Int. J. Human–Computer Studies 181 (2024) 103137

Contents lists available at ScienceDirect

International Journal of Human - Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

From reader to experiencer: Design and evaluation of a VR data story for promoting the situation awareness of public health threats

Qian Zhu [a,*], Linping Yuan [a], Zian Xu [a], Leni Yang [a], Meng Xia [b], Zhuo Wang [c], Hai-Ning Liang [c], Xiaojuan Ma [a]

[a] Hong Kong University of Science and Technology, Department of Computer Science and Engineering, Hong Kong, China
[b] Carnegie Mellon University, Human-Computer Interaction Institute, Pittsburgh, PA, United States
[c] Xi'an Jiaotong Liverpool University, Department of Computing, Suzhou, China

ARTICLE INFO

MSC:
0000
1111

Keywords:
Data story
Public health communication
Immersive visualization

ABSTRACT

Informing people of health threats is crucial as they may lack situation awareness (SA) of risky situations when they do not have personal experiences or lessons learned from dangerous encounters. In this work, we explored the potential of using a VR data story to raise people's SA of health risks. We first invited seven participants and conducted participatory design studies to capture the design considerations. Then, we implemented the VR data story with five design features referring to the design considerations. Using a between-subjects study (N=62), we evaluated the effects of the data story on raising SA and investigated the role of each design feature. Our results show that the data story can promote SA by enhancing people's connection to risky situations. Design features such as immersive visualizations, multiple perspectives, and embodied interactions contribute to this connection. Drawing on qualitative and quantitative findings, we discuss the implications of designing data stories in VR for promoting public health.

1. Introduction

Communicating health risk information to the public is crucial, as the purpose of communication is not simply to inform the risk, but to improve people's awareness of health threats around them and even promote effective and sustainable behaviors as a protection mechanism (Bernhardt, 2004). However, it is challenging to make people concerned and well-informed about a particular public health threat when they have no real experience or first-hand lessons learned from risky encounters (Trope and Liberman, 2010). Such integrated perceptions, comprehension and self-projection of a situation, known as situation awareness (SA), have been recognized as a critical mediator to people's protective behaviors in public health (Endsley, 1988a; Li and Cao, 2019). Research has shown that improving the SA can promote people's effective actions or decisions to respond appropriately to a risky situation (Feng and Tong, 2022).

To raise public awareness about health risks, healthcare authorities (Organization, 2022; for Disease Control and Prevention, 2022) and news agencies (Times, 2022; Guardian, 0000) have employed data stories as a potent communication tool. These data stories include a set of facts backed by data (i.e., data-driven) that are visualized and organized in a meaningful order to support intended messages (Lee et al., 2015; Segel and Heer, 2010). Their goal is to present data facts and insights in an engaging and intuitive manner to enhance communicative and persuasive power to the public. Despite the intuitive display of health risks and information, people may still not be able to connect their own experience to what happens "far away" in a data story or get the first-hand experience of the health risks. One primary reason is the reliance on 2D screens as the principal medium for communicating these stories to the public (Trope and Liberman, 2010; Liberman et al., 2007). This medium limits the audience's ability to immerse themselves fully in the story (Breves and Schramm, 2021). Additionally, the inherent limitations of 2D screens restrict users' embodied interaction within the data story, which can make it challenging for readers to form a personal connection with the health threats portrayed.

In contrast, VR experience, with enhanced levels of immersion (Ho and Ng, 2022; Ahn and Fox, 2017; Bastiras and Thomas, 2017), have the potential to foster situational communication and persuasion by immersing individuals in simulated scenarios to gain experiential insights. Isenberg et al. defined the concept of immersive data stories and claimed that bringing immersion to data stories could lead to profound involvement, engagement, and engrossment with the data (Isenberg et al., 2018). Building upon this concept, Alexander et al. developed

* Corresponding author.
E-mail address: qzhual@connect.ust.hk (Q. Zhu).

https://doi.org/10.1016/j.ijhcs.2023.103137
Received 13 February 2023; Received in revised form 20 June 2023; Accepted 23 August 2023
Available online 9 September 2023

the unit visualization in VR (Ivanov et al., 2019), aiming to evoke affective personal experiences with the data story. It has demonstrated the potential of immersive VR to provide novel ways of engaging and interacting with data stories. However, such endeavors are still in the minority and predominantly focused on examining the impact of immersive experiences on people given a pre-prepared design. They rarely explored the design process of a VR data story, such as how to identify the proper forms of interactions or how to visualize the data insights and communicate them to the viewers. Furthermore, previous efforts primarily concentrated on presenting visible entities to promote visceral understanding (Lee et al., 2020), overlooking the data visualization of invisible information such as health threats (e.g., viral infections or psychological stress Midtbo and Harrie, 2021; Sadeghian et al., 2021). Consequently, it remains an open question on how to design a VR data story to promote people's SA of health threats, while also evaluating the actual impact of increased immersion in data stories on people's awareness.

We aim to bridge this gap by exploring the design considerations for a VR data story with immersive visualizations to depict unseen health threats, while also assessing the story's effectiveness on promote the SA of health threats. We propose the following research questions:

- **RQ1**: What are the design considerations for designing a VR data story that leverages immersive experiences and visualizations to raise people's situation awareness of health threats?
- **RQ2**: What impact does the VR data story have on enhancing people's situational awareness of health risks?
- **RQ3**: How do users perceive and interact with the VR data story?

To answer **RQ1**, we first create the initial VR data story counterpart based on a representative data story. Then, using it as a design probe, we take a participatory design approach (Ehn, 2008) by inviting seven ordinary users to experience the initial VR data story and collect their needs and feedback on the story design through two formal design studies. Based on the responses and in-depth interviews, we summarize five design considerations in designing the VR data story experience for raising SA and engaging the audience. To answer **RQ2**, we improve and build the VR data story prototype by implementing five design features according to the design considerations. We conduct a between-subjects study (N = 62) to evaluate the effects of the story on improving SA of public health threats compared to the original version. The results indicate that the VR data story with immersive visualizations and interactions significantly increased participants' SA by enhancing their connection to the story situation and their perception of health threats. To explore **RQ3**, we collect quantitative and qualitative data from participants to understand how they perceive and interact with the story and investigate the effectiveness of each design feature. We found that three design features, including immersive visualizations, multiple perspectives, and embodied interaction, contribute to the improvement of SA.

The main contribution of this work is threefold: **(1)** conducting a design study to explore the design considerations of creating the immersive experience of a data story in VR, **(2)** providing evidence to demonstrate that VR can effectively enhance situation awareness (SA) of public health threats compared to reading the story on a 2D screen, and **(3)** offering design implications and insights into the factors contributing to the increased SA.

2. Related work

2.1. Situation awareness of public health

Situation awareness (SA) refers to a person's ability to identify, process, and understand what is happening in the surrounding environment (Endsley, 1988a; Salvendy and Karwowski, 2021). There are three levels of SA: (1) **perception** of elements in the situation, (2) **comprehension** of the situation, and (3) **projection** of future status (Endsley, 1988a). SA is generally characterized as the state model that reflects users' internalized model of the environment (Endsley, 1999).

In the public health field, the three levels refer to (1) perception of the information on public health data, (2) understanding of the information, and (3) prediction of future events or system states for public health decisions (Olson et al., 2013). The three levels of SA are progressive rather than independent, which means that people first need to improve their perception and understanding of health information before making correct predictions or decisions (Endsley, 1988a; Thacker et al., 2012).

In practice, it is crucial to raise the SA of health issues for anticipating any changes in the environment and taking the correct action (Thacker et al., 2012; Jessop, 2004). For instance, the U.S. government highlighted the need for SA to combat public health emergencies, such as the COVID-19 pandemic (GAO-22-104600, 2022). From the management perspective, to raise the SA, Henry et al. emphasized the importance of information exchange to increase government awareness and understanding of public health events (Rolka et al., 2008). Parse et al. proposed to enhance the SA by building a knowledge-based system to monitor and prevent public health risks effectively (Mirhaji et al., 2004). From the public's perspective, researchers explored the effects of social media in promoting people's awareness (Lamsal et al., 2022; Li and Cao, 2019). They found that media exposure could improve people's health SA as receiving more information from numerous sources could facilitate a comprehensive understanding of risky situations (Li and Cao, 2019). Furthermore, the other work has demonstrated how online media can be used as a situational-awareness resource to promote public health (Tobias, 2011). Inspired by previous works of SA-raising, our work focuses on investigating the effect of VR data story on increasing people's SA of public health threats. Before that, considering there are no clear guidelines on creating VR data stories for public health promotion, we begin by exploring how to create a VR data story by working closely with users.

2.2. Data stories for public health

Unlike traditional stories that emphasize characters and conflicts, a data story focuses on conveying data insights and information through visualizations. It organizes data in a logical manner to engage the audience and promote a deeper understanding (Segel and Heer, 2010). Data stories have been used for communicating complex and unfamiliar scientific content to the general public in various domains, such as metagenomics (Dasu et al., 2020; Sauer et al., 2016) and astrographics (Bock et al., 2019), as well as health-related topics to help the public understand diseases and their prevention. Meuschke et al. (2022) proposed a data story template for explaining diseases with narrative structures, specific patients, and interactive 3D anatomical models while leaving the evaluation to future work. So et al. (2020) applied data stories to present medical conditions to people and made them take medical conditions significantly more seriously. However, helping people understand and be aware of risk factors to prevent a disease is equally important but overlooked. Most recently, Leidecker-Sandmann and Kohler (2022) found that data stories in video and infographic formats helped the public reduce their bias on the risks of magnetic fields emanating from high voltage power lines. This work demonstrates the ability of data stories to communicate risk information. However, limited by 2D screens, users are unable to personally experience the risks depicted by the data and integrate risk awareness into their lives. Therefore, in this work, we utilize immersive VR to enhance users' situation awareness (SA) of health threats by increasing their sense of presence and information presentation in data stories. Our study complements previous literature by (1) verifying whether and how the combination of immersive characteristics with data stories could enhance the SA of public threats and (2) providing design implications of VR data stories for promoting people's SA.

2.3. VR stories

With its high immersion level and ability to create a profound sense of presence (Bindman et al., 2018), VR has emerged as a powerful medium for experiencing immersive stories. These VR stories are integral VR experiences consisting of narrative and VR storytelling (Williams et al., 2021). *Narrative* refers to the story content, including plots, scenes, and characters, while *VR storytelling* refers to the use of VR technologies to deliver the narrative. VR stories could warp the audience in a 360-degree virtual environment and give them the ability to walk around and interact with the environment (Studio, 2016, 2021). Compared to interactive VR games, VR stories focus more on information delivery rather than asking players to finish specific tasks under predefined gameplay rules and competition (Schell, 2008; Henrikson et al., 2016). Previous studies have shown that the interactive characteristic of VR stories can enhance the audience's presence, engagement, and emotions compared to the same story told on desktops or smartphones (Fonseca and Kraus, 2016; Visch et al., 2010; Bindman et al., 2018; Ho and Ng, 2022). For example, Ryan (2015) showed that introducing interactivity into VR stories can offer the audience agency and thus effectively engage them. Bahng et al. (2020) designed a VR story to simulate the experience of an elderly person living alone, facilitating viewers to reflect on loneliness and death.

Similarly, VR data stories also leverage storytelling techniques to deliver data facts or insights (Isenberg et al., 2018; Ivanov et al., 2019). Several works have used VR to promote comprehension of data in different scenarios other than public health (Lee et al., 2020; Ivanov et al., 2019; Ito and Hidalgo, 2019). For example, Takahito and Cesar created a data-driven VR story that leverages the immersive experience to promote learning from data (Ito and Hidalgo, 2019). However, it still remains underexplored how to deliver data stories properly in VR to promote health risk communication with viewers, considering the differences between data stories and regular narrative stories (Isenberg et al., 2018). This paper extends the existing literature by investigating how to leverage VR's immersive capabilities to engage users and convey invisible risks intuitively in a data story. With the goal of raising the SA of health threats, we evaluate the effectiveness of the VR data story and provide useful insights on designing immersive experiences of data stories.

3. Design process

In this work, we focus on how to use VR to deliver a data story that communicates health risks to people. To explore the design considerations (RQ1), we choose a representative data story (Bartzokas et al., 2021) and work with users to iteratively design the immersive experience of it. We first introduced the narrative of the data story and created an initial VR version of it by adding necessary functions compatible in VR. Then, we used a participatory design approach (Ehn, 2008) involving seven ordinary users in two rounds of studies and analyzed their feedback with three experts with an average of two years of VR experience and five years of HCI and visualization experience after each study. In Fig. 1, we identified five design considerations based on the first study. We then revised the VR data story with input from participants and experts. In the second study, we verified if the revised story met the participants' expectations and made minor improvements.

3.1. The data story case

Story Selection. We focused our search for data stories on the COVID-19 pandemic, which is one of the most concerning public health events in recent years. Initially, we gathered 12 related data stories (in the supplemental material) that included 3D scenarios or could be transformed into 3D models with visualizations. We selected a representative story (Bartzokas et al., 2021) that (1) is related to the theme of public health and can be leveraged to raise people's awareness of health risks, (2) was set in a real-world situation familiar to most people, and (3) had a complete storyline with visualizations, allowing us to concentrate on designing the immersive story experience. Compared to other candidate scenarios, the one we chose depicts the scenarios most common to the lay public and covers the most typical types of visualizations used for infection-related data facts.

Data Story Description. The original data story aims to inform readers of the importance of ventilation by explaining why opening windows is critical to reducing viral infections in schools (Bartzokas et al., 2021). This data story is based on the post-pandemic context of schools reopening. Data storytelling experts use visualization to demonstrate how dangerous a classroom full of viruses can be with the windows closed, and how the virus concentration is greatly diluted after the window is opened or an air purifier is installed. They use intuitive data visualizations to show the spread of Covid-19 in a classroom under three ventilation conditions: keeping windows closed, opening one window, and installing an air purifier. The original data story utilizes a scrolling storytelling approach (Sultanum et al., 2021; Seyser and Zeiller, 2018) to juxtapose the narrative text and its corresponding visualizations in web pages, allowing people to dynamically update both by scrolling down the page.

The story begins by introducing a typical classroom scene in New York City. The classroom has nine students because of the strict protocols for reopening schools. The students are seated six feet apart to keep social distancing and wear masks, and there is a teacher standing at the front of the room (Fig. 2(S1)). At the beginning, the room lacks sufficient ventilation with all of the windows closed. Then, the story introduces an infected student (Fig. 2(S2)) and draws the visualization lines that trace the student's breath as it rises and begins to disperse contaminated respiratory aerosols throughout the room. Within a short duration, the contamination within the room reaches its peak level, causing the contaminants to circulate continuously throughout the space (Fig. 2(V1)). The visualization uses dense, dark-colored lines to show the concentration level of the virus in the classroom. After that, the narrative text introduces the related policy that recommends four to six air exchanges per hour in classrooms and mandates every classroom has at least one operable window for ventilation. Next, one window opens and the fresh air dilutes the contaminants. The visualizations utilized light colors and sparse lines to depict the diluted effect of the virus in the classroom (Fig. 2(V2)). However, the story text then says that it is not enough to get six air exchanges with only one window opened. Therefore, a simple air cleaner with a HEPA filter and a box fan is added. The visualization of the contamination is further diluted in Fig. 2(V3). Then, the story says that using airflow visualization is one way to understand the importance of ventilation and raise people's awareness, people can also look at the data in another way, such as using a 2D heatmap to see the overall centration. The corresponding thermal map visualization appears, showing roughly the overall viral concentration distribution in the room. Finally, the story concludes that opening windows and installing air cleaners are both effective methods to reduce contamination. Considering the cost, opening windows is the simplest and most practical way.

3.2. Step 1. Developing the initial VR version of the data story

To effectively convey the narrative and factual information of the data story in VR, we make necessary adjustments during the creation of the initial version to ensure compatibility with the VR platform. We built the story with four components (Fig. 1), following the immersive data experience pipeline (Lee et al., 2020).

(1) Story Scene Modeling. We used *Maya3D* to model the 3D scene, students, and teachers in VR. As shown in Fig. 2, the scene has different states. We construct the scene and its corresponding changes under

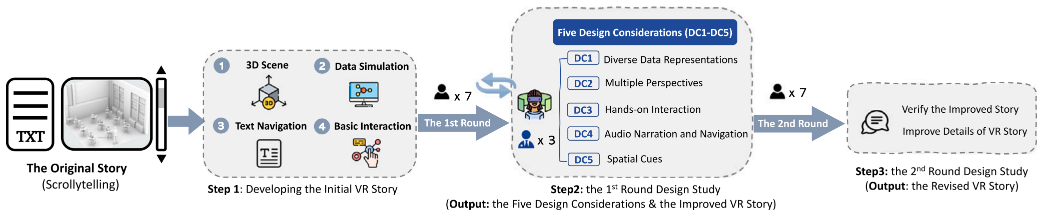

Fig. 1. The design process of the immersive data story. **In Step 1**, we transformed the data story into an initial VR version, which contains: (1) the 3D scene, (2) simulated data visualization, (3) a textual menu, and (4) basic interactions. **In Step 2**, we conducted the first study with seven participants and qualitatively analyzed their feedback with three experts. We summarized the five design considerations and then improved the story based on them. **In Step 3**, we conducted the second study to verify the revised data story and improved several details.

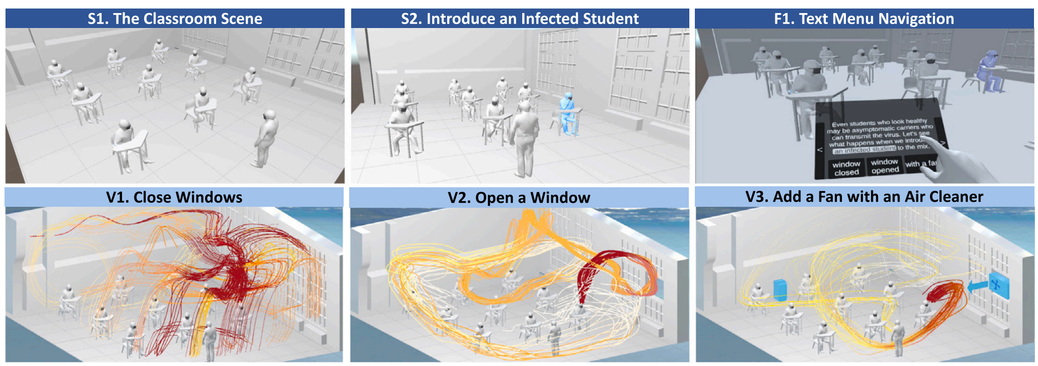

Fig. 2. The initial VR version of the data story. (S1) shows the classroom scene and (S2) displays the infected student. (F1) shows the menu for users to read and control the narratives, with the 3D scene changed accordingly. (V1-V3) show the three ventilation conditions with data visualization: (V1) windows closed, (V2) one window opened, and (V3) installing an air purifier.

different conditions according to the narrative and visualizations of the data story. For example, the second scene (Fig. 2(S2)) shows the plot when one infected student (marked in blue) was introduced in the classroom.

(2) Data Simulation and Immersive Visualization. We employed airflow visualization to depict the spread of the virus in the initial VR data story. To present the data visualization, we consulted with a fluid mechanics expert for the parameters of the simulation and reproduced the visual form in VR by ourselves. We utilized the CFD software, *Ansys Fluent*, to model the flow dynamics and generated simulation results and draw the data in the three ventilation conditions (Fig. 2).

(3) Textual Menu for Narratives. We added a VR wrist menu for users to read the narrative texts of the story (Fig. 2(F1)) and they could switch the texts by clicking buttons with virtual hands with the visual scene updating accordingly. Similar to the original data story, we synchronized the narrative text with the corresponding VR scenes and visualizations. The user reads the text in the order in which the original story is told, with the VR scene and visualization dynamically updating to align with the narrative progression.

(4) Basic Interactions. We created virtual hands for users to click the menu and provided two methods for users to move in VR, including teleportation and continuous movement with a joystick. Compared to reading the data story on 2D screens from a bird's view, users have more freedom in the initial VR data story. They are allowed to walk around in the classroom to explore details of the scene from their own perspectives.

3.3. Step 2. The first round study: Exploring design considerations

With institutional IRB approval, we organized the first study with seven participants (average age = 22.43, 2 females). We recruited them from local universities by sending emails and they all signed informed consent forms before the study. We involved the participants to understand their views on how to improve the initial VR version of the story to raise the SA of public health threats (G1) while promoting user engagement with the story (G2).

Procedure. We invited the participants to view the original data story to ensure that they understood the story context and to gather useful and appropriate feedback on its transition into VR, instead of comparing the original data story with its VR version. After reading the original story, we familiarized the participants with the *Oculus Quest2* and the VR operations. Participants were free to experience the story and we video-recorded the process. Finally, we interviewed the participants to ask for their feedback on what designs could be added or modified to promote two goals (G1, G2).

Interview and Analysis. We recorded the interviews and took notes on the participants' suggestions. The first author transcribed all the interviews and analyzed the data with the three experts using inductive thematic analysis to obtain a broader analysis of data (Braun and Clarke, 2006a). We performed open coding to generate the initial codes independently (Charmaz, 2006). Then, we had two rounds of discussions to compare, group, and reshape the codes, whereby mismatches were resolved. We carefully reviewed the themes to merge them into categories. We finally eliminated the categories proposed by less than 3 participants, summarized the remaining categories, and concluded with five design considerations.

3.4. Step 3. Concluding design considerations

We elaborate on the design considerations based on user feedback and the literature.

DC1. Alternative data representations. Improving people's SA can be achieved by promoting their perception of the health threat represented by data visualizations (Li and Cao, 2019; Endsley, 1988a). Participants (6/7) reported that they prefer to view the COVID-19 spread from *"vivid and comprehensive forms beyond the lines"* to increase the sense and comprehension. This is beneficial for "kicking" people out of a fixed viewpoint and consequently enhancing their understanding (Xiong et al., 2019). Thus, we then decided to incorporate dynamic particles and immersive heatmaps based on user feedback and discussions with experts, as these two visualizations could well

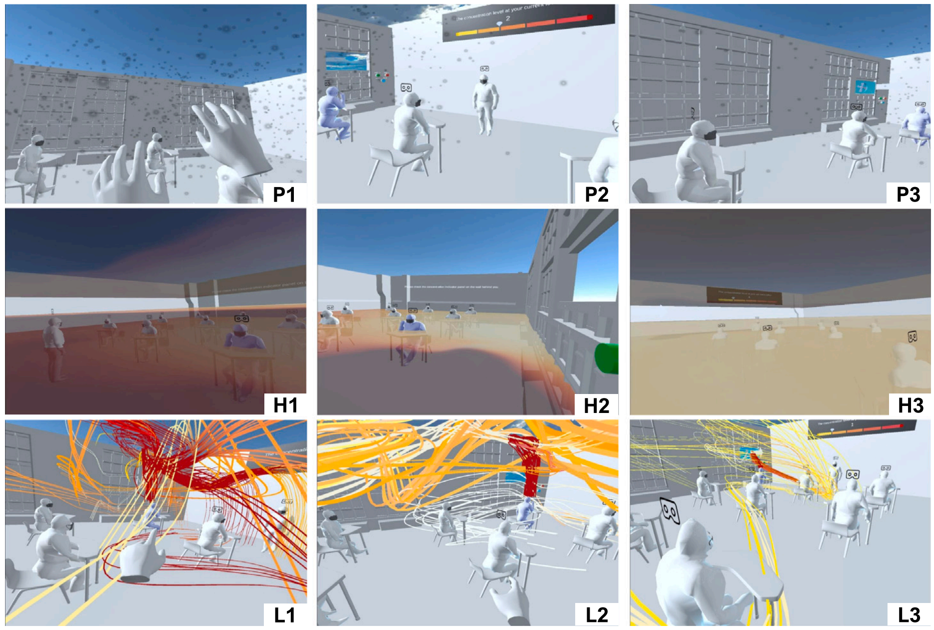

Fig. 3. The VR data story incorporates three immersive visualizations of COVID-19. P1, P2, and P3 depict the virus using a particle representation under three different ventilation conditions. Similarly, H1, H2, and H3 showcase the immersive heatmap, with H2 specifically displaying the bottom layer by applying a layer filter. L1, L2, and L3 represent the virus using 3D lines.

convey virus distribution and provide realistic effects of the virus, respectively (Kraus et al., 2020).

DC2. Multiple perspectives for situational understanding. Five participants suggested providing the third-person perspective in addition to the first-person view for them to *"observe both the overview and details of the data"*. Existing literature also proved that using multiple perspectives could enhance spatial awareness and allows people to gain a broader understanding of the situation and data (Gorisse et al., 2017; Hoppe et al., 2022; Lee et al., 2020). Hence, we then allowed users to choose freely between the third- and the first-person views in the VR data story. We also offered a perspective-taking function for users to take any character's (e.g., a student) view to promote understanding of the story scene and data.

DC3. Embodied interactions for improving the sense of presence. Interactivity and movement are useful to enhance participants' understanding of the virus spread through the environment (Radziwill, 2017). All participants needed more interactions to improve their sense of presence in the story, such as *"opening the windows with hands"*. After discussions with experts, we implemented several interactions requested by most participants, such as virtual buttons and an interactive menu. Some interactions are tied to the corresponding content and visualizations in the story. For example, users can press the button to open the window and this interaction could trigger the story description under the open window condition and update the scene and visualization.

DC4. Combining audio and visual channels. Four participants mentioned that *"frequent switching between reading text and observing story scenes in VR"* added an extra burden, as it distracted them from exploring the story scenes. In addition, they reported that *"most of the textual information can be obtained directly from the visual scene"*. Therefore, it is necessary to use the audio narrative and simplify the narrations (Fei et al., 2022; Tian et al., 2023), such as removing descriptive texts that can be obviously seen by users in VR.

DC5. Spatial cues for story exploration and awareness-raising. Five participants mentioned they did not have *"a clear direction when entering the VR story"* and recommended adding more cues, which help guide the data story exploration (Joshi, 2021; McKenna et al., 2017). Hence, it is better to highlight several objects and add textual cues (e.g., *"the button for opening the window"*) floating in the scene as the spatial cues. These cues can remind users of the interaction and information in the scene. Moreover, they need to be dynamically integrated into the story scene and presented based on the narrative audio.

3.5. Step 3. The second round study: Verifying the improved data story

We developed the corresponding functions in the VR data story (Section 4) based on the five DCs and conducted the second study to verify the refined version. Following the same procedure and analysis method as the first study, we invited the participants to experience the revised story freely and conducted interviews to ask them about their satisfaction and opinions. Generally, all participants expressed satisfaction with the revised story. They have various ideas about some details of the story, such as adding an autoplay for audio or not. We discussed these conflicts with the experts to determine what these functions should be like.

4. VR data story prototype

This section demonstrates the VR data story with the five design features informed by the design process.

4.1. Diverse data representations

We introduced two additional data representations to enhance the diversity of the Covid-19 depiction in the VR data story. First, we utilized a particle system to create dynamic visualizations of particles under the three ventilation conditions. These visualizations were generated based on a simulation where the density of particles at a specific location represents the concentration level of COVID-19 (Fig. 3 P1-P3). Then, we introduced a heatmap with three layers to depict the distribution and concentration levels of the virus at various heights. The material of the heatmap was made translucent to balance the need for visibility and immersion, minimizing obstruction of the users' view, as shown in Fig. 3 H1-H3. These visualizations, along with the initial 3D lines in Fig. 3 L1-L3, provide three immersive visualization modes for depicting COVID-19 in the VR data story.

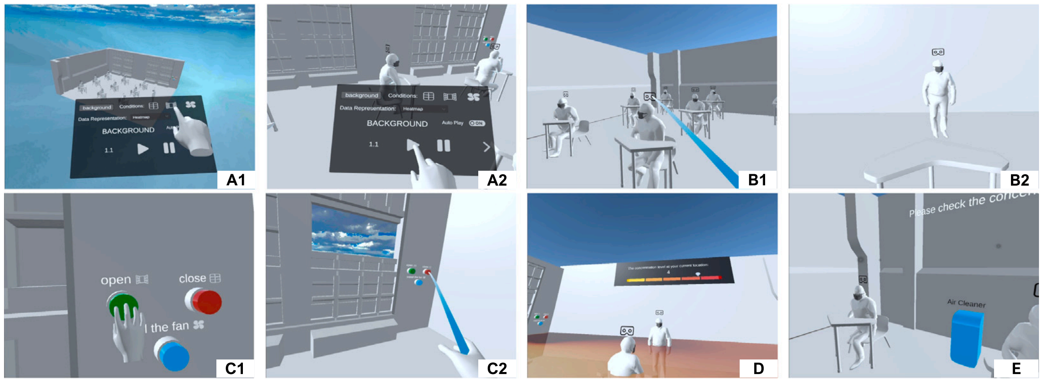

Fig. 4. The developed interactions in the VR data story. We present A1 and A2 to show the menu controlled by virtual hands in the third-person and the first-person view. B1 demonstrates triggering the perspective-taking of a student's view and B2 displays the student's view. The C1 and C2 show the buttons, which can be pressed by virtual hands or rays remotely. D presents the indicator board that displays the virus concentration level based on users' real-time positions. E presents the air purifier as a visual cue that guides users' attention to explore the story.

4.2. Multiple perspectives

We offer three types of perspectives for users to experience. In the third-person view (Fig. 4(A1)), users can have a bird's-eye view of the entire scene and explore it from different angles. In the first-person perspective (Fig. 4(A2)), users have the freedom to observe the scene in detail by walking freely. Switching between the first-person and third-person views can be done effortlessly using a switching button on the controller. Furthermore, users can select the perspective of a specific student or teacher by clicking the glasses-like button above each character, as shown in Fig. 4(B1). After entering their perspective, they could observe the scene from the character's location. Once in their chosen perspective, users can observe the scene from the location of the selected character. For instance, Fig. 4(B2) illustrates the vision of a student who is seated at the front of the classroom after assuming their perspective.

4.3. Embodied interaction

We implemented four kinds of embodied interactions in the VR data story to enhance the people's presence and understanding (Kilteni et al., 2012).

VR wrist menu. We introduced a VR wrist menu to replace the previous textual VR menu. As shown in Fig. 4(A1) and (A2), this new menu offers buttons for users to select the three mentioned ventilation conditions, switch visualization modes, and play the narrative audios. Importantly, users can access and interact with the menu seamlessly in both the third-person and first-person perspectives.

Interactive buttons. Drawing inspiration from popular VR games known for their use of interactive buttons to control the virtual environment and enhance embodied experiences (MetaQuest, 2021; Tong et al., 2022), we incorporated interactive buttons into our VR data story. These buttons allow users to manipulate the ventilation conditions. To enhance the sense of embodiment, we implemented physics and collision detection, enabling users to press the buttons using their virtual hands (Fig. 4(C1)). Additionally, users can trigger the buttons remotely using the raycasting selection method (Fig. 4(C2)).

Interactive concentration indicator board. In order to enhance engagement and comprehension of the data story, we introduced an interactive board that dynamically displays the concentration level of the virus based on users' positions in real-time. This concentration number is calculated using simulated data. The interactive board is positioned in front of the classroom (Fig. 4(D)), allowing users to easily monitor the updated concentration number as they move within the scene.

Continuous movement and VR teleportation. We offer two methods of movement: physical walking and assisted walking (Fung et al., 2006). Physical walking allows users to physically move around in the VR environment, while assisted walking enables movement without physical locomotion through VR teleportation and continuous movement techniques.

4.4. Audio narration and navigation

To enhance the immersive experience, we converted the textual content into audio clips (Microsoft, 2022) and refined the narratives based on user feedback. Once immersed in the story, audio can serve as the narrative voice, providing background information and describing the insights conveyed by data visualizations. Users can control audio playback using a VR wrist menu. After experiencing the complete story in order initially, users have the freedom to explore and select scenes of interest (e.g., windows closed) in any desired sequence. In addition, we incorporated various audio cues to guide users through the story and facilitate their exploration and interaction. These cues include descriptions of the immersive visualizations, such as the heatmaps and particles, as well as indications of the current ventilation conditions or visualization modes. Additionally, we provided audio prompts to guide users' interactions, such as *"please push the button to open the window"*.

4.5. Spatial cues

To facilitate users' attention and exploration in the VR data story, we implemented spatial cues in the form of visual and textual elements. Visual cues, such as the presence of the air purifier, the legend on the indicator board, and highlighted buttons next to the window, serve as visual indicators accompanying the story narrative. Text cues are displayed in conjunction with or separately from visual cues, providing additional information and instructions. For example, we included text prompts like *"open the window"* near the corresponding button to clarify its function. In addition, cues such as *"check the indicator board behind you"* automatically appeared based on the story narrative, guiding users' attention to relevant interactions within the story. We adjusted the directions and styles of all the textual cues to the user's line of sight for text legibility and accessibility (Jankowski et al., 2010; Chen et al., 2004).

5. Experiment overview

Our study had two primary goals. The first is to verify the impact of the VR data story on enhancing situation awareness (SA) regarding public health **(RQ2)**. To achieve this goal, we conducted a between-subjects study involving 62 participants. We compared the effects of the VR data story condition with a control condition, where participants read the original data story through 2D screens. Pre-test and post-test data were collected to assess the improvement in SA in both conditions. The second goal is to gain insights into users' perceptions and interactions with the VR data story, employing a user participation design approach to derive design implications **(RQ3)**. To achieve this objective, we conducted a comprehensive analysis of both quantitative and qualitative feedback gathered from participants in both the control and VR conditions. This analysis provided a deeper understanding of how users perceive and engage with the VR data story.

5.1. Participants

We obtained institutional IRB approval before recruiting 62 students (28 females) from three universities through mailing lists and social media. English is the language of instruction in all of these universities, with two being local institutions and one being a US-based university. The participants were of Asian descent and their ages ranged from 19 to 28 years old ($MEAN = 21.90, SD = 3.03$). The participants were randomly assigned to either the original story group or the VR data story group. In the VR group, 20 participants had prior VR experience without experiencing VR sickness, while 11 participants had no prior VR experience. On a 7-point scale, participants self-reported a familiarity with 3D games or 3D modeling with a mean score of 3.80 ($SD = 1.67, MAX = 7.00, MIN = 1.00$) and a familiarity with visualization with a mean score of 4.03 ($SD = 1.72, MAX = 7.00, MIN = 1.00$).

5.2. Experiment setup

We set two conditions: the control condition, which involved reading the original data story (Section 3.1), and the experimental condition, which involved experiencing the revised VR data story (Section 4). Participants were randomly assigned to one of the two conditions. In the control condition, participants read the story on a standard 27-inch monitor with a resolution of 1920 × 1080. On the other hand, participants in the experimental condition experienced the VR data story using an *OCULUS QUEST 2* headset. The experiment, including both the VR condition and the control condition, took place in an indoor laboratory, while the VR condition was conducted in a 12 × 10 ft room that is free of obstacles. For the experiments with the participants (N = 3) from the US-based university, one of our co-author located in the US conducted the experiment. We recorded the study sessions using videos in both the VR and control groups. In the VR condition, we used the built-in recording feature of the Oculus Quest 2 to capture the participants' first-person perspective experience. Additionally, we projected the VR images onto a computer screen for real-time observation during the study. In the control group, we used screen recording software to record the entire process of participants reading the data story. We took notes in both groups to record some immediate feedback (if any) from the user during the experiment. Participants in both conditions were given unlimited time to view the story and had the freedom to stop at any point.

5.3. Study procedures

Prior to the study, participants provided informed consent and completed a pre-test questionnaire to assess their initial situation awareness (SA) of health risks regarding their real-life experience in schools. Then, we introduced the data story concept and the story's background to the participants. Participants in the VR group received a training session to familiarize themselves with the operations in VR. Throughout the experiment, participants were encouraged to verbalize their thoughts.

After reading or experiencing the data story, each participant completed a post-test on SA and responded to a post-study questionnaire that assessed their engagement and comprehension of the story. We conducted individual interviews with participants from both conditions to gather their reflections on their viewing experience and the factors influencing their SA ratings. Additionally, we interviewed participants from the VR condition to obtain their feedback on the implemented features (Section 4). Participants in the original story group dedicated approximately 25 min to the entire experiment and received $7 as compensation for their time. In the VR group, each experiment lasted approximately 65 min, and participants were provided with a $20 gift card as compensation.

Pilot Study. We conducted a pilot study involving four additional participants to gather preliminary insights before the formal experiment. The findings revealed variations in the amount of time participants spent on the three immersive visualizations in the VR data story. In the main experiment, we aimed to mitigate the potential influence of anchoring effects (Valdez et al., 2017). Therefore, we created three versions of the VR data story, only varying in the order of immersive visualizations (lines, heatmaps, particles) presented. We randomly assigned one version to each participant in the VR condition, and participants could switch between different visualizations when experiencing the story.

5.4. Data collection and analysis

We collected quantitative and qualitative data, including self-reported questionnaire results, user feedback from the interviews, and user interaction logs in VR. We first introduce the questionnaires. Detailed questions are in the supplementary materials.

Situation awareness. Before and after viewing the story, participants were asked to respond to a 7-point Likert scale, which measured the three levels of SA (Endsley, 1988a): the **perception** *(how much attention people paid to the situation)*, (1: *"never care about"*, 7: *"always pay attention to"*); **comprehension** *(to what extent people understood the information conveyed by the situation)* (1: *"not at all"*, 7: *"definitely understood"*); and **projection** *(how people intended to act upon the described situation)* (1: *"definitely not"*, 7: *"definitely"*). We adopted these questions in reference to previous work on measuring SA from a comprehensive perspective by Endsley and public health (Endsley, 1988a,b; Feng and Tong, 2022; Li and Cao, 2019). In the pre-test, we asked participants to answer these questions in the context of their college life. We provided them with a situation reference by adding "on your campus" to the question, such as *"How much attention do you pay to whether the window is opened on your campus?"* (perception). We took the pre- and post-test approach rather than the "frozen" method that pauses the story at random times to get the rating of SA (Endsley, 1988b), as the disruptive simulation halts can cause interruption of the immersive story experience. The pre-test scores were taken as the "ground truth" information to measure an individual's SA improvement. We also measured participants' **perceived level of threat** in the post-test as people's protective behaviors are mediated by their perceived threat Li and Cao (2019).

Story engagement and understanding. Following the methodology used in Busselle and Bilandzic (2009) for immersive stories, we assessed participants' engagement and understanding of the story using a Likert scale ranging from 1 (not at all) to 7 (extremely). The metrics included narrative understanding, attentional focus, emotional engagement, and narrative presence. Narrative understanding measured participants' comprehension of the story, attentional focus gauged their level of attentiveness, emotional engagement assessed their empathy towards the characters, and narrative presence captured their sense of immersion and involvement in the situation. We further evaluated the impact of the VR data story by incorporating questions from previous studies on data stories. These questions aimed to assess participants' affective involvement, enjoyment, aesthetics, and cognitive involvement. Affective involvement measured the emotional impact of the story, enjoyment assessed the level of interest it generated, aesthetics gauged its visual appeal, and cognitive involvement

Table 1
Independent samples t-Test on the pre-test and post-test scores.

	2D			VR			Gain scores		
	Pre (SD)	Post (SD)	*P-value*	Pre (SD)	Post (SD)	*P-value*	2D	VR	*P-value*
Attitude	3.11 (1.78)	5.10 (1.49)	p < .001	2.74 (1.85)	5.23 (1.27)	p < .001	1.98 (1.65)	2.48 (1.86)	p < .05
Comprehension	3.27 (1.74)	4.98 (1.71)	p < .001	2.50 (1.78)	5.81 (1.11)	p < .001	1.71 (1.64)	3.31 (1.92)	p < .001
Projection	2.19 (1.39)	3.85 (1.81)	p < .001	1.97 (1.86)	4.31 (1.46)	p < .001	1.66 (1.39)	2.34 (1.32)	p < .05
Perceived threats	–	2.81 (4.09)	–	–	5.16 (2.94)	–	–	–	p < .001

evaluated the intuitiveness of the story's visualization (Amini et al., 2018; Hung and Parsons, 2017).

Ratings of the VR data story design. We asked participants to rate the design features (DF1-DF5) of the VR data story on a 7-point Likert scale (1: least effective", 7: "most effective"). The ratings include the ratings of their characteristics (Fig. 6(A)), the preference scores for each immersive visualization (Fig. 6(B)), voting for different perspectives and their effects on raising SA (Fig. 6(C)), and overall ratings for each design feature in contributing to SA-raising and story engagement (Fig. 6(D)).

5.4.1. User interactions

We implemented logging functions in the VR data story to capture user interactions (Hufnagel, 2022), including interactive manipulations (e.g., clicking buttons), the number of times each interaction was triggered, the time duration under different conditions or visualization modes and the movement of the participants. All participants were informed of the data collection for research purposes.

5.4.2. Interview

We conducted a semi-structured interview with each participant to ask (1) how and why they gave the SA scores in the two conditions and (2) for feedback on the immersive story experience design from the VR group. VR data story interviews averaged 25 min, while those in the control condition averaged 15 min. Two authors analyzed the interview responses and performed a thematic analysis (Braun and Clarke, 2006b) based on the audio transcripts and video recordings. We first performed open coding (Charmaz, 2006) independently to generate the initial codes. Next, we iteratively reviewed, modified, and developed the themes. We solved the conflicts through multiple rounds of discussion with the other two co-authors and finally reached a consensus.

6. Results

In line with the goals of our user experiment, which aim to verify the impact of the VR data story **(RQ2)** and gain insights into users' perceptions for design implications **(RQ3)**, we present both quantitative and qualitative feedback pertaining to these two objectives.

6.1. Quantitative feedback: Improvement of SA and audience engagement

6.1.1. Improvement of SA

Table 1 presents the average scores of the pre-test and post-test, along with their standard deviations (SD). We conducted independent-sample t-tests to examine the statistical significance of the differences between the pre-test and post-test scores within and between the two conditions. The results indicate that both the VR data story and the control condition led to significant improvements in situation awareness (SA) across the three levels of perception, comprehension, and projection. To further assess the difference in the effect of the VR data story compared to the control condition, we calculated the gain scores by subtracting the pre-test scores from the post-test scores (Zimmerman and Williams, 1998). Subsequently, we conducted t-tests to compare the gain scores. The results (Fig. 5(A)) reveal that the VR data story experience significantly increased SA to a greater extent than the control condition in terms of comprehension ($t(60) = 3.98, p < .001$) and projection ($t(60) = 5.31, p < .001$). Furthermore, participants in the VR condition reported a significantly higher level of perceived threat ($t(60) = 2.22, p = 0.03 < .05$) than the control condition.

6.1.2. Story understanding and engagement

Referring to Fig. 5(B), participants in the VR condition exhibited a significantly stronger sense of presence ($t(60) = 3.30, p = 0.0016 < .05$) compared to the control condition. Additionally, the VR condition showed higher levels of affective involvement ($t(60) = 5.51, p < .001$), and enjoyment with visualization ($t(60) = 2.07, p = .042 < .05$) than the control condition. The differences in the other dimensions are not statistically significant.

6.2. Qualitative feedback: Reasons for the SA enhancement

6.2.1. SA enhancement in both conditions

Based on participants' justification for their responses to pre-test and post-test questionnaires, we identified two common reasons for the enhanced SA in both conditions. Stories in both conditions **(1) made the COVID-19 health threat that is hidden in real life visually observable** and **(2) guided viewers to identify potential causes of the health threat through the narrative.** Participants in both conditions all mentioned that they *"did not pay much attention to the described situation before viewing the story"* (Control, P3), and realized the importance of good ventilation after seeing the *"apparent difference before and after the Covid-19 was greatly diluted"* (VR, P6). This indicates that the information that was transparently conveyed by data stories in both conditions contributed to the SA promotion, which may also explain why there were no significant differences in the information perception (Fig. 5(A)).

6.2.2. The difference in SA enhancement between the two conditions

Based on the qualitative analysis, we observed three reasons why the participants who viewed the VR data story had significantly higher scores in raising SA than those who viewed the data story. First, **the immersive experience increases the sense of presence and thus promotes participants' projection into the future.** Approximately half of the participants (15/31) in the VR condition reported a *"strong sense of presence"* and expressed the feeling of connected to the story situation, as they were fully wrapped in the immersive scene. In contrast, participants in the control condition described themselves as *"distant spectators of a story"* (Control, P6), lacking the same level of emotional and experiential connection. VR participants also mentioned *"being reminded of similar scenes in their own lives when staying in the room"* (VR, P24) that may further provide evidence of the benefit of immersion in enhancing participants' self-projection and personal connection to the story. In comparison, the original story did not evoke a similar level of self-projection or emotional impact, as participants found it *"less memorable and lacking in emotional elements"* (Control, P24). This echoed the scores of the projection (Fig. 5(A)) and the presence of story engagement (Fig. 5(B)).

The second reason is that **the story experience with embodied interactions deepens the situational understanding of the story.** Participants who experienced the VR data story could interact and observe the story scene and immersive data visualization in a natural way. They reported that this experience enhances their engagement with the story because they could *"feel more engaged by interacting with the elements in the story scene and taking the perspective of the students"* (VR, P15). In contrast, the control condition participants only saw the visualization on the screen, without stepping into the virtual scene and interacting with the story's scene or elements, and as a result,

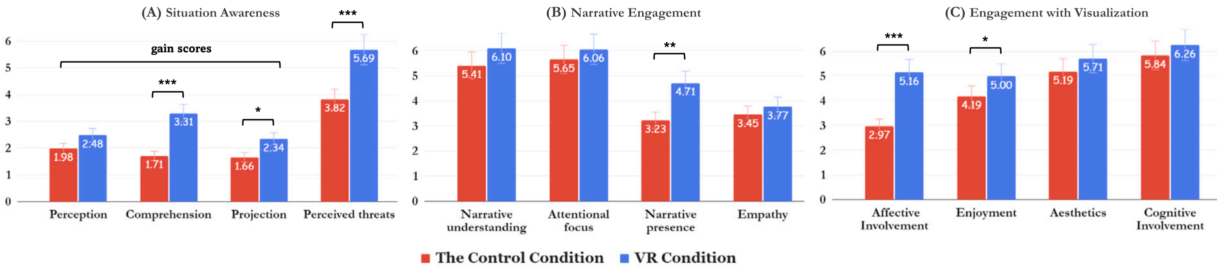

Fig. 5. The results of situation awareness (SA) measurement, story understanding, and engagement in the two conditions. (A) displays the average (gain) scores that measure the SA calculated based on the pre-test and post-test. (B) shows mean scores of the four dimensions related to understanding and engagement with the immersive story. (C) presents the mean scores of viewer engagement of the visual representation in the two stories.

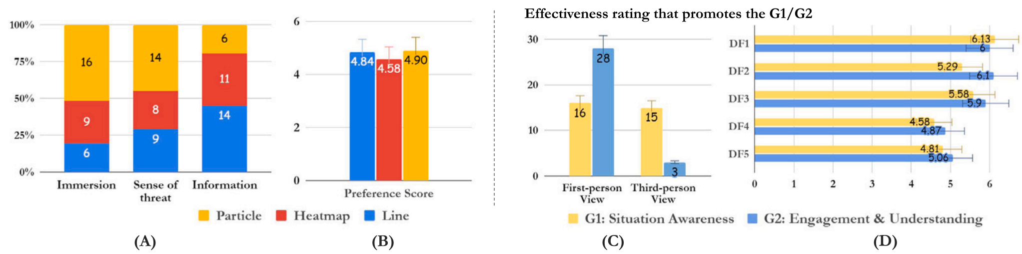

Fig. 6. Feedback on Design Features. (A): Participants' ratings on immersive visualization in terms of immersion, sense of threat, and information. (B): Participants' preference scores for each visualization. (C): Participants' votes on two perspectives based on their promotion of goals G1 and G2. (D): Participants' ratings on the contribution of each design feature to the story goals (G1 and G2).

they said they did not feel *"empathizing with the characters in the story"* (Control, P26). This explains the significance of the comprehension and self-projection scores in SA (Fig. 5(A)).

Additionally, **the immersive visualization provided by the VR experience enhances the sense of threat.** Both groups acknowledged the intuitiveness and vividness of the visualizations, but VR participants, in particular, expressed *"a sense of crisis surrounded by the immersive visualization"* (VR, P12). The reason is that in VR, they could *"witness the spread of COVID-19 in their surroundings"* and they said this experience made them feel *"strong feelings of crisis"* (VR, P25). However, the majority of participants (26/31) in the control condition reported that *"the visualizations are limited to conveying information without evoking strong emotional responses"* (Control, P17). These qualitative findings align with the quantitative feedback on perceived threats and engagement as depicted in Fig. 5(A) and (C).

6.3. Quantitative feedback: Design features of the VR data story

In this section, we present participants' quantitative feedback and their interactions on the design features in the VR data story (Section 4) to understand how people perceive and interact with the story **(RQ3)**. Participants gave their scores for each design feature on how well they contributed to the two goals of the VR data story, respectively (G1: raising the SA of health threats and G2: promoting understanding and engagement with the story).

6.3.1. Diverse immersive data representations (DF1)

Participants were asked to select the best representation among the three immersive visualizations in terms of immersion, threat, and information conveyance. In Fig. 6(A), the particle received the highest number of votes for both immersion (16/31) and threat (14/31), while the immersive line was perceived as the most informative visualization (14/31). Participants also provided preference scores for each visualization in Fig. 6(B), with the particle ($MEAN = 4.90, SD = 1.33$) and the line ($MEAN = 4.84, SD = 1.39$) receiving slightly higher scores compared to the heatmap ($MEAN = 4.58, SD = 1.78$). Regarding their perceived contribution to G1 and G2, as shown in Fig. 6(D), the immersive visualization (DF1) obtained the highest scores (G1: $MEAN = 6.13, SD = 0.92$, G2: $MEAN = 6.00, SD = 0.89$), which were significantly higher than other design features in promoting G1, and than DF4 and DF5 in promoting G2 based on t-test analysis ($p < .001$).

For the interaction logs, we calculated the number and duration of interactions with the three visualization types in VR. Fig. 7(A) shows that participants clicked on the heatmap mode significantly more times than on the other modes (heatmap vs. line: $t(54) = 3.09, p = 0.003 < .01$, heatmap vs. particle: $t(54) = 2.54, p = 0.014 < .05$). There is no significant difference in the duration of interaction with the three modes.

6.3.2. Multiple perspectives (DF2)

The first-person perspective and the third-person perspective got similar numbers of votes (15:16) in terms of their ability to raise SA (G1). However, the first-person view received more votes (28:3) than the third-person view in promoting G2 (Fig. 6(C)). Generally, the result indicates that participants rated DF2 as significantly more efficient in promoting G1 than DF4 ($p < .05$), and more effective than DF4 and DF5 in promoting G2 ($p < .001$). Participants' interaction logs in Fig. 7(C) indicate that they spent significantly more time exploring the VR story under the first-person perspective (t-test: $t(54) = 12.43, p < .001$), with significantly more interactions than the third-person perspective ($t(54) = 4.21, p < .001$).

6.3.3. Embodied interactions (DF3)

As mentioned in Section 4, we provided several embodied interactions, including the interactive buttons to manipulate the props, an interactive board, a VR wrist menu controlled by virtual hands, and VR teleportation locomotion. We invited participants to rate these interactions generally. From Fig. 6(D), DF3 received a significantly higher score in promoting G1 ($MEAN = 5.58, SD = 0.85$) and G2 ($MEAN = 5.90, SD = 0.98$) than DF4 ($p < .01$), and was rated more effective than DF5 for G1 ($p < .05$) We logged the interactions under the three ventilation conditions (V1: windows closed, V2: a window opened, V3: an air purifier installed), summarized in Fig. 7(B). We found that participants spent significantly longer time under V3 than the other two conditions (V1-V3: $t(54) = 5.32, p < 0.001$, V2-V3: $t(54) = 3.78, p < 0.001$). Furthermore, participants had significantly

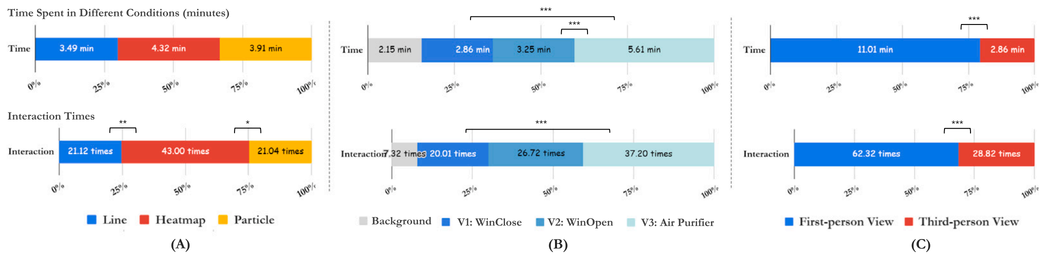

Fig. 7. User interaction and duration across visualization modes and ventilation conditions. (A): Average time (minutes) and interaction times in different visualization modes. (B): Data depicting interaction and duration under varying ventilation conditions. (C): Interaction data comparing first-person and third-person perspectives.

more interactions in V3 than in V1 ($t(54) = 3.91, p < 0.001$), but the difference with the windows open condition was not statistically significant.

6.3.4. Audio narration and navigation (DF4) and spatial cues (DF5)

The effectiveness scores of DF4 and DF5 are significantly lower ($p < .05$) than the other design features for both SA improvement (G1) and narrative engagement (G2); and there was no significant difference between them (Fig. 6(D)). To explore whether how participants perceive and leverage the audio or spatial cues despite their relatively low assistance to SA improvement, we analyzed and presented users' qualitative feedback in Section 6.4.

6.4. Qualitative feedback on the design features

6.4.1. Diverse immersive data representations (DF1)

This subsection presents the participants' feedback on each immersive visualization **(RQ3)**.

Immersive particles. Participants noted that the particles closely resembled the virus in the shape and the dynamic movement, which made them perceive it threatening. This explains why the particle was chosen as the most threatening visualization in Fig. 6(A). However, some participants mentioned they experience adverse effects from the realistic effect of the particles, reporting feelings of nausea (P17, VR) because of the particles appearing to *"fly and jump towards them"* (P6, VR). Participants also indicated that the particles conveyed **the least amount of information compared to the other data representations**, as they could only gain *"a rough sense of the virus density from the particles"* (P9, VR). This is consistent with the feedback on the particles in Fig. 6(A).

Immersive heatmaps. More than 10 participants chose the heatmap as the most informative one as *"they are continuously distributed [across the space] from the first-person view, giving me the impression of being wrapped"*. (P15, VR). However, participants also mentioned two limitations of the heatmaps. First, it was challenging to perceive the overall distribution of the heatmap from the first-person view (P12, VR), necessitating participants to walk around to observe it. Second, a few participants (3/31) said the heatmaps are not immersive enough and suggested that *"using a cube instead of three layers for the heatmap may enhance immersion"* (P2, VR).

Immersive 3D lines. Some participants (6/31) thought the 3D line was immersive and reported that *"the line crosses my line of sight, making it terrifying"*. (P17, VR) when they were standing in an area with high virus concentration levels. Other participants reported that the lines are not frightening or immersive as *"they are relatively abstract and cannot cover the entire classroom"*. (P7, VR) In addition, about half of the participants voted for the line visualization as the most informative visual (14/31) as *"the static lines provide accurate and detailed visual cues from different directions"* (P28, VR).

Generally, each immersive visualization in our study possesses unique characteristics and collectively portrays the threat of the virus from distinct perspectives. In some cases, they may complement each other. As one participant said *"the heatmap gives me an intuitive distribution while the lines offer more details. They compensate for the shortcoming of particles"* (P3, VR).

6.4.2. Multiple perspectives (DF2)

Participants expressed positive comments about both the third-person view and the first-person view. The third-person view was praised for providing *"a comprehensive overview of the virus spread, especially when viewing the heatmap"* (P14, VR). On the other hand, participants' mentioned that the first-person view allowed them to *"observe detailed information, interact with the scene of the story"* (P3, VR). While participants rated both perspectives contributed to raising the SA in the quantitative reports, they showed a preference for the first-person view in terms of engagement with the story. The reason is that they mentioned they prefer to the personal connection and the ability to interact with the story in the first-person view. This may explain why more time was spent and more interactions occurred under the first-person view (Fig. 7(C)). Regarding perspective-taking in the VR data story, participants frequently chose to view the situation from the teacher's or the infected student's perspective. They reported enjoyment in seeing the entire room with the virus from the teacher's perspective and inspecting the virus above the infected student. Participants expressed a desire for more information from these characters through interactions, such as checking their health status or engaging in conversations. Overall, participants would like to utilize multiple perspectives to gain a comprehensive understanding of the data story.

6.4.3. Embodied interactions (DF3)

Participants reported that the embodied interactions in VR may contribute to their enhancement of SA by providing a sense of immersion and control over their surroundings. The interactive indicator board (Section 4.3), in particular, was highly favored by participants (19/31) as it provided real-time feedback for them based on their personal positions, constantly alerting and making them aware of the virus concentration around them. They reported that the board offered precise information through numerical virus concentration levels, which can compensate for the abstractness of visualizations. Additionally, participants found the pressable buttons next to the windows intuitive and empowering, as they allowed them to exert control over the environment.

6.4.4. Audio narration and navigation (DF4) and spatial cues (DF5)

This section examines the roles of audio (DF4) and spatial cues (DF5) in the VR data story. While participants **acknowledged the importance of the design features in initially guiding them through the story, their contribution to situational awareness (SA) was perceived as less significant**. Participants described the audio as *"providing guidance for interacting with the scene"* and the spatial cues as *"reminding me of relevant information to view"* (P20, VR). However, they viewed these cues as more of a one-time occurrence, particularly when they were unfamiliar with the story scene. This possibly explains why participants gave lower scores of these two DFs in Fig. 6(D). While audio and spatial cues play a crucial role in helping users navigate the story, participants may no longer rely on them once they are acquainted with the environment. It would be worthwhile to explore effective placement and implementation of navigational cues to enhance users' exploration of virtual environments, a topic we discuss in Section 7.2.

7. Discussion

This section discusses the unique benefits of the VR data story in improving situation awareness (SA) of health threats (Section 7.1) Then, we summarize the design implications and the lessons learned for designing VR data stories (Section 7.2). Finally, we report the limitations of our work and provide several avenues for future work (Section 7.3).

7.1. Benefits and reflections of the VR data story in SA-raising

With the iteratively-designed story, our qualitative and quantitative results demonstrate two key findings. First, an appropriately designed VR data story could enhance the situation awareness (SA) compared to a desktop-based equivalent (Sections 6.1–6.2). Second, we identify that the inclusion of three design features in the VR data story, namely immersive visualizations, embodied interactions, and multiple perspectives, contribute to this enhancement (Sections 6.3–6.4). Previous research on data stories have shown the potential of integrating immersive experience with the data visualizations on the evoking emotions (Ivanov et al., 2019), scale understanding (Lee et al., 2020) and data learning (Ito and Hidalgo, 2019). Our work expands the application of immersive data story experience and evaluates the value of immersive visualization for health promotion through the design and evaluation of a VR data story.

According to the qualitative feedback, we find that the immersive experience in VR brings the risky situation closer to readers, which provides a first-hand experience with the situation through enhanced sense of presence (McRoberts, 2018; Bucher, 2017). This strengthens people's connection to the story and thus raises their perception and understanding of health threats. In addition, the study results show that the VR scene allows users freely observing and interacting with the story elements and immersive visualizations. This level of freedom facilitates users' familiarity with the story situation, leading to enhanced situational understanding and self-projection, ultimately contributing to the elevation of situation awareness.

Our second key finding highlights the significance of immersive visualization in SA-raising. Specifically, we observed that the immersive visualization effectively reveals imperceptible and invisible health threats and elicits emotional responses such as disgust, uneasiness, and a sense of being threatened. These emotional responses contribute to SA-raising by enhancing individuals' self-projection. Importantly, our study expands the understanding of immersive visualization beyond its traditional applications in data understanding and emotion elicitation (Lee et al., 2020; Ivanov et al., 2019), demonstrating its value in public health promotion. In addition, our findings suggest the benefits of the first-person view in promoting the perception of health threats as it enhances people's perception of the depicted risks. The results also indicate that individuals may also utilize the third-person perspective to obtain a comprehensive understanding of the information conveyed by the data story. Therefore, we conclude that the first-person view can effectively evoke subjective emotions and experiences, while the third-person perspective can aid in comprehending risky information. Finally, our findings imply that incorporating embodied and natural interactions, such as walking and manipulating elements in the story, could contribute to raising the SA, because the interactive experience with the story engaged users with the story while improving the sense of "living in the story" comparing to simply reading the data story on a screen.

Based on the above key findings, next, we summarize several design implications based on the participants' feedback as well as our observations and analysis in the experiment.

7.2. Design implications

Make Use of Diverse Immersive Data Representations to Convey Health-related Situations. Our findings strongly encourage researchers to explore the potential of immersive visualizations for improving perception, cognition, and decision-making across various domains. When designing immersive data stories, careful consideration should be given to the selection or creation of immersive story materials, recognizing the pivotal role of immersive visualization in shaping the overall user story experience. In addition, our study highlights the significance of finding the right balance between abstraction and realism in immersive visualizations, considering the specific goals and intended messages of the story. For instance, while immersive particles can enhance the perceived realism of COVID-19 health threats, they may also induce discomfort in some users. Conversely, abstract representations like heatmaps can convey high-level information for understanding, but they may not evoke the same level of perceived risk as particles. To fully leverage the benefits of different immersive visualizations, designers should employ a combination of multiple data representations in their stories. It is also important to find the right balance between effectively conveying information and enhancing the perception of threats.

Provide a Range of Perspectives to View and Interact with Immersive Data Stories. In a VR data story, it is crucial for users to have the opportunity to observe and gain insights from immersive visualizations and the story scene through different perspectives. To enhance the overall viewing experience, designers may considering offering several preset viewpoints at different positions and distances in the environment and/or by role-playing different characters for users to observe the story scene or the immersive data, ensuring a more comprehensive and interactive storytelling experience. Additionally, to increase engagement and strengthen users' connection with the story, designers may also consider offering more interactive elements within the story, such as interactive conversations to access the information or data insights. In brief, designers need to provide various views and interaction experiences to enhance engagement and understanding with the story.

Support Embodied Interactions for Situational Understanding and Involvement. It is recommended that designers need to incorporate a sense of control through interactions in a VR data story as it can positively increase presence in the story and engagement with the data. Moreover, designers need to pay attention to striking a balance between guiding users through the story experience and providing them the freedom to explore the story. For example, in our VR data story, We guide users' exploration within the narrative logic by associating narrative audio playback with partial user interactions and linking spatial cues with audio segments. Our study highlights two key approaches for seamlessly integrating interactive elements into a VR data story: (1) interactions that advance the plot, such as opening a window, and (2) interactions beyond the storyline that offer additional information or encourage user engagement, such as exploring the environment or switching perspectives.

Utilize the Multi-modal Cues for Open Story Navigation and Immersive Exploration. It is crucial to carefully plan the placement and timing of navigation cues within the VR story scene to guide the user's attention and exploration effectively. These spatial cues can direct the user towards important elements of the story. However, determining when to present these cues can be challenging without the ability to track user behavior. To ensure a seamless and unobtrusive story experience, it is advisable to make the cues easily dismissible or hidden when not in use, rather than occupying valuable visual space. The effectiveness of navigation cues also depends on their integration with the story scene and visual salience. For example, cues should be positioned in a way that enhances the immersive experience, rather than disrupting it. Their prominence should be proportional to their importance in guiding the user's attention.

7.3. Limitations and future work

This work has several limitations. First, in this work, we only selected one representative story as the design material for a case study and conducted a series of design activities to iteratively improve and build the immersive experience of the data story in VR. While we tried to ensure the generalizability of our case study from the typicality of the story scene and the coverage of data visualization types (see Section 3.1), we acknowledge that testing our design considerations on other cases could further ensure their practicality. Although the findings show that the VR data story could significantly increase the situation awareness of health risks, we may not directly generalize the findings to other types of stories. However, the design considerations and implications obtained from users may be useful for designing similar data stories in VR. In the future, it would be valuable to include multiple cases or datasets. Given the amount of effort required to build one VR data story application based on current technology, it is also valuable to explore how to apply generative models to help designers quickly create 3D story scenes and elements in the future.

In addition, it is important to validate the effectiveness of the design features in the VR story by testing them with different types of stories or public health issues. In future research, we plan to investigate the specific effects of each design feature on individuals' awareness of health risks in greater detail. To enhance risk perception, further studies can be conducted to explore and assess additional aspects of VR data stories, such as incorporating emotional elements into audio or visual representations. This will expand the design space and enable a more comprehensive understanding of how to effectively leverage VR storytelling to promote the communication of data stories for public health communication.

8. Conclusion

The paper explores the potential of an interactive VR data story to raise public health awareness. To achieve this goal, we built the story iteratively through two rounds of design studies. A user experiment was conducted to assess the story's effectiveness and understand how people interact with it. We found that immersive experiences with visualized health threats increased people's situation awareness (SA) of health risks and their sense of threat significantly. We discussed the benefit of the VR data story in increasing the SA and offer several design implications for designing immersive experience of data stories. We hope our work can encourage and support the further development of immersive experience that facilitates deeper engagement and intuitive understanding of health risks and immersive data.

CRediT authorship contribution statement

Qian Zhu: Conceptualization, Methodology, System development, User study, Data analysis, Writing – original draft, Writing – review & editing. **Linping Yuan:** User study,Data analysis, Writing – original draft, Writing – review & editing. **Zian Xu:** System development, User study. **Leni Yang:** User study, Writing – original draft, Writing – review & editing. **Meng Xia:** User study, Writing – review & editing. **Zhuo Wang:** Data analysis,User study. **Hai-Ning Liang:** Conceptualization, Writing – review & editing. **Xiaojuan Ma:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

I have shared the data and links in the attached files

Acknowledgments

We thank all the participants for their valuable support. This work is partially supported by the Research Grants Council of the Hong Kong Special Administrative Region under General Research Fund (GRF) with Grant No. 16203421.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhcs.2023.103137.

References

Ahn, S.J.G., Fox, J., 2017. Immersive virtual environments, avatars, and agents for health.

Amini, F., Riche, N.H., Lee, B., Leboe-McGowan, J., Irani, P., 2018. Hooked on data videos: assessing the effect of animation and pictographs on viewer engagement. In: Proceedings of the 2018 International Conference on Advanced Visual Interfaces. pp. 1–9.

Bahng, S., Kelly, R.M., McCormack, J., 2020. Reflexive VR storytelling design beyond immersion: facilitating self-reflection on death and loneliness. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. pp. 1–13.

Bartzokas, N., Gröndahl, M., Patanjali, K., Peyton, M., 2021. Why opening windows is a key to reopening schools. https://www.nytimes.com/interactive/2021/02/26/science/reopen-schools-safety-ventilation.html.

Bastiras, J., Thomas, B.H., 2017. Combining virtual reality and narrative visualisation to persuade. In: 2017 International Symposium on Big Data Visual Analytics (BDVA). IEEE, pp. 1–8.

Bernhardt, J.M., 2004. Communication at the core of effective public health. Am J Public Health 94 (12), 2051–2053.

Bindman, S.W., Castaneda, L.M., Scanlon, M., Cechony, A., 2018. Am I a bunny? The impact of high and low immersion platforms and viewers' perceptions of role on presence, narrative engagement, and empathy during an animated 360 video. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. pp. 1–11.

Bock, A., Axelsson, E., Costa, J., Payne, G., Acinapura, M., Trakinski, V., Emmart, C., Silva, C., Hansen, C., Ynnerman, A., 2019. OpenSpace: A system for astrographics. IEEE Trans. Vis. Comput. Graphics 26 (1), 633–642.

Braun, V., Clarke, V., 2006a. Using thematic analysis in psychology. Qual. Res. Psychol..

Braun, V., Clarke, V., 2006b. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2), 77–101.

Breves, P., Schramm, H., 2021. Bridging psychological distance: The impact of immersive media on distant and proximal environmental issues. Comput. Hum. Behav. 115, 106606.

Bucher, J., 2017. Storytelling for Virtual Reality: Methods and Principles for Crafting Immersive Narratives. Routledge.

Busselle, R.W., Bilandzic, H., 2009. Measuring narrative engagement. Media Psychol..

Charmaz, K., 2006. Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis. sage.

Chen, J., Pyla, P.S., Bowman, D.A., 2004. Testbed evaluation of navigation and text display techniques in an information-rich virtual environment. In: IEEE Virtual Reality 2004. IEEE, pp. 181–289.

Dasu, K., Ma, K.-L., Ma, J., Frazier, J., 2020. Sea of genes: A reflection on visualising metagenomic data for museums. IEEE Trans. Vis. Comput. Graphics 27 (2), 935–945.

for Disease Control, C., Prevention, 2022. Data modernization initiative. https://www.cdc.gov/surveillance/index.html, [Online; accessed 29-May-2023].

Ehn, P., 2008. Participation in design things. In: Participatory Design Conference (PDC), Bloomington, Indiana, USA (2008). ACM Digital Library, pp. 92–101.

Endsley, M.R., 1988a. Design and evaluation for situation awareness enhancement. In: Proceedings of the Human Factors Society Annual Meeting, Vol. 32. Sage Publications, Sage CA: Los Angeles, CA, pp. 97–101.

Endsley, M.R., 1988b. Situation awareness global assessment technique (SAGAT). In: Proceedings of the IEEE 1988 National Aerospace and Electronics Conference. IEEE, pp. 789–795.

Endsley, M.R., 1999. Situation awareness in aviation systems.

Fei, D., Gao, Z., Yuan, L., Wen, Z.A., 2022. CollectiAR: Computer vision-based word hunt for children with dyslexia. In: Extended Abstracts of Annual Symposium on Computer-Human Interaction in Play. pp. 171–176.

Feng, Y., Tong, Q., 2022. Exploring the mediating role of situation awareness and crisis emotions between social media use and COVID-19 protective behaviors: Cross-sectional study. Front. Public Health 1024.

Fonseca, D., Kraus, M., 2016. A comparison of head-mounted and hand-held displays for 360 videos with focus on attitude and behavior change. In: Proceedings of the International Academic Mindtrek Conference. pp. 287–296.

Fung, J., Richards, C.L., Malouin, F., McFadyen, B.J., Lamontagne, A., 2006. A treadmill and motion coupled virtual reality system for gait training post-stroke. CyberPsychol. Behav. 9 (2), 157–162.
GAO-22-104600, 2022. COVID-19: Pandemic lessons highlight need for public health situational awareness network. https://www.gao.gov/products/gao-22-104600/.
Gorisse, G., Christmann, O., Amato, E.A., Richir, S., 2017. First-and third-person perspectives in immersive virtual environments: presence and performance analysis of embodied users. Front. Robot. AI 4, 33.
Guardian, T., The Guardian[link]. URL [https://www.theguardian.com/data].
Henrikson, R., Araujo, B., Chevalier, F., Singh, K., Balakrishnan, R., 2016. Multi-device storyboards for cinematic narratives in VR. In: Proceedings of the Annual Symposium on User Interface Software and Technology. pp. 787–796.
Ho, J.C., Ng, R., 2022. Perspective-taking of non-player characters in prosocial virtual reality games: Effects on closeness, empathy, and game immersion. Behav. Inf. Technol. 41 (6), 1185–1198.
Hoppe, M., Baumann, A., Tamunjoh, P.C., Machulla, T.-K., Woźniak, P.W., Schmidt, A., Welsch, R., 2022. There is no first-or third-person view in virtual reality: Understanding the perspective continuum. In: CHI Conference on Human Factors in Computing Systems. pp. 1–13.
Hufnagel, M., 2022. Visualization of human behaviour in VR. https://github.com/torantie/Master-Thesis-Visualization-of-Human-Behaviour-in-VR/.
Hung, Y.-H., Parsons, P., 2017. Assessing user engagement in information visualization. In: Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems. pp. 1708–1717.
Isenberg, P., Lee, B., Qu, H., Cordeil, M., 2018. Immersive visual data stories. In: Immersive Analytics. Springer, pp. 165–184.
Ito, T., Hidalgo, C.A., 2019. Biodigital: transform data to experience, beyond data visualization. In: ACM SIGGRAPH 2019 Posters. pp. 1–2.
Ivanov, A., Danyluk, K., Jacob, C., Willett, W., 2019. A walk among the data. IEEE Comput. Graph. Appl. 39 (3), 19–28.
Jankowski, J., Samp, K., Irzynska, I., Jozwowicz, M., Decker, S., 2010. Integrating text with video and 3d graphics: The effects of text drawing styles on text readability. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. pp. 1321–1330.
Jessop, E.G., 2004. Situational awareness in public health. J. Public Health 26 (1), 1. http://dx.doi.org/10.1093/pubmed/fdh121, arXiv:https://academic.oup.com/jpubhealth/article-pdf/26/1/1/4386451/fdh121.pdf.
Joshi, A., 2021. Learning cues to improve the understanding of explanatory storytelling.
Kilteni, K., Groten, R., Slater, M., 2012. The sense of embodiment in virtual reality. Presence: Teleoper. Virtual Environ. 21 (4), 373–387.
Kraus, M., Angerbauer, K., Buchmüller, J., Schweitzer, D., Keim, D.A., Sedlmair, M., Fuchs, J., 2020. Assessing 2d and 3d heatmaps for comparative analysis: An empirical study. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. pp. 1–14.
Lamsal, R., Harwood, A., Read, M.R., 2022. Socially enhanced situation awareness from microblogs using artificial intelligence: A survey. ACM Comput. Surv..
Lee, B., Brown, D., Lee, B., Hurter, C., Drucker, S., Dwyer, T., 2020. Data visceralization: Enabling deeper understanding of data using virtual reality. IEEE Trans. Vis. Comput. Graphics 27 (2), 1095–1105.
Lee, B., Riche, N.H., Isenberg, P., Carpendale, S., 2015. More than telling a story: Transforming data into visually shared stories. IEEE Comput. Graph. Appl. 35 (5), 84–90.
Leidecker-Sandmann, M., Kohler, S., 2022. The effect of narrative visualizations on public risk perception of magnetic fields emanating from high voltage power lines–and the role of anxiety.
Li, X., Cao, B., 2019. Media variants, situation awareness, and protective public-health behaviors. Chin. J. Commun. 12 (4), 467–483.
Liberman, N., Trope, Y., Stephan, E., 2007. Psychological distance.
McKenna, S., Henry Riche, N., Lee, B., Boy, J., Meyer, M., 2017. Visual narrative flow: Exploring factors shaping data visualization story reading experiences. In: Computer Graphics Forum, Vol. 36. Wiley Online Library, pp. 377–387.
McRoberts, J., 2018. Are we there yet? Media content and sense of presence in non-fiction virtual reality. Stud. Doc. Film 12 (2), 101–118.
MetaQuest, 2021. Hand physics lab. https://www.oculus.com/experiences/quest/3392175350802835/.
Meuschke, M., Garrison, L.A., Smit, N.N., Bach, B., Mittenentzwei, S., Weiß, V., Bruckner, S., Lawonn, K., Preim, B., 2022. Narrative medical visualization to communicate disease data. Comput. Graph. 107, 144–157.
Microsoft, 2022. Azure services. https://azure.microsoft.com/en-us/free/cognitive-services/.
Midtbo, T., Harrie, L., 2021. Visualization of the invisible. J. Geovis. Spat. Anal. 5 (1), 1–4.
Mirhaji, P., Zhang, J., Srinivasan, A., Richesson, R.L., Smith, J.W., 2004. Knowledge-based public health situation awareness. In: Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense III, Vol. 5403. SPIE, pp. 198–209.
Olson, D., Mathes, R., Paladini, M., Konty, K., 2013. Defining public health situation awareness-outcomes and metrics for evaluation. Online J. Public Health Inform. 5 (1).
Organization, T.W.H., 2022. Insights and visualizations: Visual stories about health, wellbeing and healthcare driven by the data of the World Health Organization. https://www.who.int/data/stories, [Online; accessed 29-May-2023].
Radziwill, N.M., 2017. Designing for situation awareness: An approach to user-centered design. Qual. Manag. J. 24 (2), 56.
Rolka, H., O'Connor, J.C., Walker, D., 2008. Public health information fusion for situation awareness. In: International Workshop on Biosurveillance and Biosecurity. Springer, pp. 1–9.
Ryan, M.-L., 2015. Narrative as Virtual Reality 2: Revisiting Immersion and Interactivity in Literature and Electronic Media. JHU Press.
Sadeghian, P., Duwig, C., Romero, M., Sadrizadeh, S., 2021. Visualizing bacteria-carrying particles in the operating room: exposing invisible risks. In: Healthy Buildings 2021–Europe. Proceedings of the 17th International Healthy Buildings Conference 21–23 June 2021. SINTEF Academic Press.
Salvendy, G., Karwowski, W., 2021. Handbook of Human Factors and Ergonomics. John Wiley & Sons.
Sauer, F., Neuroth, T., Chu, J., Ma, K.-L., 2016. Audience-targeted design considerations for effective scientific storytelling. Comput. Sci. Eng. 18 (6), 68–76.
Schell, J., 2008. The Art of Game Design: A Book of Lenses. CRC Press.
Segel, E., Heer, J., 2010. Narrative visualization: Telling stories with data. IEEE Trans. Vis. Comput. Graphics 16 (6), 1139–1148.
Seyser, D., Zeiller, M., 2018. Scrollytelling–an analysis of visual storytelling in online journalism. In: 2018 22nd International Conference Information Visualisation (IV). IEEE, pp. 401–406.
So, W., Bogucka, E.P., Šćepanović, S., Joglekar, S., Zhou, K., Quercia, D., 2020. Humane visual ai: Telling the stories behind a medical condition. IEEE Trans. Vis. Comput. Graphics 27 (2), 678–688.
Studio, B., 2016. Invasion. https://www.baobabstudios.com/invasion, [Online; accessed 24-August-2022].
Studio, B., 2021. Baba yaga. https://www.baobabstudios.com/baba-yaga, [Online; accessed 24-August-2022].
Sultanum, N., Chevalier, F., Bylinskii, Z., Liu, Z., 2021. Leveraging text-chart links to support authoring of data-driven articles with vizflow. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. pp. 1–17.
Thacker, S.B., Qualters, J.R., Lee, L.M., for Disease Control, C., Prevention, et al., 2012. Public health surveillance in the United States: evolution and challenges. MMWR Suppl. 61 (3), 3–9.
Tian, J., Cao, Y., Feng, L., Fu, D., Yuan, L., Qu, H., Wang, Y., Fan, M., 2023. PoeticAR: Reviving traditional poetry of the heritage site of jichang garden via augmented reality. Int. J. Hum.-Comput. Interact. 1–17.
Times, T.N.Y., The New York Times[link]. URL [https://www.nytimes.com/spotlight/graphics].
Tobias, E., 2011. Using Twitter and other social media platforms to provide situational awareness during an incident. J. Bus. Contin. Emerg. Plan. 5 (3), 208–223.
Tong, W., Chen, Z., Xia, M., Lo, L.Y.-H., Yuan, L., Bach, B., Qu, H., 2022. Exploring interactions with printed data visualizations in augmented reality. IEEE Trans. Vis. Comput. Graphics.
Trope, Y., Liberman, N., 2010. Construal-level theory of psychological distance. Psychol. Rev. 117 (2), 440.
Valdez, A.C., Ziefle, M., Sedlmair, M., 2017. Priming and anchoring effects in visualization. IEEE Trans. Vis. Comput. Graphics 24 (1), 584–594.
Visch, V.T., Tan, E.S., Molenaar, D., 2010. The emotional and cognitive effect of immersion in film viewing. Cogn. Emot. 24 (8), 1439–1445.
Williams, E., Love, C., Love, M., 2021. Virtual Reality Cinema: Narrative Tips and Techniques. Routledge.
Xiong, C., Van Weelden, L., Franconeri, S., 2019. The curse of knowledge in visual data communication. IEEE Trans. Vis. Comput. Graphics 26 (10), 3051–3062.
Zimmerman, D.W., Williams, R.H., 1998. Reliability of gain scores under realistic assumptions about properties of pre-test and post-test scores. Br. J. Math. Stat. Psychol. 51 (2), 343–351.