Workshop on Visualisation in Environmental Sciences (EnvirVis) (2024)
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ExtremeWeatherVis: Visualizing Extreme Weather Events for Multi-City in Virtual Reality to Support Decision Making

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Abstract

The occurrence and severity of extreme weather events are changing due to the impact of climate change, resulting in significant hazards to human lives and critical infrastructure. While data are abundant on the consequences of these extreme weather events, it is often challenging to communicate this data to the appropriate people in a way that resonates. In this paper, we present ExtremeWeatherVis *to immersively visualize extreme weather events for multiple cities in Virtual Reality allowing user interaction with the temporal evaluation of specific events in day and night cycles from different viewpoints. The current visualization allows users to visualize potential heavy rainfall resulting in pluvial floods and heatwaves for Dresden, Bautzen, and New York. We conducted a user study, followed by a longitudinal study, to explore the effectiveness of our method in supporting decision-making by capturing participants' emotions. The emotional aspects of participants were assessed using three distinct AI models to investigate whether our method supports decision-making by enabling a sense of presence while capturing the emotions of the participants.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Visualization—Immersive, Extreme Weather Events

1. Introduction

The frequency and the threat of extreme weather events are increasing every year due to the temperature rise for several regions [IPC21]. Despite the warnings from scientists, the damage caused due to climate change has cost more than $15 billion followed by 113 deaths only in the United States by August 2023 [fEI23] [fEIN23]. According to *European Commission* [fCA23] the increase in global temperature is leading to an increased occurrence of heavy rainfall resulting in floods, flash floods, and droughts, making it more ubiquitous across different regions of the world. The effects of climate change go beyond the visible damage including psychological problems in a significant proportion of the population. Multiple research state that the delicate balance of nature is disrupted due to human activities that release greenhouse gases, alter ecosystems, and alter landscapes, resulting in a higher vulnerability to extreme weather events [WGK12]. The vulnerability of communities and ecosystems to extreme weather impacts is directly influenced by this disruption, which is often driven by the pursuit of development and economic growth [CR20]. The role of emotion and effective communication of natural risks play a crucial role in reducing damage and mitigating threats to people and communities [ATS*20]. In general, most policymakers and the general public do not have the expertise to unravel complex climate data. To bridge this knowledge gap, it is crucial to visualize climate data in a way that can connect people more intuitively. In the context of extreme weather, critical events and conditions may not manifest clarity in a flat 2D format, leading to diminished understanding of their severity. By elevating the visualization to geospatial data in an immersive 3D environment, the challenges can be solved. Virtual reality (VR) visualization is becoming a transformative tool in the field of disaster risk reduction, making a significant contribution to reducing the damage and threats posed by natural hazards [KMM*22]. The immersive power of virtual environments is harnessed by this cutting-edge technology to simulate and replicate real-world scenarios, resulting in an innovative approach to preparedness, response, and recovery. A powerful union that transcends technology and human experience is formed by emotions and natural disaster visualization [AJM21].

In this paper, we collaborate with environmental development and risk management experts, scientific visualization experts, and

DOI: 10.2312/envirvis.20241137

psychologists to present *ExtremeWeatherVis* offering the following contributions:

1. Multifunctional Visualization: The ability to simultaneously visualize multiple extreme weather events across different cities.
2. Validation: The applied method is evaluated by a group of multidisciplinary domain experts using a qualitative and longitudinal study.
3. Emotion Capture: The integration of emotion capture during the study adds a human-centric dimension to the evaluation process.

2. Background Study

Due to both natural and anthropogenic factors, the global climate has undergone significant changes in recent decades [CZL*23]. The increase in frequency and severity of extreme weather events is one of the most concerning manifestations of this transformation. Based on research findings, the influence of emotion [WSS20] [CEH*21] and sense of presence [SMP*20] are strongly connected to extreme weather events and these factors have a deep potential to raise awareness to mitigate the effects of natural disasters [FQB20] [CMC23]. The instinctual emotions triggered by climate-related events, for example, empathy for affected communities or concern for future generations, can serve as powerful catalysts for action for individuals when they experience them. According to *The Ostrich Paragox* published by *Meyer et.al* [MK17], people are under-prepared for natural disasters due to less frequent peril experiences. According to fundamental human instincts, we often overlook threats that we haven't directly experienced.

VR proves to be an invaluable asset in dealing with this situation, fostering a profound sense of presence [SKF*20] by supporting remote communication [WGK*23]. VR can bridge the gap between the unfamiliar and the inexperienced by allowing individuals to immerse themselves in lifelike simulations [MGDN21] and has the potential to evoke similar instinctive responses and emotions that people would typically feel when directly facing a hazard. VR provides a unique chance to improve understanding and preparedness, even for threats that have not been encountered in person [CG19]. Despite the debate, about whether VR is really necessary to visualize extreme weather events to support decision-making, several studies represent a positive understanding of surroundings using VR [TWJtD18], [CWT*11] [MBL22], [vGMY*23] [SPKK22].

Carrozzino et al. [CGT*23] introduced *VRescue*, an immersive VR simulator for urban search and rescue operator training. *VRescue* replicates a range of operational scenarios and conditions, allowing trainees to practice equipment usage and decision-making in realistic situations. According to their evaluation, VR-based training can deal with shortcomings of dangerous situations at a low cost and with no consequence to other people. However, *VRescue* is constrained to the reconstructed street network of a satellite image exclusively from the old town of Pisa, Italy. The extrapolation of this approach to other geographical locations is uncertain.

In *Korani et al.* [KM23] a framework for constructing VR models to enhance the communication of coastal flood risk by using UAV imagery and digital photogrammetric techniques is presented. The goal of this research was to support the understanding of climate change for people living in coastal cities. *Fino et al.* [FTB*23] provided a study that includes serious game training for heatwaves and earthquakes using VR. They integrated behavioral and phenomenological data from outdoor temperature, falling debris, and crowd motion. Their study focused on the investigation of communication in critical situations as mitigation strategies. Nonetheless, their VR environment depicts a uniquely modeled urban space rather than replicating any geospatial data. *Oyshi et al.* [OMS*22] visualized ensemble flood projections in VR for a specific municipality in Germany to support decision-making, leveraging the sense of presence. The evaluation of *FloodVis* is conducted through a user study centered on decision-making. Nevertheless, the scalability aspect of this visualization remains unaddressed.

Investigations are currently underway to utilize the advantages of VR to reduce the damages resulting from extreme weather events. However, most of the research is scenario-specific apart from the study by *Fino et al.* or city-specific. Additionally, the examination of emotional aspects has not been explored within the realms of decision-making, increased awareness, and enhanced community resilience in the aforementioned research. To bridge this gap, *ExtremeWeatherVis* aims to propose a novel method to visualize extreme weather events focusing on multi-city and multi-scenario.

3. Methodology

ExtremeWeatherVis aims to provide a novel method that allows users to visualize extreme weather events in VR using existing technologies. For the development of VR visualization, the *Unity* [Uni] game engine was selected due to the beginner friendliness and resource availability.

3.1. Requirement Analysis

To complete our requirement analysis, we investigated scientific approaches/tools/serious games presented by multiple authors to visualize extreme weather events in VR. Our goal was to identify approaches that support visualization flexibility for geographic locations and extreme weather events, shown in table 1. We identified our stakeholders as Decision-Makers, City Planners, Meteorologists and Climate scientists, HCI (Human-Computer Interaction) specialists, and General People. Our functional requirements include historical data integration, VR visualization as part of immersive visualization and customization. For non-functional requirements, we focused on performance, usability, and scalability. To support our design requirements, we collaborated with the environment and risk assessment specialist and *HCI* specialist. Their feedback primarily emphasized aspects related to interactivity, a user-friendly interface, realistic sound effects, and accessibility.

3.2. Data Collection and Pre-Processing

To leverage the potential of temporal evaluation of climate data, we selected the data platform Regionales Klimainformationssystem *(ReKIS)* [Sac] due to the availability of localized region-specific climate information with a temporal resolution of hourly data within Germany. Data encompassing observations such as precipitation and temperature spanning from 2010 to 2021 was chosen from a

Table 1: *Requirement Analysis*

	Multi-City	Multi-Event
Oyshi et al. [OMS*22]	-	-
Gevelt et al. [vGMY*23]	-	-
Simpson et al. [SPKK22]	-	-
Fino et al. [FTB*23]	-	✓
ExtremeWeatherVis (Proposed)	✓	✓

distinct weather station located in Saxony, Germany. Our initial data was stored as *.kli* [WUF]. As *Unity* does not accept this data format, it was converted into .JSON using a *python script*. During the pre-processing, identification of interesting points to represent heavy rainfall resulting in floods and heatwaves that might lead to drought or wildfire was considered. The scripting can vary depending on the data type and complexity. However, the converted .JSON file should be structured with scenario names, positions including latitude and longitude, start date, end date, parameters, and data details. Parameters describing other scenarios for example storms, tsunamis, and others can be added to visualize them to support data scalability.

3.3. Precipitation, Flood Height Approximation and Temperature

Identifying periods of above-average precipitation is essential for depicting heavy rainfall. We graphed cumulative rainfall over a seven-day timeframe, specifically from August 4th to August 16th, 2002 where a concentrated and substantial amount of precipitation contributed to the subsequent flooding of the Elbe later that month. To estimate the pluvial flood height, we used a custom model that assumes, in urban areas including surfaces like roofs and streets, 45% of the ground is sealed, which prevents water from permeating directly. We characterized heatwaves as a sequence of at least 5 consecutive days with temperatures reaching 30 degrees Celsius or higher. Parameters like temporal (day, month, year), mean temperature two meters above ground, precipitation, relative humidity two meters above ground, sunshine duration, potential evaporation according to *Turc-Wendling* [Ger], UV-index, wind chill, heat index, wildfire danger index, and others were taken into consideration while analyzing the data.

3.4. Data Visualization

To visualize the pre-processed test data and real data in VR, we developed an immersive environment in 3D using *Unity*. To create the 3D environment for multiple cities we used *CESIUM* [Ces23a] that offers 3D models for different cities as 3D tiles. We used a custom-tailored skybox and two custom-tailored shaders to visualize flood and heat waves. In *ExtremeWeatherVis*, we visualize heavy rainfall resulting in floods and heatwaves in *Dresden* (a state capital in Germany), *Bautzen* (county town in Germany), and *New York*, shown in Figure 1. To support scalability in the context of multicity, we offer switching between cities, by a specified spawn point with specific latitude and longitude for the corresponding cities. The spawn points need to be added to the data structure. The visualization can be extended to other cities as well.

3.4.1. Rendering

In terms of visualization, we opted for *Unity*'s *Universal Render Pipeline (URP)* as it provides better performance compared to *High Definition Render Pipeline (HDRP)*. Furthermore, it offers a higher degree of customization compared to the *HDRP* since it does not use physical simulations for the most part, whereas the *HDRP* provides a more realistic look at the cost of performance and compatibility with other modules of *Unity*. *Unity*'s built-in particle system is employed to visualize rain using sprites as raindrop images projected onto camera-facing rectangles. To achieve a raindrop-like appearance, appropriate scale, shape, and color, the particle system needed to be adjusted, and rain behavior then was replicated by altering initial velocity, travel direction, stop points, and creation locations. Two particle systems are involved in the final effect: one that produces the majority of rain particles and the other that emits fewer particles closer to the camera. The second system creates a short, realistic effect by detecting collisions and spawning a smaller particle system at collision points. To achieve the visual effect of flooding we used a horizontal plane with a shader applied to it using Unity's Shader Graph feature. The shader itself was made to be as customizable as possible allowing among other things to change the water's color, opacity, refraction on the water surface, foam, velocity of the water, and many more. Additionally changing the appearance of the water surface shaders also gave the possibility to change the geometry of the object on which it is applied. Using the global coordinate system of *Unity* and a noise texture the vertices of the object can be displayed on the vertical axis allowing for a wave-like movement shown in figure 2 a) and b). To visualize heatwave, we used Unity's built-in fog system through a global setting, which interacts seamlessly with other environmental effects creating a layered atmospheric experience. We applied different densities and colors from grey to orange tones to represent a heatwave where the temperature is above 30°for 5 consecutive days, represented in Figure 2c).

3.4.2. Immersiveness

To enhance the immersiveness, we implemented a day-night cycle incorporating two light sources emitting parallel light globally across the entire environment. To ensure accuracy we used *Microsoft timezones* using *Timezonedb API* [Tim]. The lights were set to rotate around a central point, symbolizing the sun and moon. The rotation of those light sources is calculated using astronomical calculations to get the accurate (error $< 0.5°$) direction of the sun and moon at a given location and time. The changing weather and the day-night cycle are shown in figure 2 d). As sound plays a significant role in increasing immersiveness in VR, we used 3D spatial rain audio from *Mixkit* [Mix], partnered with *Evanto* [Eva] to amplify the immersiveness.

3.5. Interaction

Three modes for VR interaction using the HTC Vive headset and controllers are available: default, data browser, and bird's-eye view. Controller mappings vary by mode, viewable on the left controller's trigger. A tutorial video can be accessed by pressing the left controller's grip for guidance. Users can access data files, such as cities, through the file directory interface that can be accessed using

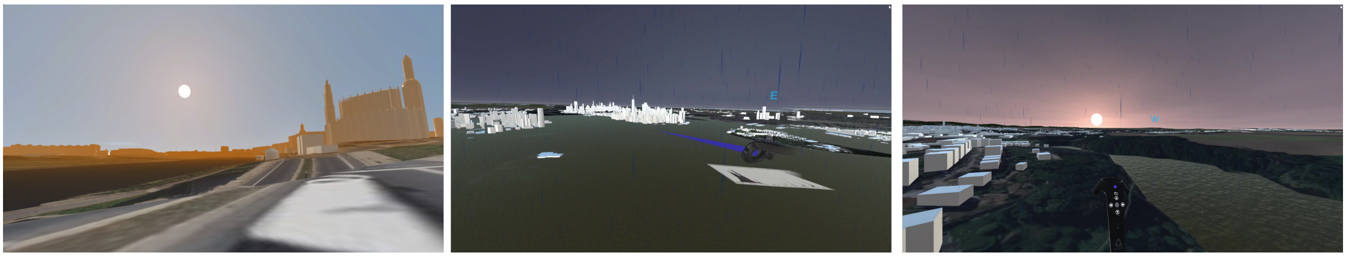

Figure 1: *a) Heat-wave in Dresden (Germany), visualized from ground view; b) Heavy rainfall resulting in a pluvial flooding event in New York (U.S.) c) Pluvial flood caused by heavy rainfall in Bautzen (Germany).*

Figure 2: *Flood, Rain, and Heatwave. a)Under-water flood visualization with Partial Rain (Top -left); b) Flood visualization before changing color at day-light (Top - right); c) Heatwave as smoke with a density of 0.03 (Middle -right) to 0.00 (Middle -left); d) Day (Bottom-left) and night (Bottom-right) cycle.*

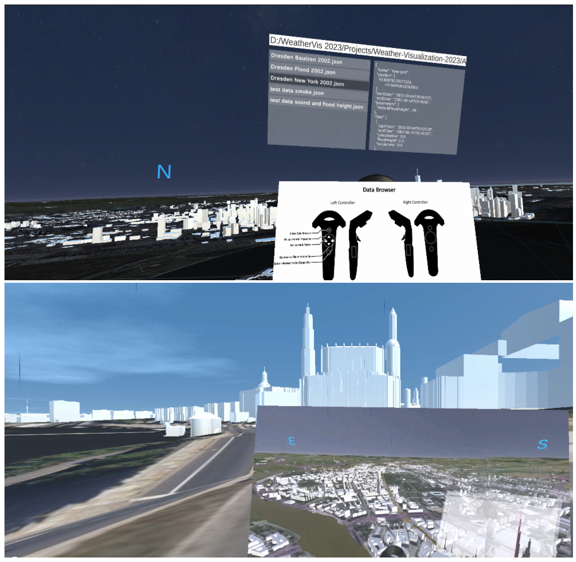

Figure 3: *a) New York from bird's eye view with the north indicator, data browser, and controller mapping (top); b) Instruction video playing inside VR environment from ground view (bottom)*

the menu button on the left side of the controller. Users can use teleportation within the virtual environment to navigate smoothly without experiencing motion sickness. The menu button on the right controller has a minimap for tracking position and switching between bird's-eye and default views. The use of a watch on the left wrist is used for temporal evaluation, which can be adjusted for playback speed. A 2D graph on the right controller's trigger displays the current time to gauge the intensity of rain, flood, or heat. Improvements in user interaction were made possible through the integration of evaluation insights into the system. Interaction details and feature highlights are in Figure 3 and Figure 4.

4. Evaluation

To evaluate *ExtremeWeatherVis*, we explored the following research questions:

Q1 How does immersive VR visualization affect users' understanding and perception of extreme weather events compared to traditional 2D visualizations?
Q2 How can VR be leveraged for educational purposes to improve public awareness and preparedness for extreme weather events?
Q3 Can VR environments influence behavior change and preparedness actions in response to extreme weather events?

4.1. Study Details

Two distinct studies, denoted as "Study-1" and "Study-2", are part of the evaluation. The objective of "Study-1" is to conduct a complete evaluation of performance and usability, presence and immersion levels, simulation sickness occurrences, and the emotional impact caused by virtual reality (VR) experience compared to traditional visualization techniques. All the participants performed the following tasks with a duration of 40 minutes to 70 minutes:

- Identification of areas of vulnerability

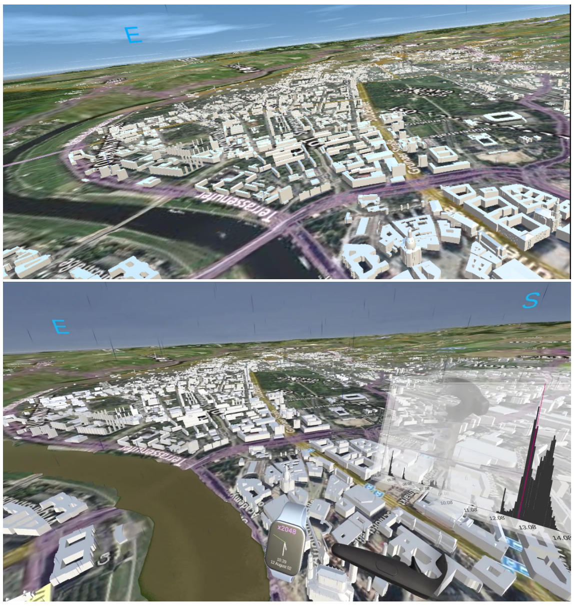

Figure 4: *a) Dresden from bird's eye view with the east indicator at day-light without flood (top); b) Controlled time and graph from birds' eye view of Dresden with flood (bottom)*

- Identification of vulnerable time-point
- Priority allocation to support evacuation decision
- Saving oneself

The purpose of "Study-2" is to conduct a longitudinal study to determine the long-term impact of VR interventions, which can add valuable insights into their enduring effects. Both studies were guided by a single researcher and audio recorded to identify the emotional impact on the participants. For the evaluation, we selected six experts from the different domains: artificial intelligence, visualization, distributed computing, geo-visual communication, and automation. All participants live in Germany and originated from India, Germany, China, and Bangladesh. The panel was composed of five males and one female with five participants in the age range of 25-35 years and one participant in the range 18-25 years. Two participants had prior experience in VR.

4.2. Study - 1

"Study-1," includes two interview sessions and one study session. The initial interview comprised three different questions aimed at gauging participants' general awareness regarding extreme weather events and their associated consequences. These three questions were asked both before and after the study to identify the study's influence. These questions combine the likert scale for q1: 1 (Not concerned at all) to 5 (Very concerned) and for q2 and q3: 1 (Do not believe at all) to 5 (Strongly believe). The general understanding improved for almost all the participants after the study, shown in Table 2. Due to the low number of participants we measured the effect size using *Cohens'D* [Die10] to quantify the magnitude of the differences observed in our study. For q1, *Cohens'D* value is 0.45 indicating relatively small magnitude of the effct size and

Table 2: *Assessment of Perception Study Questions*

	SD	Mean
Assessment of Perception (Before Study)		
How do you feel about the potential impact of extreme weather events in your area	1.10	4.0
Do you believe that extreme weather events can have serious consequences for your community	2.07	3.66
Do you believe that proper preparation for extreme weather events is important to reduce potential risks and damages	0.00	5.00
Assessment of Perception (After Study)		
How do you feel about the potential impact of extreme weather events in your area	1.12	4.5
Do you believe that extreme weather events can have serious consequences for your community	0.41	4.83
Do you believe that proper preparation for extreme weather events is important to reduce potential risks and damages	0.00	5.00

q2 is 2.85 suggesting a large magnitude on the effect size. Since the standard deviation is 0 for both the "Before Study" and "After Study", *Cohens'D* cannot be calculated for q3. Additionally, participants were queried regarding their willingness to invest time in learning about climate change and mitigating the damages caused by hazards, both before and after the study. The study included a non-VR map, a graph, an animation representing traditional visualization approaches, and the VR visualization *ExtremeWeatherVis* for the same extreme weather events to perform the tasks. Following the task completion, participants were queried about the ease and effectiveness of task performance using both non-VR and VR visualizations. The majority of participants expressed a preference for VR visualization, citing its ease of use. Notably, only one participant (p2 - a visualization expert) favored non-VR visualization over *ExtremeWeatherVis* initially. P2 provided valuable feedback and identified design flows that were incorporated later. Upon feedback incorporation, P2 was interviewed again and the visualization expert preferred the updated VR visualization over non-VR visualizations. Subsequently, participants were prompted to respond to a series of questions spanning general aspects, user engagement, user interface and interaction, comparison with non-VR visualization, emotional impact, and tool-specific inquiries. Employing a strategic approach, a blend of positive and negative questions was utilized to engage users' cognitive processes, prompting thoughtful consideration before responding. The study included some more user and study-specific questions. Apart from the user and study-specific questions, in total, all the participants were asked 65 questions combining both the interview and study. Due to the number of questions and page limitation, we did not include all of them directly in the paper. **All the questions and the results can be found in the supplementary material**. However, we did not include the audio files due to data privacy.

To measure the user experience and impressions of *ExtremeWeatherVis* our investigation continued by rating general questions ranging from 1 (strongly disagree) to 5 (strongly agree). Overall, the feedback for *ExtremeWeatherVis* was positively reflected. All the participants agreed or strongly agreed to be engaged during the VR experience of extreme weather events (Q1[User Engagement]: Mean=4.67, SD=0.55) scaled as 5 (very strongly) to 1 (Not at all). 5 participants out of 6 agreed or strongly agreed about VR visualization providing a better overview of the data (Q3[Comparison with a non-VR Visualization]: Mean=4.33, SD=1.21) scaled as 1 (strongly disagree) to 5 (strongly agree). Tool-specific questions received positive feedback as well (Q6[ExtremeWeatherVis]: Mean=4.33, SD=0.82), for example, almost all the participants agreed or strongly agreed to have better visualization over time using the playback.

To evaluate the performance and system usability we used *System Usability Scale - SUS* [JTWM96]. *SUS* is widely being used for determining the usability of specific tools combining 10 different questions scaled as 1 (strongly disagree) to 5 (strongly agree) and following a specific scoring system [Git]. According to the *SUS* calculation, the average score for *ExtremeWeatherVis* is 77.5 representing a "Good" system having room for improvement. The sense of presence evaluation was inspired by the *Presence Questionnaire*, published by *Witmer & Singer* [WS94] in 1994. This evaluation included 5 different questions on the context of immersiveness on a scale of 1(Not at all) - 7(Very Strongly). The majority of the participants agreed to have a strong involvement in the virtual environment (Q3[Sense of Presence]: Mean=6.17, SD=0.75). Most of the participants agreed to have increased involvement due to auditory aspects (Q4[Sense of Presence]: Mean=6.17, SD=1.17). As VR might trigger simulation sickness we also asked questions from the *Simulator Sickness Questionnaire* [KLBL09]. No participant complained of major simulation sickness. The simulation sickness study is evaluated on a scale of 1 (Not at all) - 5 (Very Strongly). Upon answering these questions, we asked the same questions in the context of general awareness regarding extreme weather events, their consequences, and the willingness to spend time learning climate change and hazard damage mitigation. For most of the users, the willingness increased apart from the visualization experts (p2, p3).

Emotional Impact To identify the emotional impact, we analyzed each recording and applied three different speech-to-emotion recognition AI models *Speech-Emotion-Analyzer* [Mit21] (Model-1) with approximately 70% accuracy , *EmotionRecognition* [Tas23] (Model-2) with unknown accuracy, and *OpenVokaturi* [Dev23] (Model-3) with 67% accuracy. All the models were pre-trained. The original audio included both the instructor's and participants' voices. The participants' audio was separated and split into segments representing the answers. Model-1 uses a neural network to identify emotions in a range of 0 - 9 to represent angry, calm, fearful, happy, and sad for females and males. Model-2 uses a 1-layer CNN (Convolutional Neural Networks) range of 0 - 11 to represent neutral, happy, sad, pleasent_surprise, fearful, surprise, angry, disgust, calm, excited, frustrated, and boredom. Model - 1 detected "female_sad" for a male participant (p2 = male), as well as detected female emotion for "male_fearful", "male_happy", "male_sad" (p5 = female), indicating error-prone detection. Model - 2 identified the emotional status of the participants as neutral and sad emotions for all the participants. To have strong confidence in the emotional impacts, we opted for the third model - an open-source version of *Vokaturi* having five different emotion classifications - anger, happiness, neutral, sadness, and fear. The emotional response of the participants using model-3 is illustrated in Figure 5a). Using all three models, the most detected motion is sad/sadness. The emotional response of sadness to visualizing extreme weather events can have both positive and negative implications for damage mitigation efforts. Feeling sad can increase empathy for individuals and the emotional connection can drive the individuals to support advocating for climate change mitigation including motivating behavioral changes like reducing carbon footprint, adapting to sustainable practices, and investing time, energy, and resources to prepare for extreme weather events [Bro21]. Increasing engagement in advocacy efforts can be a result of sadness. The emotional impact of users may increase their advocacy for policies that address climate change, improve disaster preparedness, or allocate resources for disaster relief and recovery [GAa23]. However, the feeling of sadness can also trigger emotional overload, fear, or anxiety, or to some extent, too much emotional exposure can reduce the emotional impact which might result in reduced motivation to take action [SNO23]. During the study, none of the participants reported having emotional overload also it was not detected by the models. During the VR visualization, especially while drowning underwater, the emotion specified by *Participant 01* is scary, sad, and depressing. *Participant 02*, mentioned the current emotional status as sad and worried. The rest of the participants also described strong emotions compared to non-VR visualization. Participants were also asked emotion-specific questions during the study to have a manual cross-check. Almost all the participants agreed or strongly agreed to be emotionally evoked in VR (Q1[Emotional Impact]: Mean=4, SD=1.09), and almost all the participants agreed or strongly agreed

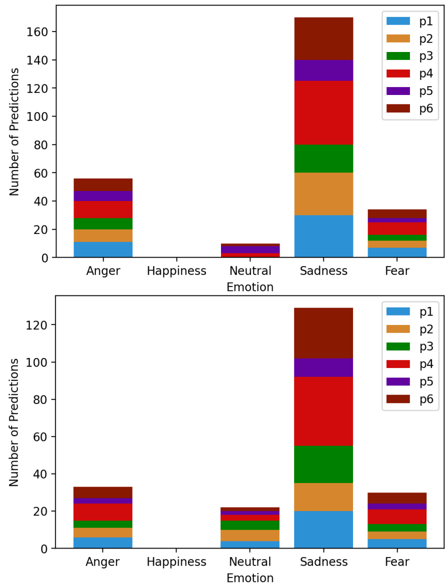

Figure 5: *Emotion Recognition of the* ExtremeWeatherVis *participants using* Vokaturi *(Model-3) for a) Study - 1; b) Longitudinal Study using*Vokaturi.

to be more emotionally connected compared to traditional visualization methods (Q2[Emotional Impact]: Mean=4.5, SD=1.22).

4.3. Study - 2

We undertook a longitudinal study to investigate the sustained impact of the VR experience in the context of assessment of perception and measuring emotional impact. Three months later, we re-engaged the same group of 6 experts who participated in "study-1." The study comprised a set of three retained questions (please check Table 2) along with the introduction of four new questions. Our research indicates that VR experience has a significant impact on comprehending extreme weather events for almost all experts. However, the result of the last question from the longitudinal study received mixed feedback where two participants mentioned not changing any actions for personal preparedness after the study, one having minor changes and the rest agreed to modify actions from moderate to strong agreement, as detailed in the Table 3. *Cohens'D* value for the retained questions are 0.62 and 0.42 for q1 and q2 respectively, indicating moderate to small and positive magnitude on the effect size. For the new questions, *Cohens'D* could not be calculated for q1 as the standard deviation is 0, for q2, the value is 0.42 indicating small magnitude, q3 is 2.02 indicating relatively large magnitude and q4 is 1.3 indicating relatively moderate magnitude on the the effect size. To investigate the emotional impact of the longitudinal study we used *Vokaturi* as this model was used to have confidence in the results of "Study-1" and also for having promising accuracy [GGPLF22]. According to our findings, there is a drop in emotion for sadness, anger, and fear for all the participants and an increase in neutral emotion over time, illustrated in Figure 5 b). However, it is important to highlight, that the participants having a higher emotional impact in "Study-1" agreed or moderately agreed having precautions - for example, limiting unnecessary energy consumption, preparing an emergency kit, checking insurance coverage, and staying informed as a result of the VR study. It is noteworthy to mention that the participants lacking precautions are visualization experts, and most of them have prior experience with VR.

Table 3: *Longitudinal Study Questions*

	SD	Mean
Retained Questions		
How do you feel about the potential impact of extreme weather events in your area	0.55	4.66
Do you believe that extreme weather events can have serious consequences for your community	0.41	4.83
Do you believe that proper preparation for extreme weather events is important to reduce potential risks and damages	0.00	5.00
New Questions		
How immersed did you feel in the virtual environment during the visualization of extreme weather events	0.00	5.00
Do you believe that the VR experience influenced your perception of the importance of personal preparedness for extreme weather events	0.41	4.83
Can you recall specific details or information about evacuation routes identified by you in the VR simulation	0.41	4.17
Have you taken any actions or made any changes in your preparedness for extreme weather events as a result of participating in the VR study	1.72	2.83

5. Discussion and Limitation

The study results helped us to answer our initial research questions as follows

- Q1 The use of immersive VR visualizations tends to increase users' understanding and improved perception of extreme weather events compared to traditional 2D visualizations
- Q2 The urgency and severity of extreme weather events can be effectively conveyed through educational VR experiences, encouraging a sense of responsibility and preparedness among the public.
- Q3 The simulation of extreme weather events in VR can encourage users to take proactive measures and make informed decisions in real-life scenarios. However, in this case, decisions can be influenced by the personal background.

According to *Participant 01*, "*ExtremeWeatherVis* is a really important tool and can be used for both the general public and disaster management to spread awareness and for defining planning and strategies to mitigate damages." As per *Participant 02*, both the general people and city planners can benefit from rising awareness and city planning. Both *Participant 03 and 06* stated *ExtremeWeatherVis* as a very important tool that could be "definitely" used to support proper preparation to reduce potential risk, damages, and decision-making. Although *ExtremeWeatherVis* received positive feedback from the majority of the participants, it was difficult to convince the visualization expert p2 on the context of interaction in "study-1". However, P2 identified interaction limitations for example limited time interaction on birds' eye view, missing cardinal information, street names, and others. Upon feedback incorporation, it was easier for P2 to perform tasks using VR compared to non-VR. As all other participants except p2 preferred VR visualization (initial version) over traditional visualization, the updated version was only demonstrated to p2. P3 responded less emotional connection as the expert enjoyed the visualization rather than being connected emotionally. Further modifications of *ExtremeWeatherVis* can be done from the design and visualization perspective. For example, the heatwave visualization can be updated by localizing the heatwave. In our current visualization, we used basic building structures without detailed textures as *CESIUM* does not offer modification of 3D tiles geometry on-the-fly at runtime. However, this problem can be solved using different tools from *OSM*. Another alternative can be using *TilesetContentLoader* [Ces23c] in *Unreal* [Ces23b], [Eng]. To ensure data scalability, we need to visualize other extreme weather event data as well. Also, the integration of emergency shelters could support better training in the evacuation process. Our limitation also includes being unable to investigate the real data for New York as the data is not publicly available. Instead, we reused the data from Dresden to have an understanding of the extreme weather events in New York.

6. Conclusion and Future Work

A proper understanding of complex extreme weather data is usually reserved for experts alone. Effective interpretation and communication of these data can support critical thinking and increase awareness during a real-life extreme weather event outcome for both experts and non-experts to mitigate damage. As a result of the collaborative work between environmental development and risk management, scientific visualization, and psychology, we proposed a novel method to visualize extreme weather event outcomes, where we visualized heavy rainfall resulting in floods and heat waves for three different cities. As we can extend our visualization for different cities and different scenarios we can argue about scalability, although there is room for improvement. We can also highlight the immersive experience and positive feedback received from users as key strengths. According to *Participant 04*, "*ExtremeWeatherVis* is a futuristic idea to face climate change and support evacuation, if used properly within a collaborative manner". As per *participant 05*, still non-VR visualization is easier, particularly for the fast processing speed, but VR visualization has a higher potential to support evacuation planning, training, and city infrastructure planning. We evaluated our method in the context of performance and usability, presence and immersion, and simulation sickness by capturing the emotions of participants. We investigated the influence of users' emotions on the context of decision-making for risk mitigation. The study results indicate that the elicited emotions can support decision-making for risk mitigation. In the future, we would like to investigate the efficiency when more extreme weather data and cities are incorporated. We can conclude, that our method can mostly be used by city planners and disaster management experts as accessing city-specific extreme weather data should not be an issue. This method can be used to raise awareness, evacuation, and damage mitigation training. Finally, we experienced VR visualization to enable effective interpretation and communication supporting critical thinking and increasing awareness during a real-life extreme weather event outcome lavering emotions. Especially, within the field of decision making there's great potential to support decision-makers accounting for mitigation measures. In the future, we would like to overcome the shortcomings, visualize more scenarios, and conduct extensive user studies to identify the significance of small and big study group results.

7. Acknowledgement

This work was supported by the German Federal Ministry of Education and Research (BMBF, 01/S18026A-F) by funding the Center for Scalable Data Analytics and Artificial Intelligence *ScaDS.AI Dresden/Leipzig*. The authors gratefully acknowledge for providing data through through the Regionales Klimainformationssystem and Leibniz Institute or Urban and Regional Development. This work also received funding from Deutsche Forschungsgemeinschaft through DFG grant 389792660 as part of TRR 248 and the two Clusters of Excellence CeTI (EXC 2050/1, grant 390696704) and PoL (EXC-2068, grant 390729961). Further funding was provided by the Foundation for Environment and Loss Prevention (Stiftung Umwelt und Schadenvorsorge) of the Sparkassen-Versicherung Gebäudeversicherung, Stuttgart.
Finally, the authors acknowledge all the participants for taking part in the user study and for sharing their valuable feedback. Special thanks to Apurv Deepak Kulkarni, Nishant Kumar and Benjamin Russig from TU Dresden for the fruitful discussions and the responses.

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