the research outlines effective design methods. The iterative DBR approach serves as the backbone, facilitating an agile methodology that explores the integration of IDNs, Affordances, Emotions, and Identity as UX influencing factors, within VRE. The cyclic nature of DBR ensures continuous refinement, aligning with the dynamic landscape of immersive media. The design methods elucidated in this research encompass not only the technical aspects of VR development but also the creative and narrative dimensions, acknowledging the interdisciplinary nature of VR design.

The adoption of the DBR approach was pivotal in guiding the research process. Prior to each case study, a meticulous analysis of related work and theory laid the groundwork. The incorporation of DBR aligns with the dynamic and iterative nature of IMEs. Consultations with industry experts, educators, and fellow researchers from WoWW during the design and development phases ensured the interventions seamlessly transitioned to real-world contexts. The iterative nature of the methodology allowed for the adaptation of interventions based on real-time feedback, fostering a collaborative and adaptive research environment. The methodological considerations, including the exploration of proposed definitions of IDNs, using IDNs to represent the complexity of NHs, and VR framework for visualization of NHs and then assessing the Vr for UX influencing factors of emotions and Identity, add layers of depth to the research process, contributing to the robustness of the overall methodology.

5.1.4 C4: IDNs for Representing Complexity

This research attempts to understand the role narrative plays in the psychological indicators of human experience for complex representations in IMEs. The results of case studies 1 and 2 revealed an overall positive experience for VR users when the VRE was aided with IDNs. The present studies also help us to understand the influence of IDNs and affordances and how incorporating narrative in an immersive environment can enhance VR-specific attributes such as spatial presence, engagement, naturalness, immersion, flow and positive experience of the users.

5.1.5 C5: Framework for Visualization of Geophysical flows in VR

A pivotal contribution of this research is the creation of a framework for integrating and visualizing numerical simulation results of various geophysical flows. The framework allows users to perceive the hazards in their true, real-world dimensions, rather than relying solely on color maps. The resulting VR visualizations immerse users in VRE, allowing them to observe the flood in its realistic representations from various perspectives. This realistic presentation enables users to grasp the scale and impact of the hazards on critical structures like roads, bridges, and other essential infrastructure (Figure 7d in Paper 7). Furthermore, the capability to access the temporal variations of the flow attributes at specific locations enables users to relate numerical values representing flow depth with the corresponding physical changes observed in the VRE.

This VR framework offers flexibility in integrating additional non-physics elements, such as environmental sounds and weather conditions. By combining realistic flood simulations with heavy rain with corresponding audio in the VRE, an enhanced sense of realism is achieved, which in turn strengthens the connection of the users to the simulation, enhancing their perception and comprehension of the hazards and, in turn, enhancing the UX.

In contrast to numerous hazard and risk maps, the VR visualization achieved in this research excels in portraying the dynamic nature of geophysical flow hazards. This capability enables users to intuitively grasp the speed of these flows, facilitating their consideration of evacuation times in real-life disaster scenarios. Consequently, this VR visualization holds immense potential as a tool for NH disaster preparedness and emergency planning.

5.2 Implications

The implications of this research extend beyond the immediate scope of VR design and evaluation. By understanding the interplay between IDNs, affordances, emotions, and identity in VR, the findings hold significance for NH preparedness strategies, educational practices, and immersive media design. The research underscores the potential of VR as a training tool, emphasizing the importance of IDNs in creating impactful training VR experiences. The implications extend to diverse stakeholders, including educators, industry experts, and VR designers, offering actionable insights for the development of immersive and effective training tools for various scenarios.

The findings are relevant to educators and instructional designers, offering insights into how narrative-rich VR experiences can enhance learning outcomes. This has broader implications for educational applications beyond natural hazard preparedness, extending to fields where immersive and experiential learning is valuable.

The research provides practical guidelines for VR designers on integrating IDNs, spatial affordances, and investigating emotions and identity. Designers can leverage the identified positive effects on engagement, presence, and physiological responses to create more compelling and effective VR experiences.

By leveraging VR technology and realistic numerical models, VR framework (presented in DBR cycle 3) offers an innovative and immersive approach to visualize geophysical flow phenomena. The integration of VR enhances data visualization on a real-world scale, providing users with an intuitive and engaging exploration experience. This approach has the potential to revolutionize how individuals perceive and respond to geophysical flow disasters.

Considering the potential integration with state-of-the-art computing alternatives, the VR visualization framework holds the promise of revolutionizing the understanding and communication of geophysical flow phenomena. Visual advancements in scientific communication, in combination with VR, offer a higher degree of immersion and understanding compared to traditional 2D visualizations provided by numerical models. This immersion enables users to better comprehend the spatial depth, scale, and complexity of geophysical flows, e.g., the user may understand the power and speed of a river flow during a flood more intuitively in VR than through a 2D visualization.

Providing a digital tool to the stakeholders and policymakers also reduces the need for travel to the affected areas, which contributes to more efficient hazard communication and sustainability. Moreover, the framework facilitates lower barriers to accessing the geohazard information, which can enable a wider range of users to engage in the exploration and understanding of these phenomena. This can be particularly beneficial for researchers, educators, and communities that may have limited access to certain study sites.

The VR visualization framework can serve as a cornerstone for creating VR-based training modules focused on geophysical flow disaster preparedness and emergency planning, potentially setting a new standard for such applications. While certain challenges, like real-time visualization, persist, they can be mitigated by employing simplified numerical models and focusing on smaller, more critical areas impacted by geophysical flow hazards. The possibility of overcoming computational and data processing demands by leveraging high-performance computing and artificial intelligence offers promising avenues for further development.

The study findings have significant implications for designing and evaluating VR applications, particularly those focused on natural hazard preparedness. The results showed that identity priming can enhance user engagement and immersion in VR, which can facilitate learning and behavioral outcomes. However, identity priming can also amplify the emotional impact of VR scenarios, leading to negative consequences such as increased anxiety and stress. Therefore, identity priming should be used with caution and tailored to the specific goals and preferences of the users. Emotional state can affect the perceived realism of VR scenarios, which influences user satisfaction and acceptance. However, emotional state did not directly affect cognitive workload, suggesting that other factors like task complexity and feedback may play a role.

Identification and exploration of practical and theoretical implications arising from the integration of UX influencing factors in VR for communicating NH. The research provides theoretical insights into users' presence, cognitive load, and emotional responses and offers practical implications for designing effective VR experiences for communicating NH. These contributions collectively enrich the fields of UX, NH preparedness, and immersive media experiences, fostering a deeper understanding of user experiences and design considerations in the context of NH.

5.3 Limitations

During the DBR cycle 1, we focused on the subjective evaluation of IDNs in VR only. It's important to note that the scope of this research was limited to a within-subject design, which means that each participant experienced multiple conditions in a randomized order. The sample size of 32 participants was small and may not be representative of the general population of VR users. Case study 1 was specifically designed and optimized for a standalone Oculus Go HMD, which reduced the frame rate and content quality of the VRE. The study did not measure the long-term effects of digital narrative on the users' learning, retention, and transfer of skills learned in VR and did not consider the individual differences among the users, such as prior knowledge, motivation, and preferences, which may influence their responses to digital narrative in VR.

DBR cycle 2, has several limitations that should be acknowledged. First, the sample size of 39 participants was small and heterogeneous, which may reduce the external validity of the results and their applicability to a broader and more diverse VR user population. Second, the study used a single VR device (Oculus Rift S) and a single VR scenario (flood simulation) to assess the effects of wayfinding cues on user-perceived experiences. However, different VR devices and NH scenarios may vary in their levels of immersion, realism, and interactivity, which may affect the users' psychological and psychometric responses. Furthermore, only the quantitative aspect of the experience, i.e., the subjective and physiological evaluations, was measured. Further, studies can incorporate qualitative and behavioral measures to capture a holistic experience of the user. Third, the study did not investigate the long-term effects of wayfinding cues on the users' spatial knowledge, retention, and transfer of skills learned in VR. Future studies may address these limitations by using a larger and more representative sample, comparing different VR devices and VR SGs, and conducting follow-up assessments to evaluate the lasting impact of wayfinding cues on VR learning outcomes.

In DBR cycle 3, throughout the development of the framework, several challenges were identified. Some challenges pertain to the framework's inherent limitations, and others to areas where further enhancements can be made.

One of the challenges faced was real-time VR visualization of the numerical simulations. Most geophysical flows occur in vast areas, and this inherently leads to extensive computational requirements. For instance, the Utvik flooding 2D simulation, with around 120,000 cells, required 122 minutes on a 6-core CPU (i5-9600K @ 3.70GHz) and only 7 minutes on a 4352-core GPU (RTX2080Ti, 11GB) high-performance computing (HPC) for a 25-hour simulation. Furthermore, geophysical flow simulations often generate massive amounts of data, which require extra time to process. This poses a significant hurdle to achieving real-time visualization, as the computational demands of both running the simulations and processing the data are substantial. Consequently, simulations had to be precomputed, limiting users to exploring and visualizing only the data provided in advance.

The affordability of VR hardware has significantly increased. This framework requires a VR-compatible computer and an HMD, which is cost-effective and accessible to public institutions working in hazard management. In addition, while compatibility has been tested with the Oculus Quest 2 HMD, ensuring that the framework can run on a broader range of devices and minimizing the hardware prerequisites is essential for increasing its accessibility and usability among a wider audience in the future.

The UX evaluation conducted for the VRE designed in DBR cycle 3 also identified several limitations, such as a sample size that limited the generalizability of the findings. Future studies should use more extensive and diverse samples to increase the validity and reliability of the results. The study used flash floods as a depiction of NH, which may not capture the variability and complexity of various natural hazard situations such as earthquakes and landslides. Future studies should use various VR environments and scenarios to test the robustness and applicability of the findings. Additionally, the study did not measure the long-term effects of identity priming and emotional state on UX in VR, such as retention, transfer, and attitude change. Future studies should use longitudinal designs and follow-up measures to examine the lasting impact of identity priming and emotional state on UX in VR. Future studies should consider these factors and examine their interaction with identity priming and emotional state in VR.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This research explores the potential of VR as a powerful tool for enhancing the communication of scientific information about NH. By using the Design-Based Research (DBR) approach, this research advances the knowledge of UX influencing factors in VR for NH preparedness and contributes to the field of immersive media experiences. DBR was conducted in three iterative cycles, where the first cycle established the crucial role of narrative elements in VR, providing the basis for further investigations. Based on our conceptual framework, we developed a VRE that combines immersive storytelling with game design elements to investigate the UX. This novel approach not only improved user engagement and experience in the VR environment but also revealed the complex relationship between narrative elements, user engagement, and presence in VR.

The second cycle examined the subtle effect of affordances on users' perceived experiences in VR. Wayfinding cues were added in VR to serve as affordances for NH preparedness, adding complexity to the VR experience. The importance of dynamic wayfinding cues became evident, showing their significant impact on users' physiological and subjective responses. These results highlight the key role of affordances in creating immersive and effective NH preparedness scenarios, offering practical insights for UX designers and educators. Furthermore, we established concepts to show how IDNs can represent complex issues such as natural hazards.

The third and final DBR cycle developed a robust VR framework for visualizing numerical simulations of geophysical flows, overcoming the traditional challenges of risk communication. This cycle integrated realistic numerical models of NH, such as floods in VR. The flexible VR framework allowed the visualization of various geophysical flow scenarios, such as snow avalanches, quick clay landslides, and flash floods. A VR system was designed based on the framework. It was evaluated for UX influencing factors of emotions and identity in VR to assess the effectiveness and usability of the system in improving the users' awareness and understanding of NHs.

The research discusses the implications of VR design and evaluation, focusing on the role of IDNs, affordances, emotions, and identity in VR experiences. The research highlights the potential of VR as a training tool for natural hazard preparedness and other educational applications, as well as a visualization tool for geophysical flow phenomena. The work also provides practical guidelines for VR designers and suggests future directions for VR development.

The research has also acknowledged the limitations and challenges encountered during the study, such as technical issues, ethical concerns, and generalizability of findings. We have suggested directions for future work, such as exploring other UX influencing factors, expanding the scope and scale of the study, and applying the findings to other domains and contexts.

6.2 Future Directions

This research has made significant contributions to understanding the design and evaluation of VR for addressing natural hazards. It presents a VR framework that creates a simulation-based immersive environment that can be used by municipalities and stakeholders for NH preparedness. Despite the significant contributions of this research, there are still many opportunities for further exploration and improvement. Following are some of the possible directions for future work that could extend and enhance the findings and implications of this study:

- Firstly, future research could conduct more extensive user studies, including diverse participant groups and demographics. This could provide a more comprehensive understanding of how user preferences, engagement, and feedback influence the design and evaluation of VR for a positive UX.

- Secondly, longitudinal studies could be employed to assess the sustained impact of IDN-enriched VR experiences over time. This would provide insights into the lasting effects on user perceptions, learning outcomes, and emotional responses.

- In addition, the research focused on traditional narrative elements; future work could explore the incorporation of emerging technologies, such as artificial intelligence, to dynamically adapt narratives based on user interactions and responses.

- Moreover, applying the insights from this research to real-world contexts, such as emergency response training, would be a valuable next step. Understanding how IDN-enriched VR scenarios perform in authentic settings contributes to the practical application of the findings.
- Furthermore, comparative studies could be conducted to assess the effectiveness of IDNs in VR compared to other narrative forms or traditional training methods. This would help position IDNs within the broader landscape of immersive media experiences.
- Additionally, future research could delve deeper into the ethical considerations of employing emotionally evocative scenarios in VR. This includes understanding the potential psychological impact, ensuring participant well-being, and establishing guidelines for ethical VR use.
- Finally, incorporating more advanced biometric measures, such as eye-tracking or facial expression analysis, could enhance the understanding of user responses. This could provide richer insights into the physiological and emotional dynamics during IDN-based VR experiences.

In conclusion, this research contributes to the evolving field of VR by unraveling the intricacies of UX influencing factors in VR. The practical applications, theoretical advancements, and methodological insights generated from this study lay the groundwork for continued exploration and innovation in the realm of immersive technologies and narrative-driven virtual experiences. As technology advances and new opportunities arise, IDNs offer a promising way to create immersive and engaging VR experiences that can benefit various domains and audiences.

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Appendix A

Publication List

Paper 1

Towards a Quality Framework for Immersive Media Experiences: A Holistic Approach

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Abstract. Immersive Media Technologies have emerged as popular media form. Their captivating nature makes them a powerful tool for participation and storytelling in a variety of domains attracting multidisciplinary interest. Existing frameworks for user-perceived quality in immersive media experiences are limited due to their exclusion of narrative dimensions. This research expands upon the current technology-centered Quality of Experience (QoE) framework by including Content Influence Factors based on learnings from IDN. Further, it proposes a conceptual framework for measuring immersive media experiences, which comprise of four constructs: Form, Content, User, and Context. These components are interrelated through their overlapping dimensions, which is discussed through the course of this paper.

Keywords: Interactive Digital Narrative · Immersive Media Experiences · Quality of Experience · Virtual Reality

1 Introduction

Over the years immersive technologies have become inherently interactive and their dependence on narrative has gradually increased [8]. When the end user experiences these technologies it results in Immersive Media Experiences (IME). Underlying concepts and dimensions of IME have been developed from a technological perspective [13, 24, 11] however quality measures are still rudimentary. Current Quality of Experience (QoE) frameworks limit their definition of content to its type (depth, texture, etc.) and reliability. Thereby, excluding the information and experiences it delivers. In turn, also excluding any narrative-based and/or task-based influences of the content on user-perceived quality. For this reason, we believe that assessing quality in Immersive Media Experiences can benefit from the rich scholarship of Interactive Digital Narratives (IDN).

In terms of user-perceived quality, it is not completely clear which factors of an IME are specifically responsible for a users emotion, involvement, and degree of interest. However, immersive media are widely understood from an experiential perspective as a users sense of presence. This framework encapsulates physical, symbolic and psychological dimensions that must be considerd for user perceived quality inside IMEs. We look at immersion, immediacy, and presence alongside quality of experience (QoE) factors to fully encompass an immersive media experience. Given the richness and complexity of these emerging media environments, it is important to understand the dynamism of these contemporary media forms before developing quality frameworks.

QoE measures are commonly used for multimedia and telecommunication services [14]. They are subject to a range of complex and strongly interrelated factors that fall into three categories of *Human*, *System* and *Context Influence Factors (IFs)* [21]. Despite their interest around user experience, existing frameworks remain predominantly system-centric. With our work we want to focus on a human-centric paradigm by taking into account all those factors that reflect on the user's experience. For this, we accept the important of the above mentioned influence factors for our framework but also include *Content Influence Factors* for their role in overall user satisfaction, and QoE.

2 Framework for Measuring QoE for Immersive Environments

This research understands IME as a union of immersive, interactive and narrative. This section discusses our quality framework in terms of its four constructs: *Form*, *Content*, *User*, and *Context*, where we look at its different dimensions and variables as shown in figure 1.

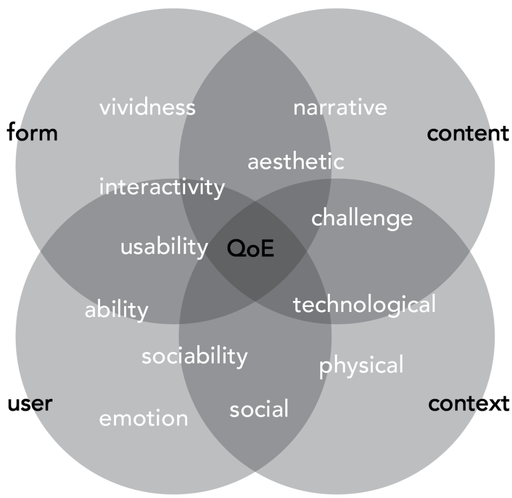

Fig. 1: Quality framework for Immersive Media Experiences (IME)

2.1 Form

We consider form to be the foundation upon which the entirety of IME is built. It comprises of a system-generated world that affords interaction to its users. Appropriating from Steuer, we denote form by its *vividness* and *interactivity*. One is the system's ability *"to produce a sensorially rich mediated environment"*, and the latter is degree to which users can *"influence the form or content of the mediated environment"* [29]. In essence, it is a correspondence between various media technologies to generate immersive-interactive environments.

System

1. **Spatial Presence as Experience Dimension:** A sense of physical presence, specifically *Spatial Presence*, is the "human experience of an immersive virtual environment" [29]. It is what the system grants. Slater [27] associates this with *Place Illusion* (user's response to system immersion) - how a user observes and responds to a simulated environment. Ryan [23] refers to it as a new dimension of *Spatial Immersion* - one that comes from technology not narrative. Elsewhere it is called *perceptual* or *sensory immersion* [32, 16, 2]. The coming together of various system factors to create an illusion of *being* in a virtual world even though one is physically not there.
   In terms of quality, the effectiveness of IME is foremost its ability to deliver a synthetic environment where a user can respond in likeness. System immersion is thus conceptualized as the level of immersion (high or low) directly granted by the system to the user [28, 19]. User-perceived quality is then a sense of presence of a user when he/she are surrounded exclusively by a media technology and provided a rich, continuous stimuli to support their various sensorimotor contingencies.
2. **Vividness as Quality Dimension:** The sensorial encapsulation of the user is ensured by a distinct quality of technology, *vividness* [28, 29]. It is the *"representational richness of a mediated environment ... that is, the way in which an environment presents information to the senses"* [29]. Further expanded into two parts: *sensory breadth* or *realism factor*, which is the number and consistency of inputs; and *sensory depth* or *realness*, which is the quality of richness or resolution of each input. In this research, we consider vividness (extent and fidelity of sensory information) as a user-perceived quality of IVEs that depends on quantifiable system factors of tracking, latency, display persistence, resolution, optics (fov), and spatial audio.

Interaction Interactivity inside IVE derives from its exploratory nature - freedom to explore and actively search. A user is not just a curious onlooker but a perceiver-actor responding to the *affordances* (action possibilities presented by digital elements, artifacts, and objects) of the simulated environment [6]. Considering which, interactivity should be understood as a stimulus-driven variable that depends upon the technological formation of the medium.

Interactivity inside a VE can be quantified under three factors: *speed of interaction* (system response time to user action), *range of interactivity* (number, and extent, of action possibilities with), and *mapping* (system ability to map user input to changes in IVE). The degree to which the interactivity of an IVE, its controller, and feedback mechanisms match the real world has an affect on user's ability in applying natural navigation and manipulation techniques in IVEs.

2.2 Content

We introduce content as a new influence factor in our quality framework for IME. A user removed from his/her immediate context is subsequently immersed into *a reality represented by the medium*, i.e. the broad category objects, actors and events. We argue that an IVE with its inherent interactive qualities is a *live box of action possibilities* produced by the system.

Content, on the other hand, is its *"meaning"*. It is what *"the virtual world purports to be about"* [7]. It is the flow of events, inclusion of social elements, nature of task/activities performed. The overall meaningfulness of the content determines various kinds of presence [15, 25, 10]. Meaning, for the user, is derived from a combination of the content and the context within which the content exists [7]. Users inside IVEs draw signification (meaning) from the aesthetics of the world, the narrative events that unfold, and the activities they perform in it. They take all that as their experience. We divide content into diegetic, non-diegetic, and aesthetic classes of information or experience. For our holistic framework, we will discuss the dimensions of two content factors in specific, i.e. narrative-based and task-based .

Narrative-based: To discuss the influence of narrative factors on quality in IMEs, we can consider the age-old tradition of storytelling [3]. What storytellers achieved through expression, improvisation, theatrics, and exaggeration are now readily available to users as immersive environments produced by computers. Ryan [23] calls it Spatial Immersion (in her triad of spatial, temporal and emotional immersion). IMEs are evolved narrative forms that summon perceptual and sensory faculties. IVE is only a *presentation context* whereas its *narrative context* is the diegetic space of the story that takes place within it [3].

These dimensions are symmetrical to the four narrative-centric factors hypothesized by Rowe et al [22]. These are *narrative consistency* (believability), *plot coherence* (logical order), *drama* (setup-conflict-resolution), and *predictability* (real-world authenticity). The result of which is a *Plausibility Illusion* - an acknowledgement of the truth of the environment [27].

Task-based: The relation between a user's ability and a presented challenge imbues a form of presence called an *experience of flow* [5]. Flow arises when perceived challenges correspond to perceived skills. It is characterized by full involvement, energized focus, and enjoyment. On the contrary, a mismatch between ability and challenge can lead to feelings of frustration and displeasure.

A task inside a VE is determined by its nature and level of challenge (cognitive/motor). Additionally, tasks are also affected by context (e.g. temporal) and depend on the kind of interaction they require, i.e. navigation, selection or manipulation. Task performance improves when a user's ability/skill is matched by the usability of a system. Another important factor (but not a subject of this paper) is the introduction of aesthetic features (e.g. interface graphics, gamification elements, etc.) to enhance user performance. It can be hypothesized that tasks performed inside IVEs influence the emotional state of the users but are also directly influenced by the user's proficiency/ability [31, 26, 1]. .

2.3 User

User, or human, influence factors are deemed influential for the formation of quality [4]. User characteristics, their learning ability and assumed agency play a significant role in shaping their overall perceived quality of an IME. **Characteristics** are demographic attributes as well as perceptual, cognitive and motor abilities of users [12]. Prior experiences of IVEs affect a willful suspension of disbelief as well as allocation of attentional resources [12] in turn, affecting presence. **Other works [33, 17, 9] have identified the effects of age, gender, cultural background, and emotional state on user-perceived quality.**

Due to their characteristic similarity to the real-world, users have a higher chance of learning IVEs [20, 30]. Nash et al. [18] consider navigational knowledge acquisition (spatial ability) as central to learning environments. This may vary across users considering their cognitive performance and perceptual limitations. However, potential for learning can be enhanced when usability aspects of a system are aligned with the goals and mental models of the users to fulfill requirements and tasks.

2.4 Context

Context factors are relevant situational properties that can be broken down into physical, temporal, social, economic, task and technical characteristics [21]. Context factors have considerable effect on the quality levels of any media experience. But since fully immersive media (such as VR) occlude the real-world, we arrive at an inside and an outside. For example, it is worth considering if the user-perceived quality of IME changes with physical locations, e.g. lab versus mall. Similarly, Simulated contextual changes inside virtual environments can also in turn affect user characteristics.

3 Discussion

Immersive Media Experiences (IMEs) are powerful because of the agency they give the end user. They are not mere simulations but entirely new spaces of signification as well. User do not just experience high-fidelity geometries with real-time responsiveness but the meanings those interactions deliver. This is why they require new inclusive measures for quality assessment.

4 Conclusion

This research paper presents a modified quality framework of IMEs. In addition to immersivity and interactivity, the framework draws from theories and approaches in IDN to include narrativity as an important facet. The paper presents a four constructs i.e. Form, Content, Context and User, that determine quality in IMEs. For its practical use, the framework emphasizes on the importance of signification (the meaning delivered) aspects of these experiences for the user. We believe that any user-perceived experience evaluation is incomplete without considering narrative-related and task-related dimensions inside content.

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Paper 2

Increasing User Engagement in Virtual Reality:The Role of Interactive Digital Narratives to Trigger Emotional Responses

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ABSTRACT

Immersive multimedia technologies such as virtual reality (VR) create narrative experiences in the digital medium, thus revolutionizing how people communicate, learn, and think. These Interactive Digital Narratives (IDN) shape end-users' experience with a broad potential for various applications. A fundamental aspect of achieving this potential is the establishment of a positive and engaging user experience. This study investigates how enabling the interactive narrative in a VR setting affects the engagement of the users. The study we base this work on involved thirty-two participants in a controlled experiment where they were asked to explore a designed VR environment, with and without a digital narrative. We observed a significant increase in the participants' level of engagement in the narrative-based environment compared to the non-narrative VR environment. The results showed how the IDN in VR generates an increased emotional response, strengthening the users' engagement, showing that IDN can be considered an essential factor in shaping the positive experience of end-users, thus shaping a better society.

CCS CONCEPTS

• **Human-centered computing → User studies**; **Virtual reality**; • **Hardware → Emerging tools and methodologies**.

KEYWORDS

Virtual Reality; Experience Design; User experience evaluation; User experience design; Immersive Multimedia Experiences; Interactive Digital Narrative; Engagement; presence

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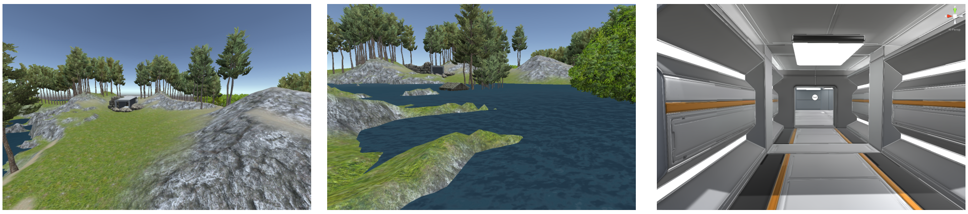
1 INTRODUCTION

Interactive Digital Narrative (IDN) is a form of digital interactive experience in which users create or influence the storyline through their actions [12]. These digitally augmented stories or narrations play an essential role in passing information through interactive digital media hence inaugurating a new form of storytelling called Interactive Digital Narrative [10]. IDN has revolutionized the way people communicate, learn, and think. When incorporated in modern-day immersive multimedia technologies such as Virtual Reality (VR), IDN can be used to enhance learning and training through various applications and platforms such as serious gamification.

VR is an interactive computer-generated experience taking place within a simulated virtual environment [16]. It incorporates auditory and visual feedback but may also allow other types of sensory feedback such as haptic. Because of this sensory feedback, the user becomes visually immersed in a computer-generated three-dimensional VR scene [14]. The past several decades have seen an onset of interest in VR technologies, with this multifaceted domain becoming a central concern in a wide range of disciplinary fields and research contexts [4]. VR has become inherently interactive, and their dependence on narrative has gradually increased [13]. VR can now be used to provide learners with a virtual environment where they can develop their skills through IDN without real-world consequences [5].

Several studies have been performed on evaluation of performance, quality modelling and assessment of VR [2, 3, 15]. Researchers have also proposed various strategies and metrics for VR systems evaluation[7]. Similarly, there is work on defining , designing and evaluating IDN in VR [1, 11]. Studies have been done in defining the dimensions and underlining concepts of VR experiences[16], however, few researchers have worked on modelling and assessing the experience resulting from using immersive and interactive digital narratives (IDN)[6] There are not many studies present that address the influence of IDN and storytelling on VR systems and how it shapes the end user experience. In order to produce positive VR , IDN needs to be incorporated in the design [6].

This research presents design and evaluation of a virtual reality serious game and demonstrates how incorporating IDN in VR serious gaming can shape a better experience and understanding for end users. The research study is part of a project where we intend to create digital twins of natural hazards with knowledge on interactive digital storytelling and human behavior to create immersive user experiences based on real data, realistic scenarios



(a) Non-narrative based VR experience (b) Narrative based VR experience (c) tunnel

Figure 1: Immersive environments showing non-narrative vs narrative VR setups

and simulations. Experiences derived from the VR will be used for preventive and emergency measures to save lives and cost thus shaping society in a better way. In the following paper our goal is to measures the influence of IDN on a VR environment through subjective user evaluation . The main objective of this research is to explore how IDN affect the user experience in an immersive VR environment in terms of user engagement. This is done through an experimental study where subjective evaluations are performed in VR with two groups i.e. non-narrative based controlled group (G1-NN) vs the narrative-based experimental group (G2-N). The following sections present the detailed methodology, results and discussion of the experimental study.

2 METHODOLOGY

2.1 Participants

Our research is done by using participants in a controlled experiment generating data to be analyzed. Our experiment comprised 32 participants between the ages of 25 and 44 (56.25% of them were male and 43.75% were females). Participants were recruited based on their familiarity with computer technologies such as VR. Almost all the participants were skilled in using the computer to some extent, with 43.8% being intermediate users.

2.2 Experimental Setup and Design

VR experience was delivered using a standalone Oculus Go head-mounted display (HMD). Although Oculus Go is a standalone HMD, it has all the components required to provide a fully immersive VR experience. The VR test environment was designed and developed in the Unity game engine installed on a high-performance DELL Opti-Plex 7060. A within-group or repeated measures experimental design was followed where the same participants (n=32) were asked to perform both experiments to test for the level of engagement inside G1-NN vs. G2-N. The independent variables of the study were narrative and non-narrative VR immersive environments. The level of engagement inside the VR was used as the dependent variable. To deal with the order effect, we altered the order in which the participants performed the experiment in each group. Therefore, the order of the two groups was counterbalanced [8].

Group 1 participated in a non-narrative based VR experience in which the user was presented with a real-world landscape designed in the Unity game engine. The landscape showcased part of a small village Utvik, located in Vestland county, Norway, as shown in Figure 1a. An audio track of natural surroundings was embedded in the VR environment to make it immersive and realistic. Participants were free to interact with the surrounding environment; however, they were not asked to perform any specific tasks. Group 2 participated in a narrative-based VR experience. It was the same landscape used in Group 1 (as shown in Figure 1b); however, a narrative was attached to it in such a way that the participants could perform the required tasks inside VR. The participants were presented with a scenario that they are in a small village where flooding is about to happen. Participants were asked to find and enter an underground tunnel and wait for the rescue team to extract them. In this VR test environment, the sound of emergency alarms was also embedded to strengthen the IDN presented to the users. Figure 1b and 1c show overview of the narrative-based VR environment.

The measures of engagement, determined by media content and media form variables (from the ITC-Sense of Presence Inventory questionnaire [9]), were used to evaluate the levels of engagement. The scale included several items about engagement i.e., user involvement, interest in the content of the displayed environment, their general enjoyment of the VR media experience, attention, involvement in the VR, the content of the presentation appeal, arousal, and emotions. Participants used a consistent scoring mechanism (1–5 point Likert scale ranging from "strongly disagree" to "strongly agree") to rate their experience after experiencing the VR.

2.3 Procedures

Volunteered participants were invited to take part in the study. Each participant filled a consent form and demographic information before starting the experiment. Participants were given detailed instructions and a brief demo on using the Oculus Go HMD and touch controller before continuing the experiments. However, they were not made aware of the goal of the experiment to prevent biased results. Participants were asked to wear Oculus Go headsets and explore two experimental conditions in random order. All the participants performed both the experiments. Participants in Group 1 were asked to explore and interact with the environment; however, no particular tasks were assigned. Participants in Group 2 were asked to perform a set of tasks i.e., find an underground tunnel and remove the obstructions to enter the tunnel to save themselves from the flood. After the experiment, they were asked to fill the questionnaire. Approximate time for each experiment per user with the questionnaire took 25-30 minutes to complete. At the end of

Table 1: Summary statistics for two groups (N=32) with 95% confidence interval (where LB stand for lower bound and UP stands for upper bound).

	N	Mean	Std. Deviation	Std. Error	95% CI for Mean		Min.	Max.
					LB	UP		
Group1	32	3.2212	0.66768	0.11803	2.9804	3.4619	1.85	4.62
Group2	32	3.8654	0.63583	0.11240	3.6361	4.0946	2.08	4.85
Total	64	3.5433	0.72367	0.09046	3.3625	3.7240	1.85	4.85

Table 2: Results of Independent Samples T-Test with 95% Confidence Interval (CI)

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Diff	Std. Error	95% CI of Diff	
									LB	UP
Engagement	Equal variances assumed	0.609	0.438	3.953	62	0.00	0.644	0.162	0.970	0.318
	Equal variances not assumed			3.953	61.85	0.000	0.644	0.162	0.970	0.318

the experiment, all subjects were debriefed about the experiment's aim and rewarded with a cinema ticket.

3 RESULTS AND DISCUSSION

Outliers were removed from the obtained data before performing the statistical analysis. Summary statistics of the data was computed, as shown in Table 1 with a 95% confidence interval. An independent Sample T-Test was performed to compare engagement in Group 1 (controlled) and Group 2 (experimental) VR test environment. Results showed that there was a significant difference in the mean scores for G1-NN with Mean=3.2212 and SD=0.11803; and controlled group (G2-N) with Mean=3.8654 and SD=0.11240 with t (62)=3.953 and p = 0.00000052. Results show that engagement for the two groups significantly differed in almost all the analyzed dependent variables. Table 2 shows the detailed results of independent Sample T-Test performed for the two groups.

To determine whether the differences between group means were statistically significant, we compared the p-value to the significance level (α = 0.05) to assess the null hypothesis (H0). H0 states that engagement means are equal for the two groups. The p-value was less than the significance level, so the null hypothesis was rejected. It was concluded that the level of engagement for narrative vs. non-narrative VR experiences is not equal. By examining the group means to check if the differences were statistically significant, confidence intervals for the differences of means were assessed. From the results, it was concluded that participants experienced more significant levels of engagement in the VR experience with IDN. From Figure 2 (see appendix A), it was observed that involvement, enjoyment, and appeal had the most significant difference in means with G1-NN having a less mean value than G2-N VR test environment. The level of attention had the smallest mean difference between the two conditions, which depicts that IDN did not influence it.

4 CONCLUSION

This study aimed to investigate the impact of Interactive Digital Narrative (IDN) in VR and its influence on users' engagement. A controlled with-in subject study was designed to compare measures of engagement in narrative and non-narrative virtual environments. Results showed a significant increase in the overall level of engagement in a narrative-based VR environment giving the users an increased sense of presence. In consequence, to obtain a high sense of presence, the VR environment should be associated with a contextualized and interactive digital narrative, and IDN should be incorporated in VR design. This study was limited to measuring engagement as part of the VR user experience only; however, further studies will be designed to measure the overall experience of end-users in IDN based VR. By carrying these results forward, we also intend to perform research on IDN's essential design elements than can result in an engaging and satisfactory VR experience for end-users.

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A RESULTS

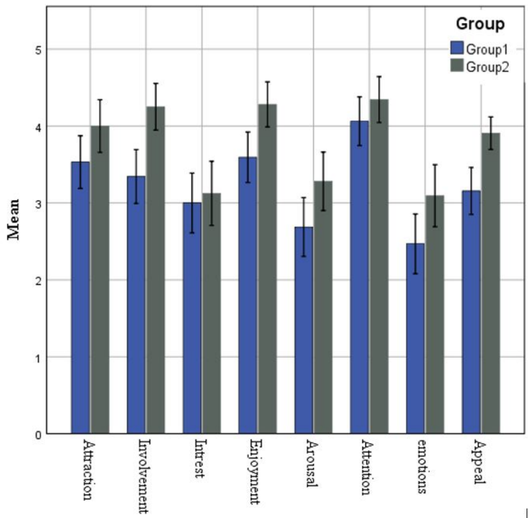

Figure 2: Bar-plot demonstrating the mean with 95% confidence interval for engagement

Paper 3

Paper 4

applied sciences

MDPI

Article

Wayfinding in Virtual Reality Serious Game: An Exploratory Study in the Context of User Perceived Experiences

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Abstract: Extended reality (XR) technologies such as virtual reality (VR) provide a promising alternative for training users through serious games (SGs). VR SGs allow people to train in emergency scenarios and improve their likelihood of survival in high-risk situations. Studies have shown that incorporating design elements such as wayfinding cues enhances the spatial knowledge of users in VR. However, the impact of these wayfinding cues on users' psychological and psychometric behaviors needs thorough investigation. An SG was designed to investigate wayfinding cues' psychological and psychometric effects on user-perceived experiences in an immersive VR environment. Thirty-nine participants experienced three variants of the VR SG using Oculus Rift- S. Participants in the control condition were exposed to the VR with no wayfinding cues, and the experimental groups were exposed to VR with static and dynamic wayfinding cues. Results showed that VR SG with wayfinding cues induced less tension, challenge, and negative affects in users' overall perceived experience. Similarly higher positive affects were observed for the experimental groups with wayfinding cues. It was interesting to observe that there were no significant effects of wayfinding on competence, flow, and immersion; however, heart rate was significantly high in the control group. These findings suggest that wayfinding cues can promote the users perceived quality of experience in the VR.

Keywords: virtual reality; serious games; exended reality; training simulations; user studies; spatial information; perception

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1. Introduction

Extended reality (XR) technologies have evolved into ultra-high-definition, immersive displays due to breakthroughs in data acquisition, data transmission, and playback output devices for media content [1,2]. XR technologies such as virtual reality (VR) can now provide more interactive and immersive experiences due to rapid technological advances such as state-of-the-art full-body motion tracking, gyroscopes, motion sensors, stereoscopic displays, and audio [3]. Although VR is primarily focused on entertainment, recent research studies highlight its implications in numerous other fields such as education [4], healthcare [5,6], and training for disaster preparedness of natural hazards such as flooding [7].

Recent research has shown that VR can administer a narrative-rich, high-fidelity environment that administers a fully immersive and interactive experience for serious games (SGs) such as disaster preparedness and evacuation training for hazardous situations [8]. Although VR SGs can be entertaining, their fundamental purpose is to provide training and education to its users. VR-based serious games offer a secure space to conduct training that would be risky and costly in real life [9]. Studies have been conducted to show that the skills learned during a well-designed VR SGs are long-lasting [10] and depend mainly on the efficiency and wayfinding capabilities of participants [11]. Wayfinding capabilities of the VR users can be enhanced by aiding the spatial knowledge through contextual cues [12]. These contextualized VR games can improve behavioral responses, learning outcomes and evacuation preparedness of users [13]. However, the role of contextual cues such as wayfinding in virtual reality environments (VRE) and its influences on user-perceived quality of experience is yet to be thoroughly researched [14].

In the current study, we designed an experiment to investigate the impact of wayfinding cues on users' behavioral and physiological responses using Oculus Rift S head-mounted display (HMD). Thirty-nine participants were presented with VRE of a flooded city and asked to navigate the city to find a safe zone in a timed scenario. Participants were divided into three groups, i.e., a controlled group without any wayfinding cues, an experimental group with static wayfinding cues (directions only), and an experimental group with dynamic wayfinding cues i.e., assistive lights along with directions. It was hypothesized that wayfinding cues would significantly impact players' physiological and psychological behavior in VRE. Our findings suggest that integrating contextual wayfinding cues in VR training simulations can result in effective VR design and enhance users perceived experiences of these applications.

The research article presents a detailed review of existing studies on VRE wayfinding in the next section. Section 3 explains the materials and methods used in the experimental design, followed by a detailed result section. Section 4 discusses the research findings, followed by a conclusion.

2. Related Work

2.1. Virtual Reality Serious Games for Natural Disasters

Floods are one of the most recurring and damaging natural disasters, universally, with adverse aftermaths and economic losses affecting 1.6 billion people worldwide [15]. In the last 20 years, the Center for Research on the Epidemiology of Disasters (CRED) emergency events' database recorded 7348 natural disasters, claiming approximately 1.2 million lives. The majority of these natural disasters were floods and storms, with an average of 44% and 28%, respectively. Numerous hazardous flooding events in Kyushu, Nepal, Indian, and most recent ones in Uttarakhand have repeatedly reminded humans of this imminent threat. Training people for disaster preparedness or emergency evacuation during floods can reduce the risk of injury and provide a better likelihood of survival.

In contrast to traditional disaster preparedness methods such as drills or seminars, extended reality (XR) technologies such as VR have gained prominence for training people at low cost through serious games (SGs) [16,17]. SGs are defined as "digital games that are used for purposes other than entertainment [18]" VR SGs allow its users to experience digitally simulated scenarios that are impossible to be experienced in the real world due to cost, time, and safety.

These VR SGs engage users by providing life-like scenarios, where they can interact with in-game objects, solve challenges, and become familiar with disaster preparedness methods [19] thus developing life-saving skills. Various VR SGs studies have been performed on the use of VR as a procedural training tool and provide empirical evidence on how VR training skills can be transferred to real-world [20]. Researchers [21] have investigated the impact of game-based learning for flood risk management and researched how training-based SGs can support lifelong learning in people.

Several research studies have focused on understanding the underlying concepts and principles of disaster preparedness in VREs. A VR framework for disaster awareness and emergency response training was proposed by Yusuf Sermet et al. [19] which presented a realistic VR gaming environment to increase public awareness, train and evaluate respondents in emergencies using simulated real-time flooding scenarios. Research has shown that participants experiencing a VR simulation of flooding showed increased motivation to evacuate, seek information, and preference to buy flood insurance compared to the other disaster preparedness methods tested [22].

VR simulates a realistic environment in which a person can navigate and interact freely in the virtual environment. When VR is used to create training simulations such as flood evacuation, complex scenarios are formed inside the VRE. In order to guide the

VR users inside these complex representations, effective design strategies incorporating navigational aids such as wayfinding cues are required [23].

2.2. Wayfinding in Virtual Reality Training Simulations

Wayfinding is defined as "the ways in which people orient themselves in physical space and navigate from origin to destination [24]". When people try to find their way to a destination in a foreign environment, they look for external information that will complement their orientation and navigation processes in this unfamiliar environment. When VR training simulations are designed for flood evacuation, it is difficult for VR users to navigate inside the unfamiliar immersive environment.

Researches have shown that when people evacuate flooded areas, their wayfinding capabilities are crucial in determining the efficiency of their evacuation and hence their chances of survival. Therefore, VR environments should be designed to ensure the transfer of flood evacuation knowledge and skills gained in the VRE to the real world by incorporating wayfinding cues [24]. Jerald [25] used the term signifier to describe wayfinding cues by stating that "any perceivable indicator (a signal) that communicates appropriate purpose, structure, operation, and behavior of an object to a user".

Wayfinding has been used extensively in evacuation and navigation experiments, since it creates affordances by prompting human actions [26,27]. Various studies have investigated design, and implementation of navigation processes such as wayfinding cues inside the VRE for training and evacuation applications [28]. Researchers have suggested that VR game designers need to incorporate wayfinding processes in the VR to aid users in navigating the environment. A recent study proposed several wayfinding affordances that need to be incorporated in the VR design to assist users in constructing mental models in virtual environments [29]. Further studies have shown the use of contextual cues such as wayfinding installations, signage systems to improve users' ability to navigate through the complex VR environments [30].

Various risk mitigation institutes across the globe are adapting VR applications to train users in hazardous situations that cannot be portrayed through traditional methods. A recent study proposed two methods to encourage early evacuations during flash floods by implementing environmental or social cues in VR [31]. Results revealed the effectiveness of using VR to promote evacuation during natural disasters. Panos Kostakos et al. [32] used VR wayfinding installations to investigate the effect of wayfinding lights on behavioral, physiological, and psychological outcomes in indoor fire evacuation scenarios. Results showed that wayfinding affordances could be used to reduce cognitive demands, and wayfinding installations along with visual stimulus can also contribute to improved brain wiring connectivity during the game.

In the past, wayfinding studies have been conducted in indoor environments [31,33] and mostly for fire [27,34,35], underground rock-related hazards safety training [33] and earthquake evacuations [10,14]. These researches have [32] suggested that further studies should be conducted to improve the evaluation process for VR evacuation trainings.

Measuring the impact of wayfinding installations on user behavior and improving their effectiveness is a very important task [36]. Although VR training simulations are becoming well accepted because of the cost-effective way of providing training, few studies have used VR experiments to test flood-related behaviors. Similarly, the validity of user behaviors in VR SGs is not widely researched [31] and is critical as VR applications are increasingly being used for training. Furthermore, the methodologies to measure these VR applications' emotional impact and influence need to be developed and tested.

We used a mixed-method approach to fully capture the impact of wayfinding cues in VRE to gain comprehensive understanding of user behaviors inside the VRE. The research question addressed was: What is the impact of wayfinding cues on users physiological signals and perceived quality of experience in a VR SG for flood evacuation training? Based on the research question, we hypothesized that implementing wayfinding cues in the VR-SG will result in a lower heart rate (HR) and enhanced user perceived quality of experience. Materials and methods used to investigate the emotional impact and influence of wayfinding cues in VR SG is presented in the next section.

2.3. Materials

2.3.1. Participants

Thirty-nine participants (13 females and 26 males; aged 18–54) volunteered to take part in the study. 20.51% of the participants were between the age group of 18–51. Most of the participants (61.53%) were aged between 25 and 34 years old and rest were older than 34. A total of 69.23% of the participants had intermedia computer skills and 23.08% of participants had expert level computer skills. 69.23% of participants had not experienced VR before, however 30.77% percent of the participants had experienced it once or twice before taking part in the study. All the participants were given detailed instructions and thorough demonstration despite their computer and VR skills. Participants with visual disturbances such as colour blindness (color vision deficiency) were not included in the study however, since Rift HMD allows for a comfortable viewing with glasses participants with farsightedness, near-slightness were included as mentioned in Rec. ITU-T G.1035 (05/2020) [37].

2.3.2. Equipment

In this study, Oculus Rift S was used for the VR gameplay. The high level of accuracy and precision (display resolution of 1280 × 1440 pixels per eye) combined with the low cost of the Oculus Rift S HMD and its use of inside-out tracking made it a viable option to be used in this experiment [38]. Five cameras inside the Oculus VR headset enable inside out tracking by tracking and translating the objects to 3D position in real time [39]. Studies show that Oculus Rift S is a powerful tool for research and provides a greater degree of immersivity and reduces motion sickness [40]. The experiment was run on an Asus ROG STRIX gaming laptop with Intel(R) Core(TM) i7-8750H processor with NVIDIA GeForce GTX 1070 graphics card. Figure 1 shows the equipment used in the study.

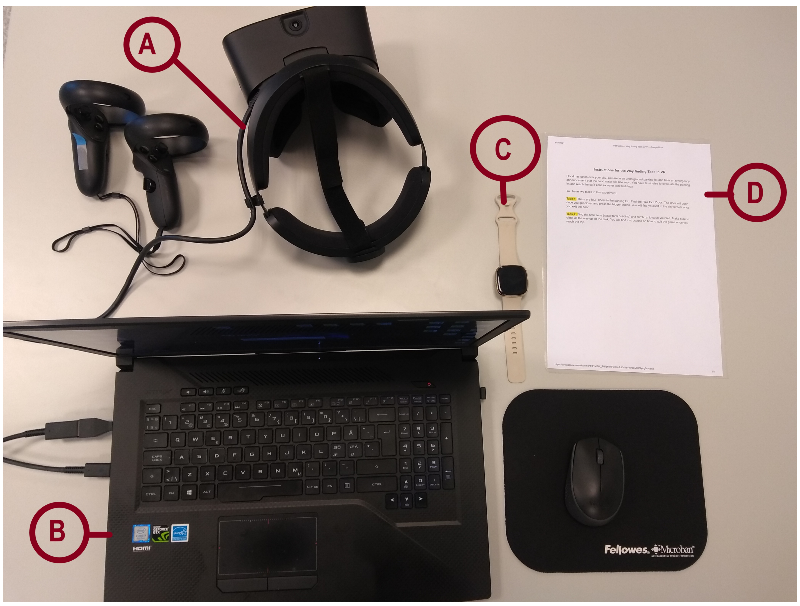


Figure 1. Figure illustrating the equipment used in the experiment: (**A**) Oculus Rift S head-mounted display (HMD) (**B**) Gaming laptop with GeForce GTX 1070 graphics card to run the virtual reality (VR) application (**C**) Fitbit Sense for measuring the HR (**D**) Instructions to perform the tasks and detailed manual to use the VR HMD.

2.3.3. Virtual Reality Environment

The VR training simulation used in this project was developed under a Research project titled "World of Wild Waters" (https://www.woww.no/, accessed on 19 July 2021). This disaster training and emergency preparedness project is part of NTNU's digital transformation initiative to reduce the casualties and effects of the disaster. The VRE serves as an assessment tool to measure the impact of wayfinding cues on users' perceived quality of experience in a serious game setting.

Unity 3D (https://unity.com/, accessed on 19 July 2021). was used to design, develop and render the virtual reality environment using several open-source libraries as shown in Figure 2. In order to ensure proper content delivery during the VR experience, VRE was a development based on the recommendations of ITU-T G.1035 [37]. Spatial audio through Oculus Spatializer Plugin [41] was implemented for a fully immersive audio experience. It allows pinpointing sounds in the VRE accurately. The VRE was deployed on the Oculus Rift S using a gaming laptop. The participants were exposed to the custom designed VRE. Schematics of the VRE experiment are illustrated in Figure 2.

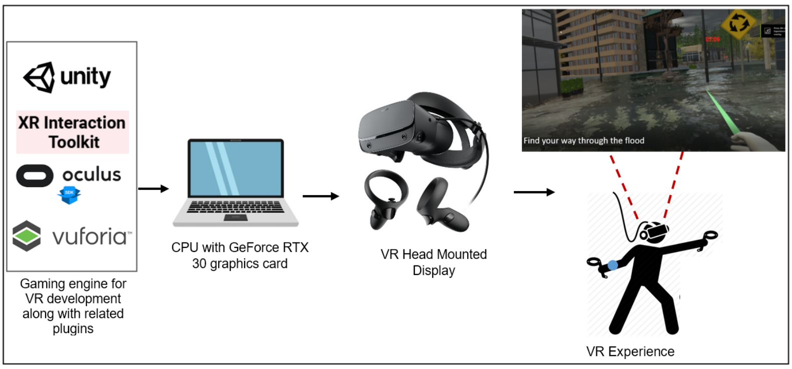


Figure 2. Figure shows the schematics of the experiment. VR SG was developed with unity game engine and deployed on Oculus Rift S via high performance gaming PC.

Participants were exposed to a VRE with an underground parking lot and several routes to navigate through the game, as shown in Figure 3. Once the users were inside the VRE, they found themselves in a flooded parking lot. Participants could hear the sirens and an emergency flood warning and were asked to evacuate immediately by performing two tasks i.e.,

1. Exit the building through the emergency exit door (see Figure 4A)
2. After evacuating the building, reach a safe zone (see Figure 4B) through the flooded city to complete the evacuation process.

In the VRE, the participants could navigate through the city both by physical locomotion and teleportation using HMD controllers. Both types of locomotion were implemented to enhance immersion and avoid simulator sickness [42]. Locomotion techniques were used because of their advantage over constant (walking-like) motion for the estimation of distances, which is an important basic spatial measure in navigation [43].

The level of flooded water was kept lower, so it was easier for the participants to move through the VRE. Underwater effect with partial submersion and water physics were implemented to allow the participants to experience as if they are navigating through real water using Crest water system (https://assetstore.unity.com/packages/tools/particles-effects/crest-ocean-system-urp-141674, accessed on 19 July 2021). A unity plugin called Enviro sky manager was used to implement a dynamic weather system for realistic thunder and rain effects. A time limit of 8 min was given to the participants to complete the tasks. The timer was visible to the participants at all times, as shown in Figure 5.

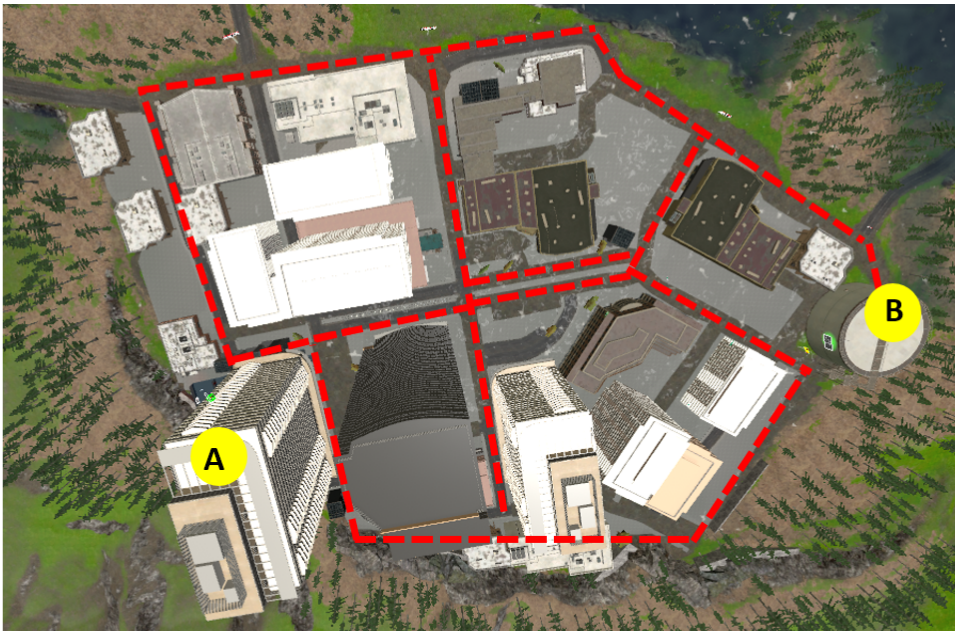


Figure 3. The figure illustrates an aerial view of the VRE. Point A indicates the location of the underground parking lot (starting point of the VR game), and Point B indicates the safe zone (the endpoint of the VR game). Red markings highlight the possible navigation routes that could be followed to complete the evacuation task.

Figure 4. (**A**) Figure illustrates the view of the parking lot in the VRE. Users were asked to exit the parking lot like their first task. (**B**) The figure illustrates the safe zone in VRE. Participants were asked to evacuate the flooded city and reach the safe zone in under 8 minutes to save themselves from the flood.

Figure 5. Detailed view of the VRE as seen by the participants inside the HMD. A timer was displayed in front of the participants while they navigated through the city.

Three variations of the VRE were made in order to examine the impact of wayfinding cues in detail, and only wayfinding cues were varied in the three VREs. These three VRE demonstrated the three experimental conditions as shown in Table 1.

Table 1. Table presents the three experimental conditions investigated with and without wayfinding cues.

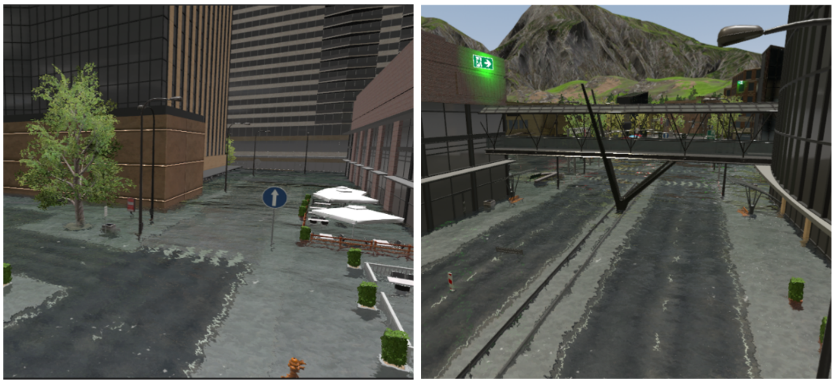
No	Condition	Variations
1	Control Condition (CC)	No wayfinding cues
2	Experimental Condition 1 (EC1)	Static wayfinding cues
3	Experimental Condition 2 (EC2)	Dynamic wayfinding cues with visual stimulus

There were no wayfinding cues implemented in the VRE for the control condition (CC). Static wayfinding cues i.e., signage, were implemented in the first experimental condition (EC1) as shown in Figure 6A. In the second experimental condition (EC2), dynamic wayfinding cues with visual stimulus were implemented as shown in Figure 6B. The design of wayfinding cues such as flashing LED lights were implemented following evacuation design guidelines [28,44,45]. We tested the VREs using a between-group design and an equal number of participants (n = 13). Details of the procedure are given in Section 2.5. To measure the impact of wayfinding on user perceived experiences, physiological and psychometric evaluations were recorded, as explained in the next section.

2.4. Evaluation Measures

2.4.1. Physiological Evaluation

Heart-rate (HR) measurements were recorded for all 39 participants throughout the experiment using the latest Fitbit Sense smartwatch. Fitbit Sense was used to measure the HR with a multi-path optical heart rate sensor that delivers PurePulse 2.0 (https://www.fitbit.com/global/us/products/smartwatches/sense, accessed on 19 July 2021) as shown in Figure 7. It offers continuous heart rate tracking and tracks heart rate variability (HRV), which varies between each heartbeat. The Fitbit devices have been used in several studies and shown to produce consistent and reliable results [46,47]. Several studies have reported the computational precision of HR through a photoplethysmogram (PPG) sensors used in Fitbit sense [48].



(A) (B)

Figure 6. (**A**) Figure shows the directional wayfinding cues used in EC1. Signage system was implemented throughout the VRE to guide the users to safe zone. (**B**) Figure shows the wayfinding cues with visual stimulus used in EC2.

Figure 7. Fitbit HR sensor showing multi-path optical heart rate sensor.

2.4.2. Psychometric Evaluation

A post-test game experience questionnaire (GEQ) was used [49,50] to collect user perceived experiences after the VR experiment. GEQ is widely used in assessing the game experience of end users in virtual environments [51] and contain four modules: (1) the core questionnaire; (2) the social presence module; (3) the post-game module; (4) the in-game module.

All modules are meant to be administered immediately after the game session has finished. The in-game experience core module probes the players' feelings and thoughts while playing the game and was used in this study. It measures game experience as scores on seven components i.e., Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge [49], as shown in Table A1. Details of the results collected from the modules is presented in the result section.

In addition to the GEQ, we used a pre-study questionnaire to gather demographic information about participant age, gender, nationality, and education. The questionnaire also measured sociodemographic information such as familiarity with VR games, computer skills, and familiarity with evacuation drills. The questions categorized in relevant categories are presented in Appendix A Table A1.

Participants rated their experience independently on a category scale using the Absolute Category Rating (ACR) System as recommended by ITU-T P.910 [52] as shown in Table 2. Player competence was measured using five questions. Immersion was captured through 6 questions. The flow was captured by measuring attributes. Tension was measured using players' annoyance, irritability, and frustration while playing the game.

Challenge was measured through constructs like the challenge, time pressure, and effort required by the player while experiencing the VRE.

Table 2. ACR used in this study.

Absolute Category	Rating Scale			
1	2	3	4	5
not at all	slightly	moderately	fairly	extremely

2.5. Procedure

Interested participants joined a volunteer list by signing up for the experiment. Information about their age, gender, educational background, visual disturbances, and availability to attend the experiment was collected. Selected participants were informed through email and, upon confirmation, notified about the venue and time. The experiment was held at Sense-IT lab at the Department of Electronic Systems, Faculty of Information Technology and Electrical Engineering, NTNU in Norway.

On the day of the experiment, participants were welcomed in the lab and briefed about the COVID Standard Operating Procedures (SOPS) they were supposed to follow. Once comfortable, the participants signed the consent form and were informed about the scope of the experiment and the content of the VR SG. Participants were asked to wear the Fitbit sensor, and the baseline HR reading was recorded. Next, they were presented with written instructions on using the Oculus Rift S and its controllers.

Participants played a short demo VR game to learn to use the Oculus Rift S HMD's controllers for locomotion and teleportation inside the VRE. To ensure participants' safety, a Guardian Boundary was set up inside the Oculus around the lab's play area of 4 m $\times$ 6 m. The virtual guardian boundary helped the participants stay inside the designated play area and appeared inside the VR when the participants crossed the designated area.

After completing the demo, participants were randomly placed into one of the three experimental conditions(CC, EC1 or EC2). Before starting the task, participants were briefed about the tasks, both orally and in written form, by the experimenter. They were shown the map of the game before and during the game . Details of the tasks given to the participants was as follows:

Flood has taken over your city. You are in an underground parking lot and hear an emergency announcement that the flood water will rise soon. You have 8 min to evacuate the parking lot and reach the safe zone. You have two tasks in this experiment.

- Task 1: There are four doors in the parking lot. Find the Fire Exit Door. The door will open once you get closer and press the trigger button. You will find yourself in the city streets once you exit the door.
- Task 2: Find the safe zone (water tank building) and climb up to save yourself. Make sure to climb up on the tank. You will find instructions on how to quit the game once you reach the top.

Participants put on their HMD and played the VR SG as shown in Figure 8.

Figure 8. Participant wearing Fitbit HR sensor and Oculus Rift S HMD attached with the high performance gaming PC during the experiment.

After the participants finished the VR experience, their HR was re-recorded using the Fitbit. Participants were asked to complete the GEQ. HR device was removed after the last step. It took approximately forty minutes (or less) for the whole experiment to be completed. Participants were compensated with a cinema ticket for their time and effort. Results from the study are presented in the following section.

3. Results

3.1. Physiological Evaluation

Figure 9 demonstrates the time series scatter graph of HR mean values between the three experimental groups. Preliminary inspection of the graph illustrates higher HR values (mean = 97.69) in the control group with no wayfinding during the VR experience, i.e., the section marked with red dotted lines. Participants in the experimental group with static and dynamic wayfinding exhibited a similar trend, with mean values of 80.5 and 79.8, respectively (Table 3). ANOVA was applied to examine any significant effects in the three groups, and results showed that the HR for the controlled group with no wayfinding was significantly higher, $p < 0.05$ (see Table 4) than the experimental groups.

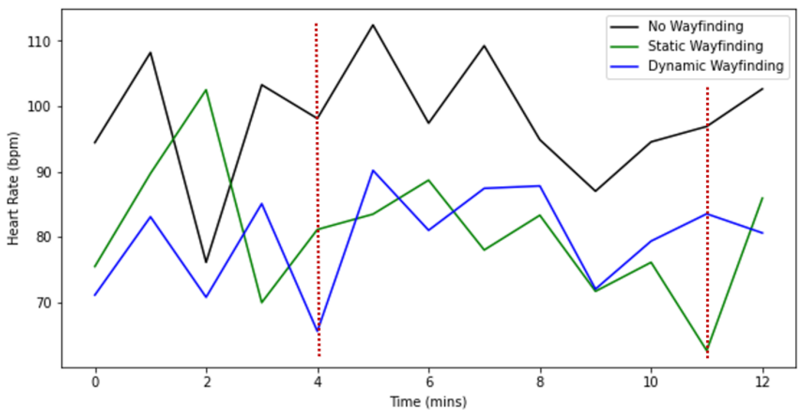


Figure 9. The graph illustrates HR data (beats per minute) recorded using an advanced HR sensor during the training and testing phase. The *x*-axis shows time elapsed in minutes. HR data between the red checkpoints exhibit the HR during the actual VR experience for the three groups.

Table 3. Mean scores of HR for the three groups.

	Control Condition (n = 13)		Experimental Condition 1 (n = 13)		Experimental Condition 2 (n = 13)	
	Means	**SD**	**Means**	**SD**	**Means**	**SD**
Heart Rate	97.69	9.60	80.53	10.134	79.83	7.57

Table 4. Results from one-way Analysis of Variance (ANOVA) for the HR measurements of the three groups.

		Sum of Squares	df	Mean Square	F	Sig.
Heart Rate	Between Groups	2660.839	2	1330.419	15.818	0.000
	Within Groups	3027.957	36	84.110		
	Total	5688.796	38			

3.2. Psychometric Evaluation

Game experience questionnaire [53] was issued to record the psychometric data in the three groups (n = 39), i.e., one control group (CC) and two experimental groups (EC1, EC2) where each group had 13 participants. A one-way analysis of variance (ANOVA) was performed to compute the effect of wayfinding cues on the users' perceived quality of experience using seven metrics [53] (Appendix A Table A1).

Control group with no wayfinding cues exhibited a significant main effect on ratings of feeling *challenged*, $F(2,36) = 4.907$, $p = 0.013$. Post hoc comparisons using the Tukey HSD test on feeling challenged indicates that the mean score for the CC (M = 2.5846 SD = 0.51291) was significantly different from the EC1 condition (M= 1.8769 SD = 0.58045). However, the EC1 (M = 2.3077 SD = 0.64091) did not significantly differ from CC and EC2 conditions as shown in Table 5. These results indicate that the control group with no wayfinding perceived the VRE as challenging compared to the two experimental groups.

The test also revealed a statistically significant difference in mean scores of tension between at least two groups ($F(2,36) = 15.700$, $p < 0.001$). Tukey's HSD test for multiple comparisons found that the mean value of tension was significantly different between CC and EC2 ($p < 0.001$, 95% C.I. = [0.6490, 1.6490]). There was no statistically significant difference between the experimental groups ($p = 1.000$). These findings reveal that the level of tension was higher in the group with no wayfinding cues. However, there was no difference in the level of tension or annoyance in the two experimental groups with static and dynamic wayfinding installations.

For positive and negative affect, the significance level of $p < 0.05$ was observed for the three groups, and mean scores for positive affect and negative affect in CC were significantly different from EC2 (see Table 5). Although there was a difference in means for immersion, flow, and competence, ANOVA did not exhibit significant main effects of feeling immersed, competent, and inflow during the VRE as shown in Figure 10.

Table 5. Mean scores of GEQ metrics for the three groups.

	Control Condition (n = 13)		Experimental Condition 1 (n = 13)		Experimental Condition 2 (n = 13)	
	Means	**SD**	**Means**	**SD**	**Means**	**SD**
Challenge	2.58	0.51	2.30	0.64	1.87	0.58
Tension	2.10	0.59	0.79	0.73	0.79	0.71
Positive Affect	2.44	0.68	2.78	0.77	3.27	0.46
Negative Affect	1.46	0.49	0.73	057	0.44	0.44
Competence	2.33	1.06	2.21	0.82	2.70	0.50
Immersion	2.66	0.69	2.91	0.72	3.03	0.51
Flow	3.01	0.51	2.70	0.60	2.67	0.75

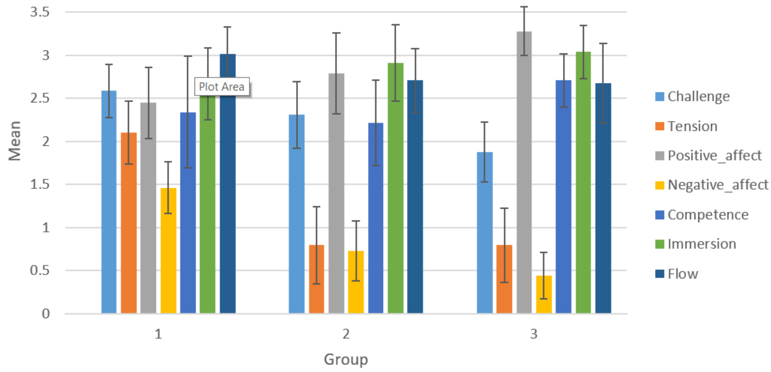


Figure 10. Clustered bar mean of GEQ items administered in this study.

4. Discussion

Recent developments in immersive multimedia technologies have allowed VR SGs to be used in training people for disaster preparedness. The present study was designed to compare the perceived experiences of participants in an immersive VR training simulation depicting a stressful flooding scenario by controlling the experimental conditions with static and dynamic wayfinding cues. Three groups of participants played the same VR game, with and without wayfinding cues guiding them to the safe zone. We hypothesized that participants in the experimental group with dynamic wayfinding (assistive lights and signage) would have a higher perceived experience than those in the control group. Furthermore, we hypothesized that participants in the control group would exhibit higher heart rates as compared to the two experimental groups due to a lack of wayfinding cues. We used Fitbit Sense to perform a physiological evaluation through HR measurements and a post-test GEQ questionnaire for psychometric evaluation to measure the user-perceived quality of experience inside the VR game.

4.1. Effects of Wayfinding on Physiological Evaluation

Results from the ANOVA test demonstrates that the HR values were significantly higher for the control group with no wayfinding while lower for the two experimental groups with wayfinding cues. These findings suggest that the presence of wayfinding cues in EC1 and EC2 may have helped the users to create spatial knowledge of the immersive VRE while navigating through the environment, thus lowering their cognitive workload [30,54]. A related study supports these findings [32] in which the HR of 17 users in two groups was observed during a navigation task in an underground tunnel. The study found HR to be significantly higher in the experimental group exposed to directional signs in the underground tunnel. Physiological measures observed in the present study suggest that implementing wayfinding cues in VR training simulations can positively create mental models inside users' brains, thus lowering the cognitive load and improving their perception of the immersive VR system.

4.2. Effect of Wayfinding on Psychometric Evaluation

Effects on challenge: Challenge was used to measure the impact of wayfinding cues on the user-perceived experience of VR application used in this study, since the challenge is a crucial metric to evaluate the gameplay experience [55]. Wayfinding cues were found to substantially elevate the element of challenge in controlled conditions, as shown in Table 6. The mean values for the challenge were significantly lower for EC2 with dynamic wayfinding cues as compared to the other two conditions. Our findings are consistent with the existing research, which states that players use emotional and cognitive efforts to understand the disposition of the game and solve the challenges presented to them [56]. Since

EC2 in this study presented the participants with wayfinding cues in the VR environment, their cognitive ability to perceive the sense of direction inside the VR was better; hence they felt less pressured. Similarly, they had to put less effort and perceived the overall experience to be less challenging as compared to the CC with no wayfinding. For EC1, the mean values of challenge were between CC and EC2 and can be explained by the fact that static cues were used in the VR experience and didn't grasp the participants' attention when they were stressful in the VRE.

Table 6. One-Way ANOVA results showing the significance of wayfinding on users perceived behavior.

		Sum of Squares	df	Mean Square	F	Sig.
	Between Groups	3.307	2	1.653	4.907	0.013
Challenge	Within Groups	12.129	36	0.337		
	Total	15.436	38			
	Between Groups	14.821	2	7.410	15.700	0.000
Tension	Within Groups	16.991	36	0.472		
	Total	31.812	38			
	Between Groups	4.537	2	2.269	5.286	0.010
Positive Affect	Within Groups	15.452	36	0.429		
	Total	19.990	38			
	Between Groups	7.176	2	3.588	13.878	0.000
Negative Affect	Within Groups	9.308	36	0.259		
	Total	16.484	38			
	Between Groups	1.707	2	0.853	1.233	0.303
Competence	Within Groups	24.917	36	0.692		
	Total	26.624	38			
	Between Groups	0.927	2	0.464	1.090	0.347
Immersion	Within Groups	15.321	36	0.426		
	Total	16.248	38			
	Between Groups	0.911	2	0.455	1.122	0.337
Flow	Within Groups	14.609	36	0.406		
	Total	15.520	38			

Effects on Tension: Feelings of annoyance, irritation, and frustration during the gameplay can lower the quality of perceived experience in users. VR serious games should be designed in such a way to lower the feelings of annoyance and tension [57] to improve the perceived user experience. Our study found that the level of tension was significantly lower in experimental groups, i.e., EC1 and EC2, compared to the control condition with no wayfinding. Since the VRE was kept consistent in all groups except for the wayfinding cues, we can deduce that the participants in these groups perceived the VR simulation as less annoying to navigate due to wayfinding. The results are supported via a study by Lin et al. [34]. Other research studies [34,58] have demonstrated similar results of lower tension and annoyance in spatially oriented VR applications in various domains.

Effects on Positive and negative Affects: Wayfinding cues were found to considerably elevate the positive affects and lessen the negative affects on the users in the VR environment [34]. We measured the positive affects through their level of enjoyment, contentment, fun, and happiness. Positive affects were highest (mean = 3.27), and negative affects were lowest (mean = 0.44) in the EC2 with dynamic wayfinding as compared to the other two groups (see Table 5).

Effects on Competence: Effects of wayfinding on competence were also observed. Although there were some differences in the mean values, our results did not show any significant effects of these three metrics on the participant's perceived experience in VR. All the participants felt successful and competent while playing the VR simulation and reached their target.

Effects on Immersion: Various studies have shown that immersion inside a VR environment can be increased by increasing spatial affordances [59,60]. However, our study showed no significant differences in immersion in all the groups, although the mean value of immersion was slightly higher in the EC2 condition. These results are in alliance with a study that explores the effects of wayfinding affordances in underground facilities during a fire emergency [32].

Effects on Flow: The flow inside a game is attributed to participants' concentration in the game, how they forget about the outer world and things around them, and the loose notion of time. We observed no significant differences in the three groups for flow measures. However, the mean value of flow in CC (Mean = 3.01, see Table 5) was higher than the experimental conditions. This abnormal increase in the flow in the no-wayfinding control condition can be explained by the fact that there was no guidance inside the VR. Hence, participants were more concentrated on the end goal. They lost the notion of time and surroundings since they were in a stressful situation (timer, sirens, and announcements in the background) and wanted to exit immediately.

The effects of immersion and flow did not show any significant differences in the study on VR training in stressful situations and align with our results [61]. This can be explained by the fact that VRE was kept consistent for all the groups and only wayfinding cues were varied [62].

This particular study investigates user behaviors in both indoor and outdoor VR settings (Task 1 and Task 2 in our study; see figure for more details Figure 4). We can conclude that carefully installed cues in VR training applications can help reduce tension in users, thus improving their overall perceived experience. The present study advances the understanding of wayfinding on users' psychological and psychometric behaviors and provides essential design implications. Further research could be done to explore the impact of wayfinding on simulator sickness in VR and how it correlates with the physiological and psychometric metrics. The findings can be used to support building better VR SGs for evacuation training.

5. Conclusions

The present study aimed to investigate the impact of wayfinding cues in a VR SG for disaster preparedness. Three groups of participants were asked to perform two tasks while navigating through a flooded VR simulation. Physiological and psychometric evaluation was performed to observe the effects of wayfinding cues on their HR and perceived VR experience. We found statistically significant differences in the HR of participants in the two experimental conditions with wayfinding cues (EC1 and EC2) compared to controlled conditions with no wayfinding cues (CC). However, there was no significant difference between EC1 and EC2. In terms of user-perceived quality of experience, we found that participants found it more challenging and tension-inducing to navigate through a flood simulation without wayfinding cues. The present study suggests that contextual cues are an essential element in VR SG design, and carefully introducing these contextual cues can increase the affordance of end-users and thus their overall perceived experience. This may improve the users' performance and learning outcomes from VR training simulations. Future studies may attempt to use advance physiological evaluations, such as electrodermal activity, and in depth analysis to better understand the relationship between immersive environments, training, and affordances.

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Institutional Review Board Statement: The experimental study followed a strict protocol developed based on NTNUs standard ethics regulations, especially for experiments in XR involving human participants. The Research protocol considers the ethical requirements for the experiment, including privacy issues. The research protocol was evaluated and approved by the NTNU Sense-It team leader A. Perkis on 15 July 2020 under project number 81771250. The evaluation concludes that no formal approval is required from the NTNU ethics committee. The privacy issues are taken care of by the Information Sheet and the participant consent form.

Informed Consent Statement: Written Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Dataset generated during the study is avalible at https://github.com/shafaq41/VR_wayfinding accessed on 19 July 2021.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

XR	Extended reality
VR	Virtual Reality
SGs	Serious games
HMD	Head mounted Display
VRE	Virtual Reality Environments
CRED	Center for Research on the Epidemiology of Disasters
HR	Heart Rate
CC	Control Condition
EC1	Experimental Condition 1
EC2	Experimental Condition 2
HRV	Heart Rate Variability
GEQ	Game Experience Questionnaire
ACR	Absolute Category Rating
SOPS	Standard Operating Procedures
ANOVA	Analysis of Variance

Appendix A. GEQ Questionnaire

Table A1. Post-Test GEQ Questionnaire.

	Questions	
Competence	Q2	I felt skilful
	Q10	I felt competent
	Q15	I was good at it
	Q17	I felt successful
	Q21	I was fast at reaching the game's targets
Immersion	Q3	I was interested in the game's story
	Q12	It was aesthetically pleasing
	Q18	I felt imaginative
	Q19	I felt that I could explore things
	Q27	I found it impressive
	Q30	It felt like a rich experience
	Q5	I was fully occupied with the game
	Q13	I forgot everything around me

Table A1. *Cont.*

Questions		
Flow	Q25	I lost track of time
	Q28	I was deeply concentrated in the game
	Q31	I lost connection with the outside world
Tension	Q22	I felt annoyed
	Q24	I felt irritable
	Q29	I felt frustrated
Challenge	Q11	I thought it was hard
	Q23	I felt pressured
	Q26	I felt challenged
	Q32	I felt time pressure
	Q33	I had to put a lot of effort into it
Positive Affects	Q1	I felt content
	Q4	I thought it was fun
	Q6	I felt happy
	Q14	I felt good
	Q20	I enjoyed it
Negative Affects	Q7	It gave me a bad mood
	Q8	I thought about other things
	Q9	I found it tiresome
	Q16	I felt bored

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Paper 5

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Investigating the user experience of IDN based virtual reality environments for solving complex issues

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ABSTRACT

Interactive Digital Narratives (IDNs) have evolved as a medium to address complex societal challenges due to its integration in advance technologies such as VR. Recent research has shown that VR provides a suitable environment to implement IDNs allowing the end users to experience narratives in a systematic and participatory setting. However, research is needed to understand the perceived user experience of these narrative experiences. This research highlights the role of IDNs in VR designed for natural hazard risk mitigation and how it affects the perceived user experience. we present two case studies quantifying the user experience of an IDN-based emergency preparedness VR system for solving the complex issue of natural hazards. The results demonstrate how spatial presence, cognitive behaviour and engagement is positively influenced by incorporating IDNs in VR. The research is part of a project called World of Wild Waters (WoWW) and illustrates the importance of narrative representations in VREs showing that IDN can be considered an essential factor in shaping the positive experience of end-users.

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1. Introduction

The application of Interactive Digital Narratives (IDNs) for solving complex issues such as natural disasters, pandemics, or global warming is slowly evolving. New practices and methods have been developed to represent, experience, and comprehend these issues via immersive media technologies, such as Virtual Reality (VR) (Ryan, 2003). Research has shown that VR, as a narrative-rich and high-fidelity environment (Koenitz & Knoller, 2017), can administer immersive and interactive experiences and complex simulations (Checa & Bustillo, 2020).

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These VR environments (VREs) can be simulated for different training types to cater to pandemics, emergency preparedness, and disaster management. They provide a cost-effective and efficient way of training people for complex situations and scenarios (Harvey et al., 2019). Skills learned during these immersive and virtual trainings are long-lasting (Lovreglio et al., 2017) and these contextualised VREs can improve behavioural responses and learning outcomes, for example for evacuation preparedness of users (Vasey et al., 2019). Recent research in IDN has also shown that combining VR experiences with IDN practices can play a prominent role in creating an informed perception of complexity by providing the end users with a rich and interactive immersive experience (Koenitz et al., 2021). However, there is limited research on evaluating the user experience of IDN-based VRE.

A fundamental aspect of achieving this potential is to perform user experience studies that can aid in improving the design, development and evaluation methodologies of these immersive IDNs(Reyes, 2018).

The research presented in this paper tries to bridge this gap and present two consecutive case studies which are part of the interdisciplinary project World of Wild Waters (WoWW).[1] The project aims to bring together knowledge on Natural Hazard's (NH) physical and statistical behaviour with digital storytelling and human behaviour to create immersive user experiences based on actual data, realistic scenarios, and simulations. WoWW aims to be the future tool for analysing and communicating the complex cause and effect of potential NH such as floods and landslides, with the main objective to increase the understanding among planners and decision-makers to better design and implement systems that save lives and costs.

WoWW has five work packages (WP) where

- WP1 is responsible for simulating realistic extreme weather events by analysing spatial and temporal dependencies within extreme weather events (rainfall, temperature, wind, etc.).
- WP2 creates realistic flood simulations via hydrological modelling and visualises flash floods in steep rivers.
- WP3 investigates the modelling and Visualization of run-out Flow Landslides of Quick Clay.
- WP4 aims at creating IDN-based VR experience based on the visualised simulations of floods and landslides provided by WP2 and WP3. The aim is to propose a methodology for design, modelling, and assessment of immersive virtual environments using IDNs targeting natural hazards (Brunnström et al., 2012). Furthermore, the WP investigates how enabling the interactive narrative in a VR setting affects the users' engagement.

[1] https://www.woww.no/.

WP5 is responsible for measuring the risk perception of these IDN-based VR experiences. The project's overall aim is to form IDNs in a complex VR setting and solve the problem of natural hazards by providing digital twins of floods and landslides.

This paper presents two studies as part of WP4, measuring the user experience of immersive media and the influence of affordances in narrative setting. The first case study investigated the role of IDNs in a virtual reality environment (VRE) and how this increases the end users' presence and level of engagement. The study hypothesised that narrative-based VR provides a higher sense of presence and engagement. A subsequent study was designed to strengthen the results obtained from the first study by investigating the influence of affordances on user behaviours. This study investigated how user-perceived experiences are affected by spatial affordances in IDN enabled VREs, where the primary purpose is to train the users for disaster mitigation. The study hypothesised that users feel a positive experience in VRE with spatial affordances. This is an ongoing study, however the case studies presented here will contribute to design and evaluate practices for VR. Furthermore, the work gives directions to researchers looking to integrate IDNs in VR environments for complexity representations, since the VRE is designed specifically for flood mitigation and training.

The following section presents the background literature and related works. Sections 3 and 4 present the case studies in detail, and the last section highlights the conclusion and future works.

2. Related work

2.1. IDNs in immersive media technologies

Narrative has been used to record, communicate, and comprehend human existence. However, with technological advances the traditional means of narratives are not adequate for these tasks. Narratives are integrated into digital media that changes according to user input, thus called IDNs (Koenitz, 2010). IDNs are defined as "expressive narrative forms implemented as a computational system and experienced through a participatory process" (Koenitz, 2015) which can be realised in many ways, including gaming, interactive films, and immersive media technologies (Koenitz et al., 2020).

Immersive media technologies such as Augmented Reality (AR), Mixed Reality (MR), and VR emulate the real world through digital or simulated content, resulting in immersive experiences (Greengard, 2019). Those immersive media provide different levels of immersions based on the used technology (Milgram et al., 1995), as explained in Figure 1.

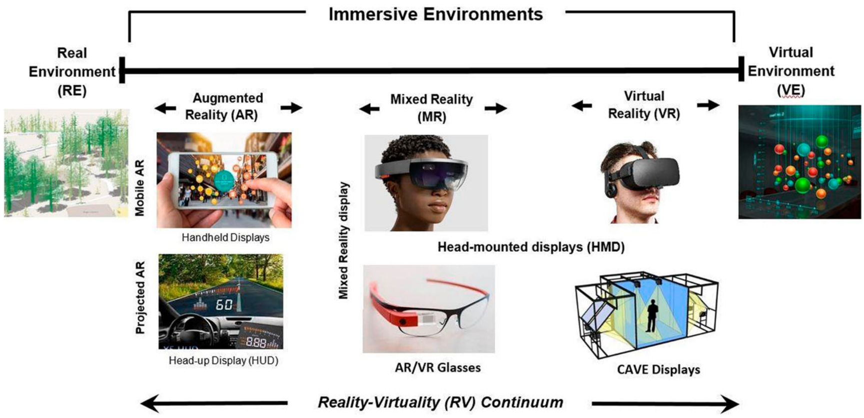

Figure 1. Milgram's VR Continuum (Milgram et al., 1995) modified to adapt existing immersive environments (Irshad et al., 2019).

AR superimposes digital content on the real environment, achieving that the users are not fully immersed in the augmented environment but are aware of their surroundings (Billinghurst, 2021). In MR, the physical and virtual objects coexist and can interact in real-time (Milgram & Kishino, 1994). Finally, VR provides a fully immersive experience to the end-users because they are enclosed in a computer-generated simulated world (Zheng et al., 1998).

Virtual Reality is " … a real or simulated environment in which a perceiver experiences telepresence" (Steuer, 1992). VR offers a narrative-rich and cost-effective tool to study and replicate interactions in a controlled environment (Sherman & Craig, 2018). In the past years, VR has diverged into various domains such as education, healthcare, culture, politics, exercise therapy, training, and learning (Checa & Bustillo, 2019). VR through spatial and immersive computing is revamping how people work in their everyday lives, learn new things, connect with others, and play by bridging the gap between physical and digital worlds (Tham, 2018).

VR can provide users with a virtually simulated environment to develop their skills without the real-world consequence, thus making it a suitable medium for narrative representation of complexity (Koenitz et al., 2020). Complex phenomenon such as natural disaster preparedness can be represented inside VR environments, where users can afford several choices and experience several outcomes based on their actions.

Various literature studies have been performed on the adoption of VR as a procedural training tool and provide empirical evidence on VRs potential to transfer training skills to real-world scenarios (Grassini et al., 2020; Holly et al., 2021). Researchers have investigated the impact of immersive learning for flood risk management and found that training-based VRs can support life-long learning in people (Breuer et al., 2017). A study by D'Amico et al. (2022) proposed a system for increasing knowledge acquisition and self-efficacy in

VREs by integrating narrative and training objectives. Results of their study showed an increase in efficacy and safety knowledge of users. The study suggests that VRE can be exploited for increasing awareness and disaster preparedness in users.

2.2. Evaluating narrative experiences in VREs

Narrative experiences inside the VRE can be measured by evaluating VRs inherit properties such as immersion, perception, and interactivity (Livatino & Koffel, 2007).

Immersion is partial or complete suspension of disbelieve and is experienced when the user perceives being physically present in the digital world surrounded by images, sound, and other stimuli (McMahan, 2003). The greater the suspension of disbelieve, the greater the degree of presence. Presence is a subjective measure and is defined as the sense of being in the VR environment (Nilsson et al., 2016). Users experience presence when they interact with the multimodal simulations such as images, sound, and virtual objects inside the virtual world (Sherman & Craig, 2018). Sense of presence or sense of being in the virtual environment can only be achieved when the user is involved and immersed inside the VRE (Gutierrez et al., 2008).

The inherit properties of VR systems i.e. presence, flow, and immersion have been shown to improve enjoyment and performance inside the system, thus creating an overall positive user-perceived experience (Ryan, 2008). They can be measured through subjective and objective measures and depicts the user's overall experience with the system (Rebelo et al., 2012).

Several studies have been performed to evaluate the user experience of VREs. Gorini et al. (2011) investigated the role of immersive technology and narrative on user's sense of presence. Results from the experimental study found that immersion and narrative are important in creating a positive VR experience. Immersion increases the place illusion, while the narrative contributes to generating an emotional response and strengthening the subjects' sense of inner presence.

Gupta et al. (2020) designed and evaluated a VR system with interactive storytelling. The users were able to experience role taking and character identification. Their research identified design patterns to support desired behaviours of users in an interactive narrative-rich environment. The study suggests that developing new methods for integrating IDNs in immersive environments can enhance the user's behaviour in narrative experiences.

Reyes (2018) suggests a methodology for measuring the user experience of IDN in Cinematic Virtual Reality. She proposes merging HCI evaluation techniques, such as observation grids, questionnaires, and a semi-structured interview with IDN user dimensions, such as agency, immersion and transformation to gather qualitative and quantitative data. The data presented overview of the user experience, in terms of system usability, narrative and perceptive immersion.

2.3. Spatial affordances in narrative experiences

In VRE, users perceive the virtual environment in terms of their ability to interact or perform actions. This perceived possibility of performing actions in an environment is termed as affordance (Gibson, 1977). VRE can implement spatial cues, such as audio and visual cues, to help users determine the function of objects inside a VRE. These cues should inform the user of their usage and function (Norman, 2004).

Regia-Corte et al. (2013) evaluated the perception of affordances in VRE. They conducted a study to investigate how the users perceive certain actions in VR as compared to a real environment. Their results revealed that users perceive affordances of everyday actions in VRE as they perceive them in real life, and these perceptions are influenced by environmental (slanted surface, position) and user factors. The study concluded that affordances in VR should be studied further to understand the effects of design on VRE users.

Shin et al. (2021) conducted research to better understand the effects of spatial affordance on narrative experience in an AR game. They compared the factors of narrative experience in an immersive environment for six spatial conditions, namely possible trajectories, movable distance, approachability, spatial complexity, viewable distance, and perceived adaptability. They provided guidelines such as controlling user movement and semantic features in real space to design immersive spaces where higher presence and narrative engagement can be achieved.

Above-mentioned studies show that VR is a suitable medium to represent complex issues, and integrating narrative in VRE can aid in solving complex problems such as natural disaster mitigation. By creating interactive narrative experiences inside VR, users can be trained to mitigate natural disasters without experiencing real-world consequences. However, the validity of user behaviours in these narrative experiences is not widely researched (Fujimi & Fujimura, 2020) and is critical as VR applications are increasingly being used for training. Furthermore, the methodologies to measure emotional impact and influence of such VR applications still need to be developed and tested. The outlined studies have highlighted a clear gap in evaluation methodologies for these narrative experiences and demand further research in this context.

3. Approach

This research tries to bridge the gap by presenting two case studies. The first case study evaluates the role of narratives in VR. The second case study explores the possibility into how the sensory VR affordances can be manipulated to design a positive narrative experiences for solving the complex issue of natural disaster mitigation by implementing a training based VR simulation.

A mixed method approach is used to measure the user experience in both the case studies, and we addressed the following research questions:

- RQ 1 How does a narrative with a specific plot affect the immersion and presence in the VREs?
- RQ2 What is the impact of spatial affordances in narrative-rich VREs?

Based on the research questions, we hypothesise the following

- H0 The level of immersion in a narrative-based and non-narrative based VRE is the same (case study 1)
- H1 The level of presence and engagement in a narrative-based environment is higher in narrative-based VR (case study 1)
- H2 Spatial affordances inside a VRE delivers an overall positive experience (case study 2)

The case studies are explained in detail in the next section. Both studies took place at the Sense-IT lab at the Department of Electronic Systems, Faculty of Information Technology and Electrical Engineering, NTNU in Norway.[2]

4. Case study 1: IDNs role in VRE

An exploratory case study was designed to investigate digital narratives' role in an immersive VRE. This was done by evaluating the mediated presence, cognitive behaviour, and engagement in an evacuation training VRE designed as part of the world of wild waters project. A comparative study was designed to measure the impact of narrative in VR.

The VRE used in this study is centred around the idea of disaster mitigation. Narrative of the VRE used in this study was built around the idea of flood mitigation. A linear narrative was developed to lead the participants in the environment.

4.1. Methodology

4.1.1. Environment design

A fully functional and immersive VRE was designed using Unity game engine [3] and Oculus software development kit (SDK).[4] A **gaming** Dell OptiPlex 7060

[2]https://www.ntnu.edu/.
[3]https://unity.com/.
[4]https://developer.oculus.com/.

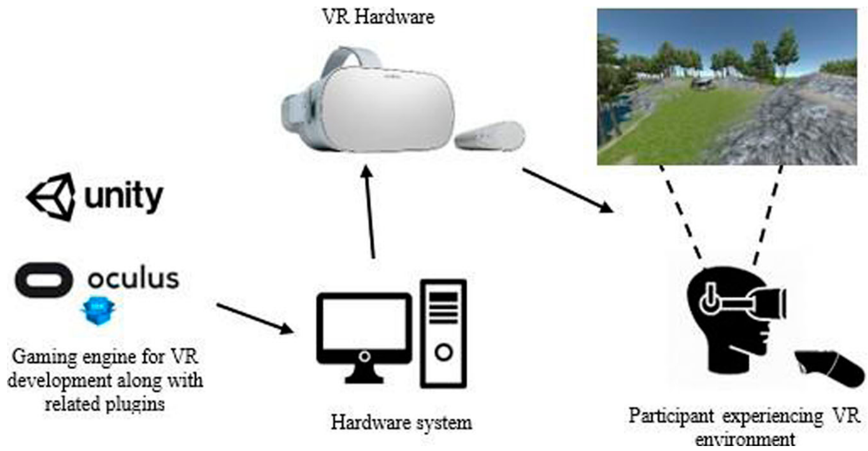

Figure 2. Experimental Setup showing libraries and hardware used in case study 1.

was used for the development of the VRE system design. Oculus Go was used to test the VRE because of its standalone nature and ability to provide non-positional 3 degrees of freedom tracking. Experimental setup and schematics of VRE design are illustrated in Figure 2. A VR environment was developed as part of the WoWW project and was based on the real-time location of a village in Norway (see Figure 3).

A First Person Controller (FPC) was implemented to navigate the VRE and interact with 3D objects, such as trees, buildings, and water, to establish realness for the user. Two VR conditions (C1 and C2) were designed as part of the experiment, with 32 participants in each condition. C1 was a non-narrative VRE in which the user performed assigned tasks without any narrative. Though both the conditions had the same VR dynamics, C2 was based on contextualised narrative, i.e. it was adapted to imply serious storytelling elements to guide the user in the virtual environment. A combination of plot, character, and environment was incorporated in C2 based on work by McDaniel et al. (McDaniel et al., 2010) to provide a complex narrative.

Participants were presented with a narrative that they are in a small village that is about to be flooded. The story unfolds with an announcement in the VRE that according to the weather forecast, the water levels are rising, and there will be a flood in the area soon and people need to take shelter in the nearby shelter. Inside the VRE, the participants could listen to the emergency alarms and sirens along with visual cues to demonstrate flooding and audio cues (sirens). Participants were given a task to evacuate the area and find a safe tunnel where they could wait for the evacuation team for rescue. All 31 participants were asked to rate their experience after the experiment. The detailed procedure of the experimental protocol is presented in the following section.

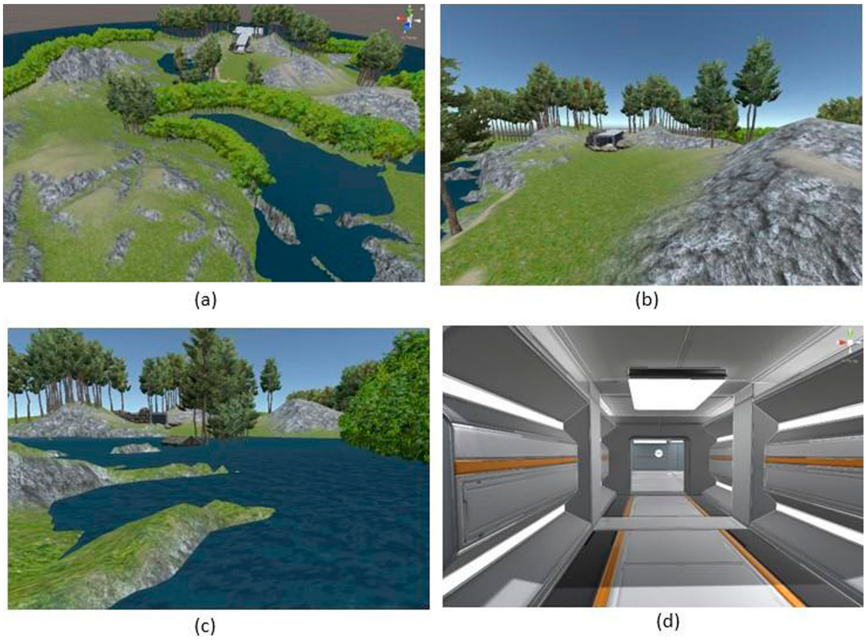

Figure 3. Figure (a) and (b) show the ariel view of the VRE. Figure (c) shows the water level rising in the VRE, and figure (d) shows the view of the tunnel.

4.1.2. Experimental protocol

Thirty-two participants (56.25% male, and 43.75% females) from ages 25 to 44 years (average age of 22.5) were selected via email by convenience sampling method. Participants were invited to participate on the site of the research facility on the experiment day (provide the date), and their written consent regarding the actual experimental performance and the use of data for this research project was attained.

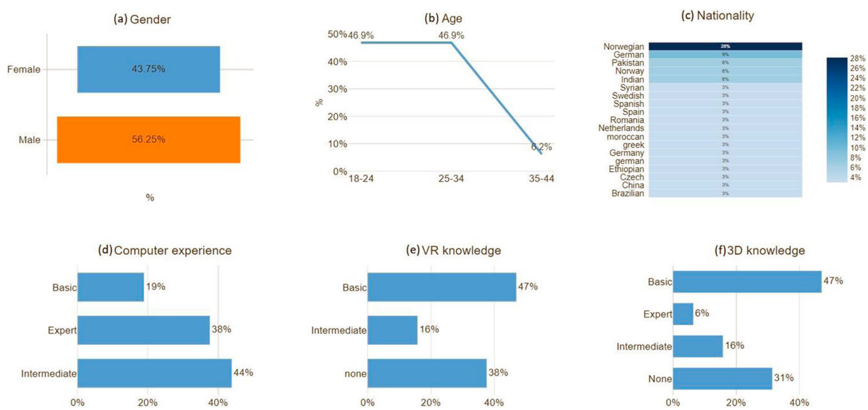

Figure 4. Demographic Information of the participants.

Their computer experience and knowledge of 3D technologies were recorded digitally, along with demographic information via a questionnaire before they experienced the simulation (Figure 4).

They were given detailed written and oral instructions about the experiment before the experiment started. Participants were provided with a demonstration of how to use Oculus Go and its touch controllers and were given time to familiarise themselves with the head-mounted display. Furthermore, they performed the simple task of navigating through the VR environment and performing to ensure they were accustomed to using controllers inside the VRE.

A controlled experiment was conducted with two independent conditions, i.e. non-narrative-based VRE (C1) and narrative-based VRE (C2), to measure the effects of narrative on the mediated presence and user's behavioural response. A with-in group experimental design was setup, and all participants experienced both C1 and C2 in random order to mitigate the carry over effect. ITC-SOPI (Lessiter et al., 2001) was used to measure mediated presence and behavioural outcomes because of its validity in measuring media experiences. The dependent variables were spatial presence, engagement, ecological validity, and negative effects. Quantitative data was collected via likert scale and close-ended questionnaires after the participants experience the VRE. The experiment lasted 45–50 min, and participants were awarded a gift card worth 120 Norwegian Crowns for their time and effort.

4.1.3. Results and discussion

Before the data analysis, the data were checked for (univariate) outliers in all combinations of two independent variables for any of the dependent variables. Similarly, data were tested for multivariate outliers to see if they have an unusual combination of scores on the dependent variables. C1 and C2 were compared through Multivariate analysis of variance (MANOVA) for the four dependent variables (DVs), i.e. presence, engagement, ecological validity, and negative effects. C1 was a VR experience with no narrative attached, and C2 was a narrative-rich and contextualised VR experience. The results of the MANOVA were significant for C2 (M = 3.53, SD = 0.602), (see also Table 1),

Table 1. Mean (M) and Standard Deviation (SD) of spatial presence, engagement, validity, and negative effects in participants of C1 and C2.

Descriptive Statistics	Condition	Mean	Std. Deviation	N
Spatial Presence	C1	2.96	.640	32
	C2	3.53	.602	32
Engagement	C1	3.22	.667	32
	C2	3.86	.635	32
Ecological Validity	C1	2.95	.721	32
	C2	3.31	.778	32
Negative Effects	C1	2.06	.736	32
	C2	1.77	.626	32

indicating a statistical difference in the level of immersion for VRE with and without narrative, and hence rejecting hypothesis H0.

The univariate test results (computed with alpha = 0.05) show a significant difference in both conditions, i.e. C1 and C2, for spatial presence. Mean values (M) depicted a significant increase in the sense of presence in C2 (M = 3.94) as compared to C1 (M = 3.53). Participants felt in control while interacting with the objects and more immersed in C2.

Almost all items in the engagement (M = 3.86, SD = 0.635) scale were higher in mean values for C2 as shown in Figure 5. This demonstrates the higher involvement of participants in the narrative-rich VRE along with attraction and enjoyment, validating H1.

Although there were no significant differences in C1 and C2 for ecological validity, participants perceived the VRE with narrative (C2) to be more natural, real, and believable (Table 1). Results showed that the participants overall experience for ecological validity was positive for C2, as they believed that the environments and the 3D objects within it were close to real-life objects. From these results, it can be deduced that the IDN-enriched environments provide a significantly higher user experience.

The negative effects of the VRE were not significant (M = 1.77,SD = 0.626), and the level of dizziness and disorientation in users in C2 was more as compared to users in C1. Furthermore, box plots were used to understand each group's overall pattern of responses. The box plot of each dependent variable for the two conditions is shown in Figure 6. It shows that the median values

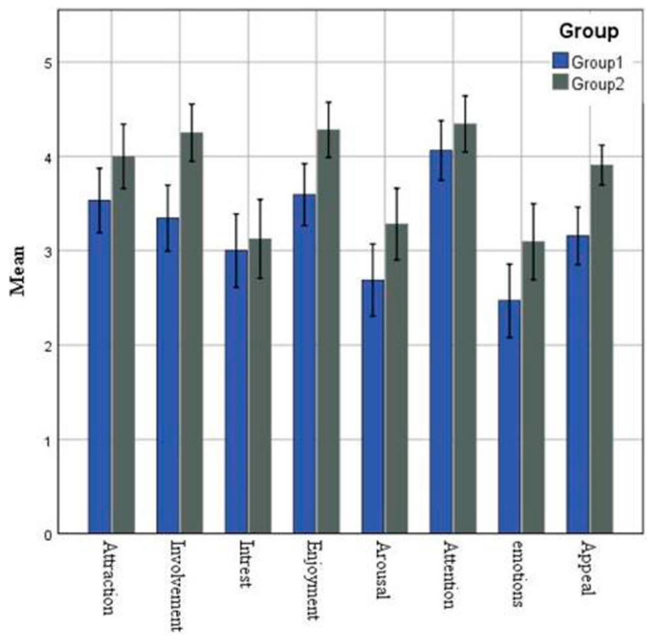

Figure 5. Figure shows the mean (M) of all dimensions of engagement.

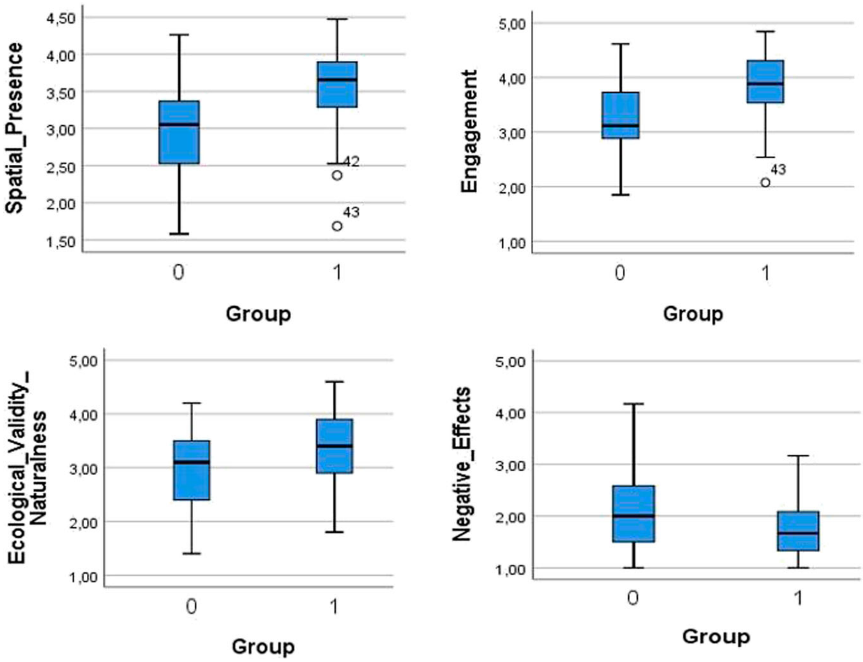

Figure 6. Figure shows the box plot with median, lowest and highest data points of the dependent variables measured through ITC-SOPI.

of each dependent variable in C2 are significantly higher than C1 except in negative values.

4.2. Summary of findings

The main aim of the present study was to investigate the impact of narrative on users in an immersive VRE. Presence and engagement were used to as part of user experience evaluation. Results showed a significant influence of immersion for narrative on all the prominent factors of media quality measured through a sense of presence inventory (Lessiter et al., 2001). Higher mean scores for presence and engagement were observed in narrative-based VR conditions compared to non-narrative VR, thus accepting H1. Objects and environments were perceived as more natural in the immersive and narrative condition, and the narrative experience was more exciting and involving. When asked to perform a task in a contextualised VR condition, participants remembered more details and wanted the experience to continue.

5. Case study 2: IDNs complexity representations in VRE

The primary focus of case study 2 was to investigate the effects of spatial affordances (Hartson, 2003) in IDN-based VREs. Spatial affordances are an essential attribute in VR systems and refer to a set of inherent possibilities of action presented in VRE (Stucky et al., 2009). The following study investigated how the incorporation of IDN in complex VREs with and without affordances affect end users. The purpose is to understand end-user experience based on the inherent possibilities of actions provided within VREs.

A design-based research methodology was used to design and evaluate the VRE for disaster preparedness by incorporating narratives to train people in flood situations (based on the guidelines as outlined in section 2.3). The disaster training and emergency preparedness VR game "Flood *Rescue-VR" was* used as the IDN to portray a flooded city. The game was designed and implemented as part of WoWW 's WP4 (see sections 1 and 5.1.1 for more detail). Design of the VR considered interface, protostory (material), and the mechanics for executing the game (engine).

The study aimed to compare the perceived experiences of participants in an immersive VRE depicting a stressful flooding scenario by controlling the experimental conditions with spatial affordances. Wayfinding cues were implemented to measure the impact of spatial affordances in VRE. Three groups of participants experienced the same VRE Flood Rescue-VR, with and without spatial affordances. The detailed study is presented in the following section.

5.1. Methodology

5.1.1. System design

Unity3D[5] together with open-source libraries was used to design the VR system and deployed on a computer-powered Head Mounted Display (HMD) called the Oculus Rift S[6] as shown in Figure 7.

Flood Rescue-VR comprises a small city where users can navigate and reach a safe location. The Ariel view of the VRE and the safe location is shown in Figure 8. Using the teleportation technique, the user could navigate freely via a natural walk and an Oculus Rift Controller. Both locomotion techniques were implemented to reduce motion sickness. When the VR experience started, the users were located in a parking lot (see Figure 9). They could hear sirens and emergency announcements to evacuate the city and find a safe place where they could be rescued.

Three VR modules were developed to measure the impact of spatial affordances in an IDN-rich, immersive environment. To investigate the role of affordances for VR, wayfinding cues were altered in all three modules, and user-perceived experiences were observed. The three VR gaming modules varied such that the controlled condition had no wayfinding cues, the

[5]https://unity.com/.
[6]https://www.oculus.com/rift-s/.

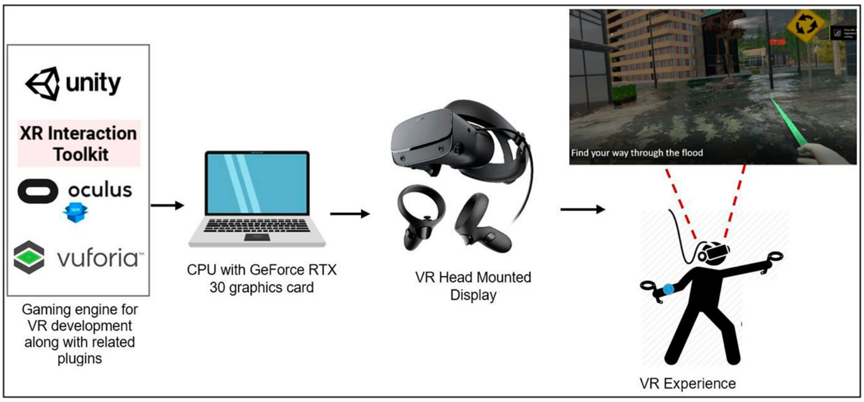

Figure 7. The figure illustrates the software and hardware components used in the design and development. A high-performance gaming PC with Oculus Rift S was used to exhibit the VR experience.

(a) Ariel view of the city inside the VR (b) Safe zone where the user had to climb up to save themselves from the flood

Figure 8. VRE shows the holistic view of the VR environment, and the finish point users had to reach to finish the game.

(a) (b)

Figure 9. Figure (a) shows the 3D rendered parking lot of the VRE "FloodRescueVR" The parking lot started to flood as the user started the VR experience. The green line in Figure (b) shows the teleportation beam, which helped the user navigate the VR. (a) Ariel view of the city inside the VR (b) Safe zone where the user had to climb up to save themselves from the flood.

other modules had static (condition 1) and dynamic wayfinding cues (condition 2). Static cues were signage systems inside the virtual environment, and dynamic cues were signage with flashing LED lights. The design of wayfinding cues such as flashing LED lights was implemented following evacuation design guidelines (Cosma et al., 2016; Vilar et al., 2018; Vilar & Rebelo, 2008).

To measure the impact of spatial affordances on user-perceived experiences, subjective and objective evaluations were recorded. A post-test game experience questionnaire (GEQ) was used (IJsselsteijn et al., 2013) to collect user-perceived experiences after the VR experiment. Heart rate was measured as part of the objective evaluation. Previous studies have shown the reliability of measuring HR for objective evaluation of the level of immersion in VR (Egan et al., 2016; Malińska et al., 2015; Marchiori et al., 2018). Fitbit sense was used in this study because of its computational precision to measure the HR (Strik et al., 2021).

5.1.2. Experimental protocol

5.2. Participants

Participants were recruited via email and informed about the time and venue of the study. All the participants and the experimenter followed the COVID protocols during the study procedure. Participants signed the consent form and filled in a pre-test questionnaire to gather the demographic information such as age, gender, education, computer and VR skills, etc.

Thirty-nine participants without colour vision deficiency (colour blindness) and average visual acuity were recruited for the present study. Participants were aged 18–54 years (44% were females and 66% were males with average age of 20.51). 69.23% of the participants had intermedia computer skills and 23.08% of participants had expert level computer skills. However, 69.23% had never played VR games or experienced any before.

5.3. Experimental setup

Before the experiment, a Fitbit sense (heart rate measuring device) was fitted to the left arm of each participant, and the baseline heart rate (HR) readings were recorded. Before starting the training phase of the study, participants were briefed about the study and the use of Oculus Rift S.

Participants played a demo VR game to learn the use of Oculus Rift S controllers and game mechanics. Once the participants were comfortable with VR, they were given instructions about the actual study. Participants were adjusted with an Oculus Rift S HMD, and they were asked to perform the tasks assigned to them and navigate through the VRE.

Participants were asked to find their way through the city and reach a safe zone where they could be saved. The narrative unfolded as the participants navigated through the city. They were given written instructions by the experimenter and a map of the city inside the VR. They were also asked to perform several tasks throughout the VR experience. It was up to the participants what type of decisions they make and how they navigate the city.

After they finished the VR experience, their HR was measured again using the Fitbit watch. An in-game experience module from the questionnaire called the Game Experience Questionnaire (GEQ) (IJsselsteijn et al., 2007, 2013) was applied. The in-game experience core module probes the participants feelings and thoughts while playing the game and was used in this study to measures game experience as scores on seven components, i.e. Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge. Participants were compensated with a cinema ticket for their time and effort. The whole study lasted 40 min. Results and discussion from the study are presented in the following section.

5.4. Results and discussion

The participants' heart rate in the control condition with no spatial affordances showed a mean value of 97.69. Participants in the two conditions with dynamic and static affordances showed a mean value of M = 80.5 and M = 79.8, respectively, as shown in Figure 10. ANOVA was performed to examine any significant differences, and results showed that the HR of the controlled group (SD = 9.96, $P = 0.05$) was significantly higher than the other two groups. The results suggest

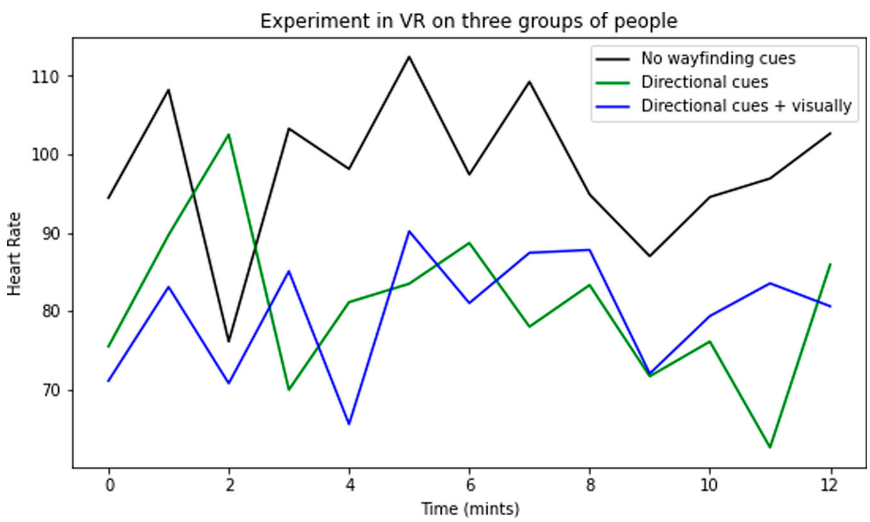

Figure 10. The graph shows Heart Rate (HR) data (beats/minute) with time on x-axis and HR on the y-axis for three groups, i.e. CG (represented with black line) EG1 (blue) and EG2 (green).

that creating affordances in EG1 and EG2 helped the participants create spatial knowledge while navigating through the immersive game, thus lowering their cognitive workload and relate thus to existing studies (Sharma et al., 2017; Verghote et al., 2019).

Results of the subjective evaluation showed the mean score of challenge for CG (n = 13, M = 2.5846) was higher than EG1 (n = 13, M = 2.30) and EG2 (n = 13, M = 1.87). The data revealed that participants with spatial affordances implemented in the VR perceived the system as less challenging. It can be deduced from the results that EG1 and EG2 with static and dynamic affordances helped in unfolding the cognitive and emotional processes of the participants. The cognitive ability to perceive the game improved; thus, participants had to put less effort into completing the task.

The mean score of tension for CG (M = 2.10) was higher than EG1 and EG2 (both M = 0.79), indicating a higher level of tension in the group without spatial affordances as shown in Figure 11. The results are similar to a study by Lin et al. (2019) suggesting that affordances can lower the levels of annoyance and tension in immersive games. Recent research studies (Lin et al., 2019; Zhou et al., 2018) have shown similar results of lower tension and annoyance in spatially oriented VR applications.

Positive emotional affects were measured through enjoyment, fun, happiness, and contentment metrics, and negative affects were measured by boredom, tiresomeness, and bad mood. The mean values of positive affects were higher for the EG2 as compared to other two conditions with dynamic wayfinding cues, i.e. M = 3.27, and the mean for negative affects were also the lowest for EG2 (M = 0.44) as shown in Table 2. Again, this finding is in line with literature that has shown that spatial affordances inside the game help to elevate player’s mood and the overall positive experience (Lin et al., 2019).

Competence was measured by skilfulness, competence, success, and users’ perception of how fast they reached their target in the game.

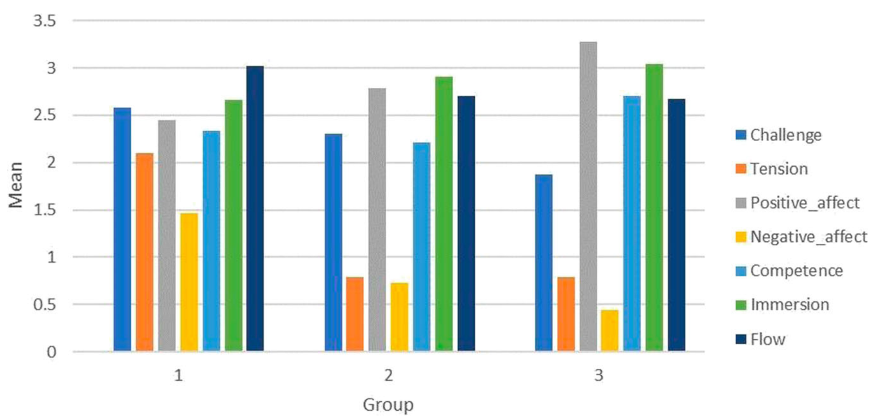

Figure 11. Bar graph of the mean values of the seven items for each group.

Table 2. Table showing the mean values of GEQ scales.

	CG	EG1	EG2
Challenge	2.58	2.30	1.87
Tension	2.10	0.79	0.79
Positive Affect	2.44	2.78	3.27
Negative Affect	1.46	0.73	0.44
Competence	2.33	2.21	2.70
Immersion	2.66	2.91	3.03
Flow	3.01	2.70	2.67

Similarly, immersion was measured by constructs of aesthetics, imagination, impression, and interest in games' story and curiosity. The mean values of competence and immersion were also high for the EG2 case, as shown in Table 2, but no significant correlations were found between the groups. Results are consistent with the findings from (Balakrishnan & Sundar, 2011; Pollard et al., 2020) showing that the level of immersion and competence increases with the increase in spatial affordances.

The level of flow in the VRE was the highest for the CG (M = 3.01). This can be explained by the fact that there were no cues or directions inside the VR, so that participants lost the notion of time and the stressful situation with all the alarms and emergency announcements they wanted to exit immediately from the flooded situation. Since the results of VRE with spatial affordances is significantly positive, we accept H2.

In the current case study, we only measured the quantitative aspect of the experience, i.e. the subjective and physiological evaluations. Further, studies can incorporate qualitative and behavioural measures to capture a holistic experience of the participants. Further, case studies need to be performed to understand the constructs of cognitive absorption, behaviour involvement, and motivation which are important aspects of design and need to be measured to improve existing VR systems.

In essence, the two case studies examine the role of VR spatial attributes such as presence and affordance and shape the ways in which users explore, engage and understand VRE. VREs warrants multifaceted evaluation methodology that would usually employ numerous measures for understanding, and the above studies offer a preliminary step in the direction. This ongoing research study reveals definite indication that narrative positively affects mediated presence and participants cognitive abilities. Results suggest that integrating narrative in immersive environments can enhance learning in training and evacuation systems as our study participants performed tasks very well in narrative conditions. In future studies, we suggest examining ways of incorporating narratives in VR serious games to increase learnability. The two case studies are perpetration for the eventual IDN product to be tested (produced as a result of WoWW). Results from the existing studies can be used to propose design guidelines and practice implications for complex IDN VR systems.

6. Conclusion

This research attempts to understand better the role narrative plays on the psychological indicators of human experience for complex representations in immersive environments. Results from the case studies revealed an overall positive experience of VR users when the virtual environment was aided with IDNs. The present studies help us to understand the influence of IDNs and affordances and how incorporating narrative in an immersive environment can enhance VR-specific attributes such as spatial presence, engagement, naturalness, immersion, flow and positive experience of the users. Existing studies helped us confirm that having a story does add value to engagement and spatial presence, but how exactly it affects spatial presence and which subcategory of presence does it influence are still open questions for further research. Furthermore, the case studies present a thorough evaluation of subjective and objective experience along with physiological measures (HR in case study 2). However, for future studies, a more interdisciplinary and holistic approach needs to be applied, by integrating methods of immersive media technology and serious gaming, in which researchers incorporate additional behavioural assessment methods and new tools that can aid in measuring end-user experiences.

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No potential conflict of interest was reported by the author(s).

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Paper 6

INDCOR White Paper 2

Interactive Narrative Design for Representing Complexity

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This whitepaper has been produced by members of the COST Action 18230 – Interactive Narrative Design for Complexity Representation (INDCOR - https://indcor.eu)

INDCOR White Paper 2: Interactive Narrative Design for Representing Complexity

Executive Summary

This white paper was written by the members of the Work Group focusing on design practices of the COST Action 18230 – Interactive Narrative Design for Complexity Representation (INDCOR, WG1). It presents an overview of Interactive Digital Narratives (IDNs) design for complexity representations through IDN workflows and methodologies, IDN authoring tools and applications. It provides definitions of the central elements of the IDN alongside its best practices, designs and methods. Finally, it describes complexity as a feature of IDN, with related examples.

In summary, this white paper serves as an orienting map for the field of IDN design, understanding where we are in the contemporary panorama while charting the grounds of their promising futures.

Introduction

Since the world around us is becoming increasingly complex, we need new ways to represent it. Interactive Digital Narratives (IDNs) offer a unique form of representation due to the specific characteristics of the digital medium. IDN can present different perspectives within the same work, show the results of different decisions, and allow audiences to replay and make different choices (see INDCOR WP 0, 2023). Most importantly, IDNs transform audiences from passive readers to active participants, allowing them to experience complexity first-hand instead of merely reading about it (the so-called interactors - see below).

The potential of IDN for representing complexity has already been realized in the forms of video games and interactive documentaries, as well as in hypertext fiction, installation pieces and XR experiences. So far, however, IDN design remains highly idiosyncratic and is often not well understood outside the circle of successful IDN creators and scholars who specialize in the field.

This white paper addresses the situation by providing an accessible overview of IDN design for complexity representations. The discussion will focus on the power of the digital medium and its unique feature of interactivity, which define these cultural and often artistic works. Interactivity sets IDN apart from traditional narratives and will be a central topic in this paper.

A wide range of topics related to IDN design will be presented in the following sections, including IDN workflow and methodology, IDN authoring tools, and IDN application. To guide the reader without disrupting the flow of the text, we have provided definitions of the central elements of the practice in boxes on the side of the main text.

The main goal of this white paper is to serve as an informative guide to the field of IDN design, providing readers with a clear understanding of the current state of the field and highlighting the latest developments and promising future directions. By charting these aspects, this white paper will offer an orienting map for those who wish to explore this exciting area of digital media.

Definitions

This section provides our definition of Interactive Digital Narrative (IDN) and some of the key elements IDN is built on. In INDCOR, we understand IDN as follows:

IDN are narrative experiences that can be changed by an audience and which are created for the digital medium. What can be changed (for example outcome, progression, perspective) varies as does the particular form. Popular IDN forms include narrative-focused video games, interactive documentaries, hypertext fiction and VR/AR/MR experiences.

The table below defines some of the central elements of the practice.

Digital	All objects, including media and text that exist in digital form and that can be read by machines.

Narrative	An account of a real or fictional sequence of events that may be presented in different ways (text, speech, images, animations, videos, or any combination of these). Narratives are ways to structure and transfer information (like knowledge, feelings, experiences, etc.) shared by all human cultures.
Interactivity	Describes an active relationship between two or more entities, people or objects. In digital media, interactivity represents a two-way flow of information between the devices and its user. In other words, it is the ability of a computer to respond to the user's input.
Complexity	The phenomenon of having many parts that cooperate in a sort of symbiosis to give rise to a whole that is constantly evolving, and that is more than the sum of its parts.
Representation of complexity	The process or product of depicting a complex phenomenon, real or fictional. In the context of this text, these depictions (or representations) are meant to make such phenomena more understandable.
IDN authoring	A creative process that comprises all the tasks that are involved in the creation of an IDN artifact, from ideation to distribution. An IDN author is a person who participates in the ideation, planning, design and/or development of an IDN.
Authoring tool	A software program that assists or facilitates the creation of an IDN artifact. By providing a unified and comprehensive workspace, it simplifies the authoring process.
Interactor	The user of an IDN. The term is meant to highlight the active participation enabled by IDNs, in contrast to the more passive consumption of representations in novels or films.
Metaverse	An online virtual world that multiple people can access at the same time. The currently available version of the metaverse has simple graphics, it's interactive and allows the creation of avatars to interact with other users.
Virtual Reality (VR)	A computer-generated simulation of a three-dimensional space that a person can interact with using special equipment (like headsets, controllers, gloves, etc.). It is a type of Extended Reality.

Extended Reality	A broad term referring to various combinations of real and virtual environments, as well as human-machine interactions generated by computer technology and equipment. It includes a number of specific forms like augmented reality, mixed reality and virtual reality.

Design and Best practice for creating IDNs

This section explains how to create an IDN: what are the best design practices, what tools are available for creating IDNs, and how would one go about planning and making an IDN. There are several ideation, prototyping, and planning methods that can be used, from informal brainstorming to more structured approaches.

While the specific process of creating an IDN is unique to each work, there are some common practices that can be highlighted. As for most design tasks, it is common to work iteratively and undertake user testing. IDNs are sometimes created in collaboration with their users, who make an active contribution during the design, just as in standard user-centered approaches. There exist many tools for creating IDNs, each designed to cater to different types of artifacts the creators might want to produce.

An authoring process for IDNs generally has four main stages: ideation, pre-production, production, and post-production, with specific tasks for each stage that can be adapted to the particular IDN project. As noted in the INDCOR WP 0 (2023) there are no established production practices as well as production facilities; so, what we report here is an abstraction on singular experiences. It is important to note that the process of creation is not linear, and often involves going from ideation to production and back again: the four-stage model aims to be inclusive and iterative. It is open to the addition of new actions into each stage and to the repetition of actions to accomplish the desired results.

1. Ideation methods and early prototyping

    a. The ideation phase of an IDN is hard to abstract, as every author of any artifact proceeds in different ways. Some authors might find it useful to start by developing a range of ideas for the broad structure of the IDN and picking the best one (considering factors such as expressiveness, quality of the experience, feasibility, and production costs). Other authors may start with clear ideas for the IDN content and draft an early prototype from there. The ideation stage also comprises research and training work on the thematic of the IDN, or on the selected tools and materials that the IDN will require. During this stage, authors can also sketch an overall interactive structure with possible plot(s), create characters, draft events, and make notes for the next stage.

2. Pre-production and interaction design

    a. A key feature of IDNs is their interactivity: the interactor is active in the experience. A central question is therefore, "What is the role of the interactor?" or simply "what can the interactor do?" Decisions about the role of the interactor affect the dynamics and mechanics of the experience, the meaning ascribed to the experience, and the emotion it elicits. One approach to the early creation stages is to list different options for the role of the interactor(s) and then brainstorm what opportunities and challenges each would create, both for the interactor and for the author.

3. Production – an iterative process

    a. The process of creating IDNs is usually iterative, i.e. a version is created, tested, improved and tested again until its authors are satisfied with it. This is particularly important for IDNs, as their interactivity makes more difficult to predict the actions and responses of the interactors. This iterative testing frequently narrows down to smaller and smaller sets of components, with early iterations modifying the main elements of the IDN and later iterations concentrating on finer details, such as locating software bugs or even the precise wording of instructions.

4. Post-production and testing

    a. Informal testing usually happens throughout the whole design process. In addition, it might be helpful to perform a more formal evaluation towards the end. This can be done by having a group of people test the IDN and obtain their feedback through interviews and/or questionnaires. At this stage, the purpose is not necessarily to fix or improve the IDN at hand. Instead, it could be helpful to get information for future design processes. In a research context, the goal could also be to test a hypothesis by comparing different variations of the IDN.

IDN Authoring tools

INDCOR WG1 has been actively working on compiling an archive[1] of existing IDN authoring tools, organizing them according to taxonomic criteria and design principles, and identifying potential testing methodologies. An IDN authoring tool is pragmatically defined as digital software that eases the authoring process of interactive digital narratives. In particular, an IDN authoring tool:

1. Provides an independent and comprehensive workspace, including an IDE and GUI, which allows a prospective author to create an IDN work from start to finish. The tool gears its end products to run on an engine, which is often, though not necessarily, also embedded within the tool's environment.

2. Simplifies the authoring process: the tool streamlines the design of the story world, the end-user interaction model, and/or other central narrative elements such as characters and events, to make the IDN creative process easier and more effective than design through a general-purpose programming language would be.

3. Is actively being used or was actively used in the past to create IDN products, focused on interactive narrative aspects, by a community of practitioners besides the tool's creator(s). Prototypes and in-house tools may also meet this criteria, if they demonstrate clear and explicit potential to be actively used in the future, when they are publicly released.

Complexity IDNs

This section will focus on a specific topic on which the COST Action INDCOR has focused significant attention in the last few years, namely the relation between complexity and IDNs. In our understanding, complexity represents a significant societal challenge, particularly when

[1] https://omeka-s.indcor.eu/s/idn-authoring-tools/page/idn-authoring-tools

materializing through contemporary complex phenomena such as global warming, refugee crises, wars, colonization, globalization, pandemics and so forth (see INDCOR WP 0, 2023).

In this section, two interpretations of the relation between IDNs and complexity will be touched on, namely complexity as a feature of IDNs (and what it means for authors), and the suitability of IDNs to better represent complex topics and phenomena.

Complexity as a feature of IDNs

In IDN design, complexity can be intended as a feature of the object in question. The authors decide on the level of complexity of a particular IDN through a number of choices regarding game rules and narrative characteristics. As a feature of IDNs, complexity can be manually crafted by authors (for example, by building extremely large worlds with many interacting components) or it can sprout from the engagement of interactors with the IDN (as in the game of chess, in which authors defined very few elements but with a huge number of possible moves at each step). Complexity as a feature is necessary to provide a meaningful interaction, as it relates the interactors' choices to their outcomes, making IDNs ideal candidates for representing complex issues in an understandable way. For example, an IDN on the migration crises in the Mediterranean Sea or piracy in the Indian Ocean (see INDCOR WP 0, 2023) needs to present a number of components that revolve around the issue (people, countries, governments, policies, NGOs, etc.), and needs to allow a number of possible interactions to make this system understandable.

However, complexity as a feature also requires precautions. First of all, while designing IDNs with elements of complexity, authors must remember that interactors face the opposite end of their creation: what can look simple for the author might be complex for the audience and vice versa. A second caveat is that often complexity as a feature has to be presented to interactors gradually, to get them acquainted with this complexity step-by-step, and not overwhelm them, which might prevent them to understand what is represented and why. On the other hand, it can be sometimes useful to deliberately avoid this gradual presentation to achieve specific expressive purposes, like representing the complex situations some people face in their daily lives.

IDNs representing complexity

IDNs have significant advantages compared to traditional narratives in representing complexity: they can represent a topic with a great wealth of details, they feature dynamic representations that can change and adapt in response to user choices, they can accommodate a number of even conflicting perspectives or points of view, and they allow multiple replays to help understanding. The same kind of representation is not possible to achieve (for instance) in the text-based newspaper article, nor in the fixed form of a TV broadcast (see INDCOR WP 0, 2023). Even when talking about fiction, readers/viewers of traditional forms like novels or movies can only speculate about the progression and outcome of the story, but they cannot influence them in any way. In IDN, users can make plans, execute them and see the results of their actions.

Choices and their resulting consequences, as well as re-play, is what sets IDNs a separate entity from fixed narratives. These qualities are necessary for enabling an understanding of the dynamic nature of complex issues, allowing them to represent systems in a more direct way, and permitting users to practically engage with such systems and understand their functioning. This capability is crucial to train systemic thinking, which is the ability to understand the dynamic and interconnected nature of all phenomena in contemporary society. In addition, by understanding and engaging with these complex systems, even though fictional, users can be prompted to change their behavior regarding complex matters in real life, for example when deciding their political position, or they can change their perspective and point of view, for example by crossing the boundaries of anthropocentrism and adopting a multi-species point of view as a way to restore equilibrium among the inhabitants of our planet.

Representing complex issues through IDNs requires specific design choices and precautions:

- The wealth of details should be presented in a way that is not overwhelming for the user and that is easily understandable: an IDN is not an encyclopedia, and the information presented to the users should be selected on the basis of relevance for the scope of the object being designed, and of manageability (also in terms of practical and economic feasibility). The example IDN representing the issues connected with the migration crises in the Mediterranean Sea does not need to present all technical details of the rescuing ships, but only the relevant ones (e.g. load capacity, speed, etc.).

- The IDN as a dynamic representation, too, sprouts from design choices: the degree of adaptability of the IDN system should come from choices made early in the design process, as they can greatly affect the dimensions of the final object and therefore its feasibility. Again, this is a matter of finding equilibrium between fidelity of the object to the issue it is intended to represent, comprehension of the outcome, technical, practical and economic feasibility, and accuracy of the representation of the topics in question. Our IDN on migration crises could allow users to choose between different immigration policies to see the long-term effects of them, while other kinds of choices on social issues could be disregarded as they might have little impact on the subject, like the retirement age of involved countries.

- The conflicting perspectives should be balanced so that their respective weights allow for sufficient freedom of exploration: which also allows for freedom of choice and is eventually the prerequisite of systemic thinking. If only one perspective is represented or is dominant, IDN's ability to make a complex issue understandable will diminish. If the IDN on the migration crisis represents only or mainly the point of view of the extreme right, it would easily miss its scope of representing the complexity of the issue. This also highlights a possible ethical dilemma connected with IDN, namely the misuse or even biased use of them to support political or ideological agendas while pretending to be impartial and mindful of the different perspectives.

- Finally, the re-play should be encouraged by the design: re-plays are great enhancers of systemic understanding, as they allow users to achieve the multiperspectivity discussed in the previous point and greatly enhance their understanding of the whole system, by observing its behavior in different conditions. While users can always restart interacting with an IDN, this re-engagement can be encouraged and can be made more relevant through specific design choices. For example, by including maps or diagrams that also show not-yet-seen paths, or by hinting at the presence of multiple perspectives and endings after having explored one of them.

These features make IDNs ideal candidates to address complexity as a societal challenge when materializing in complex phenomena and issues. However, more particular application areas of IDN design for representing complexity could be highlighted.

Application areas

This section aims at providing an overview on IDNs that address complex issues to gain a better understanding of the design decisions that have been made in those prototypes and applications, and then to make the resulting knowledge available to practitioners for the representation of complex topics. This section corresponds well to the start of INDCOR WG1, where we made an inventory of available applications of IDNs in various domains.

When applied to representing complex issues, IDN design finds some important application domains, such as;

- Journalism and news
    - Journalism has benefited much from the digital medium. From interactive versions of magazines and newspapers, where readers can comment and add their voice to the authorial one, to blogs, Twitter and various types of social media which are transforming the panorama of journalistic practices. Moreover, at the cutting edge of virtual and extended reality, journalism becomes immersive with the pioneering work of the American journalist Nonny de la Peña. Efforts blossom worldwide as journalists, documentarists and filmmakers start challenging journalistic practice with IDNs. Interactive documentaries such as Last Hijack - Interactive, The Industry, or Miners Walk, The Criers of Medellin, and many others available at the MIT Documentary database (https://docubase.mit.edu) are just some of the examples (see INDCOR WP 0, 2023 for other examples).
- Education and training
    - Education is a vast area to apply IDN and its capability of representing complexity. "Edutainment", a word coming from the blending of "education" and "entertainment", has been identified as an area of development and research decades ago, with examples ranging from openly educational games for schools of all levels, to serious games, to interactive stories for children both individually and in classrooms. Examples of this application of IDNs are Periodic Fable, a story-game leveraging on characters and narratives to excite children in learning for instance chemistry subjects, Starlight Stadium, an IDN that teaches Human Rights monitoring practices, or Mobeybou, which requires young children to connect physical, tangible blocks representing characters, objects or places, to

populate a virtual world where these elements interact in different ways, to ultimately teach the richness of distant cultures.

In addition, there are a number of other application domains being explored, such as entertainment and tourism. These, however, do not necessarily address the topic of complexity as defined by INDCOR.

Existing applications present a digital narrative within a specific domain. It is possible, however, to apply interactive digital narratives to more complex issues as technology advances. For example, explorations are made for the application of IDN to represent and enable understanding of complex topics at the general and individual levels. Climate change, wars, pandemics, migrations, traumas, other mental health issues, interpersonal relationships, etc., are examples of complex topics. As a result of this work, IDN can be used to represent, understand, and create solutions for wicked problems in the future. IDN can, for example, be used to explore solutions to social injustice, poverty and homelessness, pandemics, racism, globalization, poverty, homelessness, global warming, the current war in Ukraine in the future.

Future directions

This section is a speculation of possible or probable new developments in the field of IDN design and of its application areas. Predicting exactly what will happen in the future is far beyond anyone's ability, but some motivated hypotheses will be provided here.

Augmented Reality, Virtual Reality, Extended Reality

With the focus on Extended Reality (XR), new exciting possibilities in the field of IDNs have manifested. First out was the recent revival of VR, which allows interactors to feel fully inside the action, and the design of IDNs for VR has to take the position of their interactors into account even more than when the narrative is presented through a flat screen. The ways of interacting with the narrative are other very important elements that designers have to consider: in VR, interaction can be induced with handheld devices, gestures or even gaze input. This means that an interactor can activate a reaction in the virtual environment just by performing a particular gesture or by looking at a certain point. While these features are mainly applied in simple ways that enable the interactor to control the progress of a linear story, the increasing affordability of these new technologies may allow future authors to explore fascinating new domains of IDN creation.

The combination of sensors, extended realities and AI opens up possibilities in uncharted territories for audiences and narrative creators. Narratives could be informed by real time data, processed directly from the interactors’ senses, emotions, and context, shaping up and personalizing their experiences as they live through the narrative journeys designed for and with them. As technology starts to move its first steps in this direction, authors and audiences are challenged to embark on daring new narrative journeys and experiences.

However, an important caveat is to be pointed out: features that visionaries claim would be achievable in the near future, often seem to be based on technological fantasies (inspired by movies, books and television series), rather than on actual technical possibilities. It is not uncommon, for instance, to see predictions of online virtual worlds with unlimited interaction, photorealistic environments, and believable characters. With current technological affordances, however, most of these features are impossible, but these sensationalized expectations may cause users to easily become disappointed when they are confronted with versions of a Metaverse that are much more sober and constrained than the world that fictional stories have led them to imagine. Technological progress may actually evolve in a spectacular fashion that will enable users to be immersed in interactive movies that will be indistinguishable from the world around them. Until then, the affordances that online VR offers for interactive storytelling are still very much worth exploring.

Artificial Intellingece

With digital narratives, we play the role of humans by following different storylines and creating open-ended stories. In the future, however, artificial intelligence and technological advancements will allow humans to no longer be the only agents responsible for creating storylines. We see that AI is being used in games to develop emergent behaviors for secondary non-player characters. It is likely that AI will become an essential component of interactive digital narratives in the future. Combining this with the domains and usage of IDN in complex issues and wicked problems, we can expect that artificial intelligence can have a more active role in creating interactive digital narratives to represent and understand complexity. Imagine, however, that AI is used in IDN to the fullest extent possible. It is possible, then, to imagine AIs as the only participants in an interactive digital narrative without human participants. So what will IDNs be used for if this happens?

The goal of interactive narrative is to immerse the user in an intellectual and emotional experience so that the user's actions can directly impact the direction or outcome of the storyline. Thus, the user is given the opportunity to "replay" the story in different forms. A replay will provide reflections on the various other, often opposing, directions and meanings the story might have, depending on the starting point and interactions. But, as IDN can be applied to more complex issues and wicked problems, there is an opportunity to enhance the purpose of IDNs towards a solution-finding role. The new IDN purpose may be to create solution storylines through co-creation between different stakeholders at various levels. In this way, IDN can be viewed as a method for addressing real problems that affect many people, such as those necessary for achieving the Sustainable Development Goals of the United Nations.

IDNs are slowly finding their space in a number of application areas, as we have seen (cf. also INDCOR WP 0, 2023). However, with the continuous development of new technologies, ever new directions and applications are just about to be opened.

Extending IDNs to other contexts, stakeholders and audiences

IDNs are likely to be soon introduced in contexts that are traditionally considered less driven by digital narratives, such as data science and knowledge representation. It will be especially interesting to see the effects of their use in dealing with complex issues and multi-perspective situations. For example, the World Economic Forum developed what they call “transformation maps”, interactive interfaces that “help users to explore and make sense of the complex and interlinked forces that are transforming economies, industries and global issues”. Interactive digital narrative design could help to further enrich these increasingly popular tools by making use of the expressive power of narratives, a way to share information rooted in the very core of all human cultures, and ultimately make complex topics understandable. Throughout the text, we have highlighted practices for the design of interactive digital narratives, discussed why they can be ideal candidates for representing complexity and shown possible specific areas in which IDNs can represent meaningful and helpful choices. This, we hope, will help to address complexity as a societal challenge, to assist experts in reaching shared understandings, and to engage new audiences and stakeholders to eventually change the world for the better.

Further Readings

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INDCOR White Paper 2: Interactive Narrative Design for Representing Complexity

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Paper 7

This paper has been submitted for publication and is therefore not included.

Paper 8

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