Immersive Data-Driven Storytelling: Scoping an Emerging Field Through the Lenses of Research, Journalism, and Games

Julián Méndez, Weizhou Luo, Rufat Rzayev, Wolfgang Büschel, and Raimund Dachselt

***Abstract*—In recent years, data-driven stories have found a firm footing in journalism, business, and education. They leverage visualization and storytelling to convey information to broader audiences. Likewise, immersive technologies, like augmented and virtual reality devices, provide excellent potential for exploring and explaining data, thus inviting research on how data-driven storytelling transfers to immersive environments. To gain a better understanding of this exciting novel research area, we conducted a scoping review on the emerging notion of *immersive data-driven storytelling*, extended by surveying immersive data journalism and by analyzing immersive games, selected based on community reviews and tags. We present our methodology for the survey and discuss prominent themes that coalesce the knowledge we extracted from the literature, journalism, and games. These themes include, among others, the spatial embodiment of narration, the incorporation of the users and their context into narratives, and the balance between guiding the user versus promoting serendipity. Our discussion of these themes reveals research opportunities and challenges that will inform the design of immersive data-driven stories in the future.**

***Index Terms*—immersive data-driven storytelling, data story, narrative visualization, design space, scoping review**

I. Introduction

DATA-DRIVEN STORYTELLING, also called *narrative visualization*, has gained interest recently due to its increasing use in various communities, such as journalism and business [64]. Lee et al. [44] characterize data stories by indicating that visualizations should present facts supported by data, instead of supporting free exploration without guidance. Thus, more than providing ways to explore and analyze data; data storytelling is specifically about using visualizations to explain and present data effectively [31].

Immersive experiences can benefit data storytelling as they enable valuable opportunities for explaining data [39]. Specifically, Immersive Analytics is an emerging research field that uses augmented reality (AR), virtual reality (VR), and mixed reality (MR) analysis tools to support engaging and embodied data understanding and decision making [24]. Among other benefits, immersive visualizations can facilitate 3D spatial tasks, improve collaboration, and enable better depth perception, all while increasing user engagement [39]. Immersive environments can also enhance retention of presented information [14] and comprehension of measures such as distance and height, which are often abstracted away in data visualization [43]. Given these and other benefits like situatedness [10, 66], several researchers have recently explored what we would summarize as *immersive data-driven storytelling*, which is the process of conveying data-supported insights and findings in the form of a visualization-based narrative in an interactive immersive environment (e.g., [23, 31, 49]). Compared to general data storytelling described in detail in the literature (e.g., [44, 61, 68]), there are only scattered solutions to the design of data stories in immersive environments. While design patterns of related fields, such as Immersive Analytics [60], Immersive Journalism [11, 72], or game design [7], could also be beneficial for immersive data storytelling, a deeper understanding of the unique aspect of this thriving research area as well as a systematic analysis of the existing literature is still missing.

In this paper, we therefore aim to comprehensively define the field of *immersive data-driven storytelling*. To this end, we conducted a *scoping review* [52, 71] to study the state of the literature and identify research gaps. We extended this review by surveying *immersive data journalism*, analyzing *immersive games*, and incorporating knowledge from existing related taxonomies [60, 61]. We present the methodology and results of our extended survey and contribute a detailed discussion of prominent *themes* that coalesce the knowledge we extracted from the literature, journalism, and games. This discussion consists of eight themes: 1) spatial embodiment of narration, 2) controls over the story progression, 3) incorporation of the users and their context into narratives, 4) user guidance in contrast to serendipity, 5) target audiences and accessibility, 6) adaptiveness, 7) leveraging (more) game elements and mechanics, and 8) the multiple purposes that data stories can fulfill. For each theme, we indicate research gaps, challenges, and potentials. We conclude the paper with a discussion of overarching research opportunities. We believe that our work lays the foundations for an exciting novel research area and will support researchers and practitioners in designing and creating immersive data-driven stories in the future.

II. Background & Related Fields

In this section, we describe data-driven storytelling as the interplay of narrative and visualization (II-A), present related work in Immersive Analytics, providing means of transferring data stories to immersive environments (II-B), discuss further inspiring fields that focus on immersion and engagement (II-C), and provide a unified definition of what we call *immersive data-driven storytelling* (II-D).

All authors are with the Interactive Media Lab Dresden at TUD Dresden University of Technology. R. Rzayev and R. Dachselt are also with the Centre for Scalable Data Analytics and Artificial Intelligence (ScaDS.AI), and R. Dachselt is also with the Centre for Tactile Internet (CeTI) at TUD Dresden University of Technology, Germany. Emails: {julian.mendez2, weizhou.luo, rufat.rzayev}@tu-dresden.de, {bueschel, dachselt}@acm.org

A. Data-driven Storytelling

Over the last two decades, and through the analysis of existing *data stories*, researchers have attempted to define *data-driven storytelling* and its components. Towards this, the influential work by Segel and Heer [61] introduced the term *narrative visualization*, describing *visualizations that convey stories*. They formulated a design space that discusses genres, visual narrative and structure tactics, by analyzing 58 examples from journalism. Similarly, Hullman and Diakopolous [30] analyzed 51 narrative visualizations and created a design framework to explain how visualization design prioritizes reader interpretations. Lee et al. [44] further characterized data-driven stories as those that (1) *include visualizations* that support intended messages with data highlighted by narration, and (2) contain an *order* to communicate a goal. This order or sequence of events is meant to ensure that insights and findings over the data are communicated [25, 38].

Thus, *data (or data-driven) storytelling* can be understood as the process of creating and communicating data stories [54], which consists of 3 steps: exploring data, making a story, and telling a story [44]. Several further aspects of data stories and storytelling have been investigated, such as navigation [68], user roles (e.g., presenter, analyst) and external factors (e.g., cost, legal) [18], techniques for live-streaming, presentations, and dynamic reports [86], and flow [50]. Furthermore, the literature provides insights on the design of authoring tools (e.g., [37, 63]) and various types of data stories, such as data videos [2, 82], animated narrative visualizations [65, 67], comic-strip-style narrative visualizations [5, 73], and timelines [9]. By analyzing award-winning data stories, Ojo & Heravi [54] concluded that the purpose of data stories is to *provide a deeper understanding* about a phenomenon, through the use of data analysis and data visualization.

B. Immersive Analytics

The field of visual analytics shares the purpose of data stories to provide a deeper understanding of data. Towards this, *Immersive Analytics* (IA) aims to support visual analytics processes by leveraging immersive technologies like AR and VR [16] and natural interaction [12]. Some proposed advantages of IA [39] include improved user engagement, collaboration, and spatial understanding. The emergence of this field has led to a renewed interest in 3D and mixed-reality visualizations. Several surveys on IA and related fields have been published (e.g., [10, 66]). In addition, Saffo et al. [60] proposed a comprehensive design space for IA.

Complex findings from IA may need to be communicated to audiences lacking expertise. To bridge this gap between data analysis and communication [17], one can employ immersive technologies and the novel visualization and interaction possibilities that they enable. The potential of immersive technologies for data storytelling has been highlighted, e.g., in the 2018 book chapter by Isenberg et al. [31], where the authors try to define immersion in the context of narrative visualization, and discuss research questions in the intersection of data stories and immersive visualizations. Consequently, *immersive data-driven storytelling* may build on existing IA concepts and leverage their potential to improve not only analytics processes but also narrative visualization.

C. Immersive Experiences in Related Fields

Immersion and engagement have been long discussed in *gaming* communities as key aspects that attract players [45, 77]. The gaming industry constitutes one of the largest pushes toward the advancement of technologies and general means of immersion, such as *realism* in graphics [59], *complex, multi-faceted narratives*, and *dedicated devices* (e.g., head-mounted displays (HMDs), motion trackers, and game-related peripherals [56]). Thus, studying games is a promising way to learn about effective means of inducing immersion. On the other hand, with the proliferation of data-driven algorithms and technologies in recent years, "data journalism" has consolidated itself, reaching large audiences. Hundreds of online articles using scrollytelling [62] exemplify this trend. Likewise, the notion of immersion [80] has gained popularity in journalism. In 2017, the Online Journalism Awards (OJA)[1] introduced a category for Excellence in Immersive and Emerging Technology Storytelling, which honors *"storytelling that uses virtual reality, artificial intelligence, AI chatbots, augmented reality, mixed reality, 360 video or other emerging media."* Immersive storytelling media can also be found, to a lesser extent, in other fields, such as art [46] and education [75, 84].

D. Nomenclature and Summary

Data-driven storytelling is the process of communicating data-supported insights and findings using visualizations accompanied by narration. Although immersive technologies may help increase the feelings of engagement and presence, as well as enable direct spatial connection to the data, there is up to now only a fragmented understanding of what *immersive data-driven storytelling* entails. Therefore, we define this notion as *data-driven storytelling that meaningfully employs immersive technologies*. In particular, we refer to technologies that can induce feelings of presence and immersion, by e.g., leveraging spatiality (virtual or physical). In the same way that data-driven stories are referred to with synonymous terms (e.g., narrative visualization, data narratives, data stories), in this paper we interchangeably make use of intuitively related terms such as "immersive data stories", "immersive data storytelling", and "immersive narrative visualizations". We strongly believe that this notion will play an important role in the near future as immersive technologies find firmer footing in the market for everyday audiences. As there are only scattered solutions to the design of immersive data-driven stories (e.g., [47, 57, 87, 89]), a comprehensive discussion that informs future research on this is needed.

III. Scoping Review

We conducted a *scoping review* to identify the existing literature on immersive data-driven storytelling. The scoping review is a useful evidence synthesis approach to *"identify knowledge gaps, scope a body of literature, clarify concepts, or*

[1] https://awards.journalists.org/

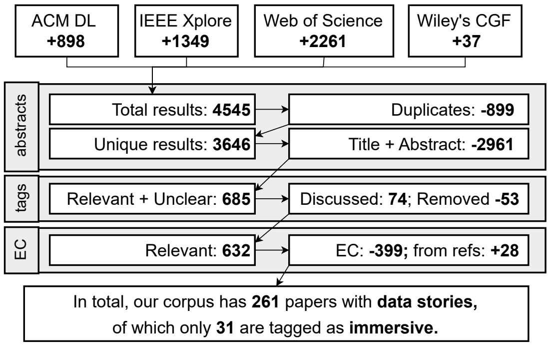

Fig. 1. PRISMA diagram of the scoping review process including counts.

investigate research conduct" [52]. We applied the Preferred Reporting Items for Systematic Reviews (PRISMA) [55] guidelines, following the Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) [71].

a) Search Strategy: In line with the recommendations by Cooper et al. [19], we first performed systematic queries using common digital libraries for publications in Human-Computer Interaction and Visualization, including ACM Digital Library, IEEE Xplore, Web of Science, and Wiley Online Library for Computer Graphics Forum. Considering the emerging nature of this field, we used keywords for general data-driven storytelling and did not specifically enforce immersiveness or using immersive technology (e.g., VR, AR). Based on this initial search and on existing criteria for data stories (e.g., involving visualizations [64]), we created the following query that incorporates variations of recurring keywords:

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(story OR stories OR narrat* OR storytelling
 OR "data-driven communication"
 OR "data communication" OR journalism
 OR "data visceralization") AND visual*
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We ran this query on the above-mentioned digital libraries that produced search results considering author keywords, titles, or abstracts of the papers. While the scoping review does not have strict quality requirements for the selected papers [3], the query was limited to articles from journals and proceedings to ensure significant results. However, the search also resulted in further publication types (e.g., extended abstracts, book chapters). We kept these outlier results considering their relevance to the topic (e.g., [31, 57]). The last search was on Jun. 20^{th}, 2024, totaling 4545 results.

b) Selection: First, we collected the search results in an online spreadsheet. Then, we applied three filtering rounds to identify and extract the final corpus. Figure 1 illustrates the complete selection process. We considered the papers satisfying the following eligibility criteria (EC):

EC1 The paper discusses data stories, i.e., contains arguments backed by data and at least one data visualization.

EC2 The paper is written in English.

EC3 Storytelling is not mentioned only as an example (e.g., as a motivation for the research work).

EC4 The paper presents enough details to chart the paper.

In the first screening (**Figure 1-abstracts**), we removed 899 duplicates and two coders checked each paper's *title and abstract* to decide on their suitability (**EC1-3**). This round excluded 2961 unique results, where (a) the publications were unusable for the review (e.g., table of contents, workshop proposals), or (b) the topics of the papers were unrelated despite the keyword overlap (e.g., data transferring, video segmentation, assistive technology using narrations, and automatic generations of textual or image-based narrations). For the remaining 685 publications, a more thorough second screening took place (**Figure 1-tags**). First, three coders discussed 74 publications that were undecided in the previous round, resulting in 53 more exclusions. The remaining 632 papers were then tagged based on their content as "discusses structure/design of stories", "data story", "journalism", and "immersive story". The third screening (**Figure 1-EC**) enforced **EC1-4** while coders considered the full article text. This round excluded 399 more results. As established in the literature (e.g., [74]), we also examined the reference lists of resulting papers and their lists of citing articles to identify any additional relevant articles missed due to their publication type (e.g., book chapters, workshops) or lack of keywords in our search. This process resulted in 28 additional results. Our supplementary material includes the resulting 261 papers related to *data stories in general*. However, for our scoping review, we proceeded with the data extraction only on the 31 papers about data stories in *immersive* environments.

c) Data Extraction and Codebook: Each of the 31 final papers from the selection process was charted by three authors for five main categories: "narrative and story unfolding", "data visualization", "actors", "environment", and "interaction". An initial set of codes was derived from relevant design spaces for storytelling [61, 68, 86] and adapted to also consider aspects specific to immersive experiences. The codes were defined by three authors through regular meetings that later involved all authors. After agreeing on a set of 21 codes, three authors performed a single extraction on the papers. This version of the codebook and the extracted values can be found in the supplementary material of this paper.

d) Limitations: Our initial search reduced subjective bias and helped ensure that we would find the majority of relevant papers. However, this search certainly influenced our keyword selection process. Furthermore, the search yielded many false positives. Some notable examples are "visual storytelling", referring to creating semantic descriptions of the visual content in images or videos (e.g., [78]), and "data communication" referring to transmission (e.g., [85]). Nevertheless, using broad search keywords ensured a wider scope of papers.

e) Going Beyond the Scoping Review: After our scoping review, we felt that the corpus of only 31 publications did not reflect the full depth of what immersive data-driven stories can offer. Therefore, we performed two additional surveys on immersive journalism (III-A) and immersive games (III-B), as we consider these to be the most prominent sources to learn from for immersive storytelling (see Section II-C). In particular, analyzing journalism articles to characterize data stories was the approach taken by Segel & Heer [61], and taking inspiration from games for data-driven storytelling has also been suggested by Zhao & Elmqvist [86].

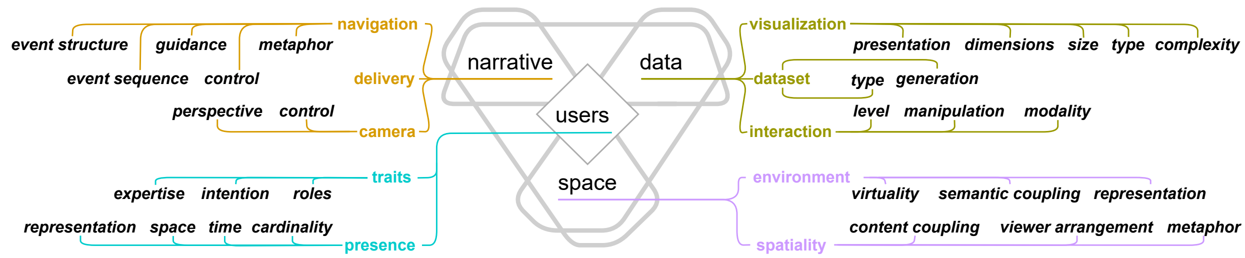

Fig. 2. Overview of our design space of *Immersive Data-Driven Storytelling*, grouped by four major design aspects.

A. *Immersive Data Stories in Journalism*

Unlike research papers, immersive journalistic productions do not have a central archive. Instead, they are scattered across the websites and mobile applications of publishers or newspapers, as well as Instagram and YouTube pages. Therefore, similar to previous works on immersive journalism [22, 49], we used the snowball method to gather immersive data-driven journalistic stories. Based on similar surveys (e.g., [49, 72, 80]), we collected immersive data stories from the New York Times, USA Today, the Washington Post, Deutsche Welle, and National Geographic. We searched for the keywords "Augmented Reality", "Virtual Reality", "immersive", "AR", and "VR" on the corresponding websites and checked dedicated sections on the mobile applications (e.g., the AR section on the USA Today application). Additionally, we browsed websites of OJA, as well as research and development teams of news agencies[2]. To meet the eligibility criteria, journalistic stories were required to contain factual arguments supported by data and at least one data visualization. The results should also employ immersive technologies such as AR, VR, or 360-degree video. Of the total 50 cases that we collected, 23 were from the New York Times, 18 from USA Today, five from the Washington Post, and two each from Deutsche Welle and National Geographic. Two authors thoroughly examined the collected immersive journalistic data stories and coded them using the same codebook used for the research papers. A third coder cross-examined this process for validity. The extracted values can be found in the supplementary material.

B. *Immersion, Storytelling (and Data) in Games*

We queried Steam, the largest and most used digital game distribution service, to find a representative sample of immersive games. We used the community-based tags[3] to ensure that results make use of immersive technology (VR or Mixed Reality) and are recognized as immersive experiences. These tags led to 85 results on Jul. 19^{th}, 2024. Despite filtering by media type to include only games, our query results include a few immersive films and simulators. We relied on written reviews and gameplay videos whenever available to examine the titles since manually exploring every feature and event in all games would prove very time-consuming. With the same codebook used for papers and journalism, two authors (different than those responsible for journalism) coded the games and collected ideas for which game mechanics and elements may be employed in data stories. A third author from the journalism coders cross-validated the process, ensuring consistency. It must be noted that some of our codes (e.g., related to visualization and data interaction) do not directly transfer to most games. This is due to the definition of what constitutes data in a game. For instance, the digital models and their motion, character or game statuses, player statistics, etc., can all be analyzed through the lens of visualization design [8]. Similarly, some games do not have an explicit story. However, even in those cases, systematically asking *"what can we learn/use for data stories?"* led to ideas that were noted as well. Each title's information (i.e., counts for tags, number of reviews, consulted review articles and videos), extracted values from the coding, and collected ideas can all be found in our supplementary material.

[2]Specifically, of the New York Times and Washington Post.

[3]Steam Query: [Type: *Games*; Tags: *Immersive, VR*; Sort by: *Reviews*]

IV. Design Space

To distill meaningful insights from the results of our extended survey, we created a Design Space (DS) across the aspects of **Data**, **Narrative**, **Space**, and **Users**. In favor of actionable takeaways, instead of describing each dimension and their possible values, we illustrate how readers may employ our DS (IV-A), and situate our findings amongst existing surveys and analyses partially related to immersive data stories (IV-B). The entire DS, including possible values for each dimension, can be found in the supplementary material.

A. *Overview and Usage*

The 31 dimensions of our DS are visible in Figure 2. They are distributed across four equally vital aspects for crafting immersive data-driven stories. **Narrative** refers to the story *Navigation* (including interaction with the story), *Delivery*, and *Camera* (perspective). **Data** describes aspects of the *Dataset* (e.g., generation), *Visualization*, and *Interaction* (with the data). **Users** refers to the human aspects, both in terms of user *Traits* and the general *Presence* (e.g., where, how many). Lastly, **Space** is concerned with the *Environment* and *Spatiality* dimensions particular to immersive data stories, such as the levels of virtuality and (semantic) content coupling.

The DS is aimed at readers of diverse backgrounds and varying expertise. Specifically, those from a data visualization background can learn from the Narrative and Space aspects to better communicate data insights in immersive environments. Those from an immersive storytelling background can learn from the Data dimension to support and justify their presented arguments. For general researchers interested in immersive data stories, our DS can suggest attractive research opportunities considering the combinations of different dimensions. For example, factors such as empathy or accessibility could be studied through the lens of second-person perspectives (from *Camera*), multi-user cardinality (from *Traits*), and high semantic coupling (from *Environment*), yielding a data story about, e.g., individuals with impairments in a social setting.

B. *Relation to other Reviews*

Our DS draws from the related fields of traditional *Data-Driven Storytelling* [61], *Immersive Analytics* [60] and *Immersive Experiences* (in particular, journalism and games). Furthermore, we coalesce knowledge from previous surveys and analyses made for narrative visualizations [61, 68, 86], framing effects [30], and types of media [86].

For instance, Segel & Heer identified *martini glass* and *drill-down* narrative structures of journalistic data stories [61]. The *Navigation (event structure & event sequence)* dimensions of our DS refer to *event graphs* (where nodes are events and edges are transitions) to describe not only these narrative structures but also more general ones like *free-form* or *linear*. Our data *Visualization* and *Interaction* dimensions incorporate knowledge from Immersive Analytics [60], partly to compensate for the previously identified lack of tutorials, stimulating default views, and typical messaging techniques [61]. The analysis of the effects of framing for data stories by Hullman & Diakopoulos [30] partially informs our dimensions about the coupling between environment, users, and content (narrative and visualizations) under the *Environment* and *Spatiality* aspects of our DS. However, the content layout and distribution are significantly more important in our case since immersive environments can uniquely leverage physical space.

Zhao & Elmqvist [86] examined the types of media that are used for data-driven stories, briefly discussing examples in Augmented Reality and (traditional) video games. Our DS and exploration of games are also motivated and informed by their initial findings and suggestions. In particular, their Cardinality, Space & Time categories with respect to Audience are also part of our DS (users *Presence*), and their Media Components, Data Components, and Viewing sequence dimensions overlap, respectively, with our *Delivery*, *Visualization (type, size, complexity)*, and *Navigation (event sequence)* dimensions. On the other hand, Stolper et al. [68] studied the recurring techniques used in (non-immersive) data stories. Their categories inform several dimensions of our DS. For instance, "Enhancing Structure and Navigation" also informs our *Navigation (event structure, event sequence)* dimensions, and "Providing Controlled Exploration" is subsumed by our *Navigation (control)* and *Interaction (level, manipulation & modality)* dimensions. Lastly, Lee et al. [44] discuss a lack of tool support and evaluation methods for data stories, which, unfortunately, remains the case according to our search results. Thus, our DS does not include these aspects.

V. Extracted Themes

In the following sections (V-A to V-H), we discuss eight overarching and cross-cutting themes extracted from our scoping review and refined through the development of our DS, which inform future research on immersive data-driven storytelling. From this point forward, we distinguish results from our scoping review using icons and brackets (i.e., [papers], [games], and [journalism]). Miscellaneous references that were not of query results are also enclosed in brackets but without icons. We also provide explicitly relevant references to our DS that the interested reader may further contextualize with the full Design Space from our supplementary material.

A. *Spatial Embodiment of Narration*

In immersive environments, it is possible to map the physical environment to the shape of an event graph (e.g., martini-glass [61]), achieving a spatial embodiment of the narrative structure of the story. This mainly refers to our DS: *Navigation (event structure, event sequence)*, *Environment (semantic coupling)* and *Spatiality (content coupling)*.

Essentially, immersive data stories can accurately recreate **both the chronology and location** of the events, allowing the audience to experience them as they originally occurred. In this vein, we identified the usage of virtual models with varied scales, such as floor maps [20, 81] and virus models [1], to convey spatial information and reconstruct spatial relations between events. For instance, in [A virtual look at last year's Capitol riot], photos and text descriptions about the riot are situated in the corresponding locations of a virtual 3D model of the Capitol building. When event chronology is not required, traversal of free-from event graphs **can rely solely on locations** or regions of interest where the narrative unfolds, such as in [58, 81] and [Guilford Castle VR]. This is illustrated by [Notre Dame: After the fire], where audiences can click on parts of a 3D AR model of Notre Dame to learn how the fire damaged the structure. Games with (partially) free-form event structures also make use of environmental storytelling (see also Section V-D), such as [Journey for Elysium] and [RUINSMAGUS].

If a story lacks location information or is decoupled from specific locations, the narration can be presented **solely depending on chronology**. To this end, space can be used to embody and enhance chronological relationships among events, such as the well-known Napoleon's Russian Campaign Flow Map in traditional storytelling as well as event timelines in [20]. In particular, immersive environments largely diversify methods of embodying chronology via space, for instance, using natural spatial cues like directionality. We provide further details in Section V-B.

Takeaways: Embodying narration with space is unique to immersive environments. We propose using this approach to facilitate the audience's understanding of the relationship between location and chronology of events. Designers should also aim to situate bite-sized narrative blocks and visualizations in referred locations or show them on demand. However, high levels of detail and visual complexity might

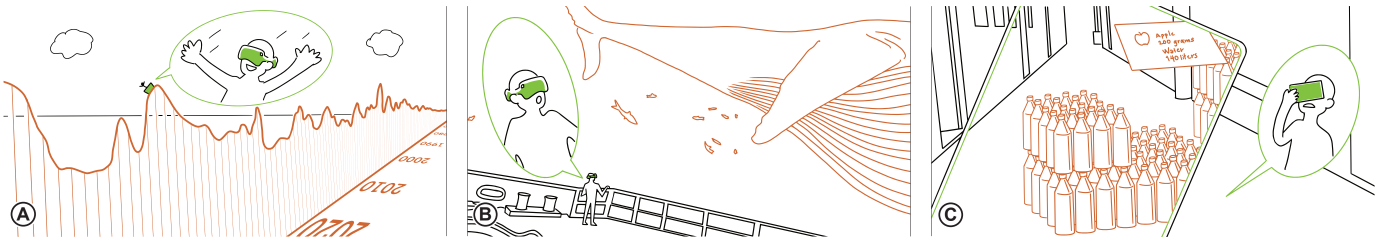

Fig. 3. Three examples of leveraging immersive environments for data stories. Sketches inspired by (A) *Ride Your Data* [15], where users experience data fluctuations as a roller coaster; (B) the VR videogame [theBlu], where the real-life scale of marine wildlife is shown to the user; and (C) the *data visceralization* [43] used in the article [Augmented Reality shows water cost of beef].

amplify perception difficulties (e.g., due to occlusion or distortion), physical fatigue (e.g., from navigating events), and cognitive load (e.g., from locating regions of interest). Thus, users need to be equipped with appropriate techniques for manipulation, navigation, and attention-guiding.

B. Natural Interaction for Narrative Progression

This theme pertains all *Navigation* DS dimensions of and *Spatiality*. When users consume a story, they perform a conceptual traversal of the event graph. In traditional data stories e.g., on web pages, the display space can be imbued with cues associated with the direction of progress, such as reading order (top-down and left-right). Users advance the story by scrolling (i.e., *scrollytelling*), which triggers audio, video, and animation effects from top-down (e.g., [Tokyo Olympics Athletes]) or outside-in (e.g., [Step Inside the Thai Cave]).

In immersive data stories, especially when the narration is strongly embodied in the environment (see Section V-A), the event graph traversal can take new forms, such as physical locomotion. In general, the involvement and control that users can manifest over this traversal vary. Thus, we distinguish between *passive* and *active* methods. Specifically, to **passively navigate** stories, audiences can embark on (metaphorical) vehicles that move through space while simultaneously traversing the event graph (DS: *metaphor* for *Navigation*). Some examples include a car on a mountain road surrounded by historical data [75], an elevator [27] (see Figure 4A), or a roller-coaster on a histogram-shaped track [15] (see Figure 3A). These metaphoric vehicles represent intuitive control elements for navigating through the space that embodies the chronology of the narration.

To **actively navigate** linear narrations, a varying degree of interaction can be found, from simple playback controls [83] to swipe gestures that are commonly used in hand-held AR journalism (e.g., [What caused two devastating crashes of the 737 MAX airplane?]). Exceptionally, despite mainly having a linear structure, 360-degree videos like [Seeking Pluto's Frigid Heart] allow the audience to explore the surroundings while following the narration. Uniquely, as natural walking becomes feasible in immersive environments, for free-form graphs, space can be designed to suggest and encourage free exploration, like a museum [89], or devised as open space according to the context of stories, like an island [35], a stadium [43], or a park [87] (DS: *metaphor* for *Spatiality*). With more freedom of exploration, there is a need for additional guidance, such as pamphlets, maps, or auditory cues, to prevent users from getting lost [35, 87]. We further discuss *guidance* in Section V-D.

Lastly, while **interacting with data visualizations** does not necessarily contribute to the progression of primary narratives, it can enhance storytelling by offering details on demand or justifications for arguments, inspiring serendipity, and improving memory [23]. However, although most systems in our survey support fundamental interactions, such as data selection [23], filtering [88], and visualization manipulation by hands [58], the potential of rich interaction with data is mostly neglected. This is captured by DS: *Interaction (manipulations, modality)* and is closely related to interaction with the narrative, captured in *Navigation (control)*.

Takeaways: Immersive technologies enable users to actively engage with the narrative through natural interaction. We encourage experimenting with interaction to manipulate the story chronology. In particular, we see potential in time-manipulating mechanics (e.g., "bullet time" in [VR Invaders]) or tying the player movement to the progression of time (e.g., [79], [SUPERHOT VR]). Besides, while we call for data interaction techniques informed by immersive analytics, we highlight the trade-off between story progression and data interactivity, as users may sidetrack from the main narration by exploring details on demand.

C. (Self-)Relations and Situated Referents

In contrast to traditional data storytelling that may remain abstract and distanced from audiences, immersive technologies can make data stories more relatable. Users can better understand and **relate to the scale** of *content* (i.e., data) when it is shown stereoscopically around them (DS: *Visualization (presentation, size)*). Examples are air flow visualizations in [Why Opening Windows Is a Key to Reopening Schools] and plastic bottle visualizations in [Augmented Reality shows water cost of beef] (see Figure 3C). This is also related to the concept of *data visceralization* [43] (see Figure 4C), which emphasizes real scales over abstract representations of the data. For example, different population densities can be shown as abstract human shapes in VR environments [32, 33]. Likewise, [No mask? Here's how far your germs can travel] shows liquid droplets traveling distances and [The Hurdler] depicts a sprinter in AR in real scale so that users can see how fast she is running.

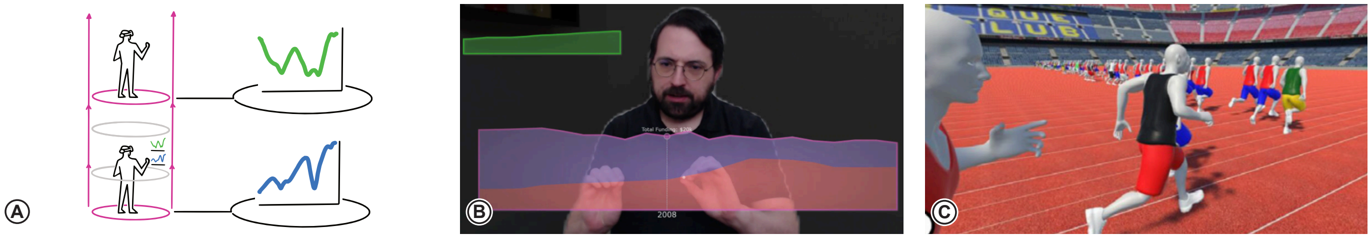

Fig. 4. Three examples from the scoping review results: (A) Sketch based on *DataHop* [27] illustrating an elevator metaphor to navigate data in a VR environment; (B) *Augmented Chironomia* [26] supports presenters manipulating and highlighting elements in chart overlays with gestures to guide audience attention (Image © Hall et al., CC BY 4.0); (C) *Data Visceralization* [43] visualizes the Olympic Men's sprint speeds in VR as one-to-one scale athletes in a stadium (Image © 2021 IEEE). All third-party images used with permission.

Furthermore, it can be easier for users to relate and understand content when shown in **concrete locations**, blending the content or data visualization and environment [70] (DS: *Spatiality (content coupling)*). For instance, reliability visualizations of hydrogen fueling can be contextualized by situating them next to respective nozzles [76] (see Figure 5C). Besides, this method could also enhance the *feeling of presence* and heighten the connection between the story (or data) and users. For example, in [theBlu], users can experience the scale (and behavior) of sea animals directly in the ocean depths (see Figure 3B). Moreover, [Hanami At Home] allows users to see the cherry blossom progress in their houses (which is preferable to an arbitrary location). A more personal approach is [You Draw It (AR): Minimum Wage], where AR visualizations are situated to the faces of the users.

By leveraging **familiar reference points**, users can also tighten the connection and more effectively contextualize and compare data in an immersive data story. For example, users can see their own city's air pollution (visualized as AR particles in [See How the World's Most Polluted Air Compares With Your City's] and the amount of waste produced at restaurants [4], visualized as virtual trash bags (see Figure 5B). In [Why Social Distancing Is So Important], users can see the appropriate social distance to others as ripples in AR. This method can also help users better relate (emotionally) to the story, such as in the VR horror game [STRANGER], where players experience a home invasion, thus triggering fear for their belongings and themselves (DS: *Environment (virtuality, semantic coupling)*).

Users themselves can be incorporated into the stories. For instance, it was shown that *embodied interaction* enhances engagement with the story [88]). This type of active participation in the progression of the story (as discussed in V-B) can lead users to see themselves as part of the story. This is related to the concept of self-insertion, which is common in games. Horror games like [Dreadhalls] and [After Dark VR] exacerbate fear thanks to the VR technology, as it makes easier for players to believe that they are the ones in danger.

Takeaways: We encourage using immersive technologies to amplify the ability of users to relate (the scale of) objects and locations to personal belongings and even to themselves. We argue for the particular effectiveness of incorporating the users and their data into the immersive data stories. One intriguing aspect to consider is the influence of the appearance of the avatar - the virtual representation of the user. Customizing avatars to strengthen the connection between users and enhance storytelling is widespread in role-playing games (e.g., [Skyrim VR] and [RESONARK X]). As immersive environments offer great flexibility, we advocate for enabling both presenters and audiences to decide how to be connected to the story.

D. Guidance vs. Serendipity in Immersive Data Stories

How to guide the viewer's attention is one of the crucial aspects of immersive data storytelling. Compared to traditional data stories, the content may be fully occluded or out of view (DS: *Navigation (guidance)* & *Delivery*). In addition, unnecessary or erroneous navigation carries a higher cost than in a traditional desktop environment. Different mechanisms for **attention guidance** have been explored in the literature. We found various forms of visual highlights (e.g., changing the color of selected objects [20] and spotlights [6]), arrows and annotations [51], examples of animations (e.g., in 3D data videos [83]), and the use of sound (e.g., [46]) and hand gestures (e.g., [26], see Figure 4B). In almost all games we examined, objects are visually highlighted, often supported by text labels or icons. Other cues include guiding lines and arrows (e.g., [Sky Strikers VR]), particle effects (e.g., [Increment]), and audio cues such as characters pointing out objects or events (e.g., [Afterlife VR]). We found similar techniques in journalism, such as highlighting (e.g., [Skateboarding with Tom Schaar]) and visual cues (e.g., [Oscars AR: The Costumes and Creators]). In particular, we found that animations are heavily used to draw attention while advancing the stories by providing a natural transition to the next event and plot. For instance, [Mission to Mars] uses animations to show how Perseverance, represented as a virtual spacecraft, would land on Mars and how each component of the rover would work to conduct investigations.

Unlike traditional storytelling, there is a potential conflict between the story structure and the possibly open-world nature of the environment in which the story is presented, which we discussed earlier in Section V-A. In such cases, visual [1] or auditory [46] cues to guide the user to some artifact or data can funnel attention toward the next step in a linear story but can also hinder the discovery of optional content (DS: *Navigation (event structure)*. Therefore, we see a similar trade-off for the design of the immersive data-driven story:

Fig. 5. Three examples from the scoping review results: (A) *Oblivion* [35] visualizes the increasing sea level in the island state Tuvalu (Image © Jang et al. [35]); (B) *ARwavs* [4] visualizes the amount of waste of a restaurant in a week as real-sized garbage bags directly in the restaurant (Image © Assor et al. [4]); (C) *HydrogenAR* [76] allows audiences to experience the hydrogen fueling process via physical props and to learn details from situating visualizations (Image © 2021 IEEE). All third-party images used with permission.

On one hand, we want to guide the user to the next part of the story. On the other hand, allowing optional "detour" or "surprise" procedures could lead to more engagement.

This is related to the concept of **serendipity** seen from research on, e.g., information retrieval, which entails finding useful or exciting information without actively searching for it. Serendipity and its potential have been examined in relation to *reality-based information retrieval* [13] in mixed-reality settings. While this trade-off between guidance and serendipity is well-known and also applies to traditional (interactive) storytelling and data stories, it becomes essential in immersive environments, where the use of space and locomotion in said space means that one might literally pass by interesting content or find (data) treasure hidden from plain sight. Serendipity is strongly related to the concept of *environmental storytelling*, which denotes the deliberate design and placement of objects in the game world to convey or enrich the story (DS: *Environment (semantic coupling)*). Examples of this can be found in the *level design* of role-playing games (e.g., [Journey for Elysium], [RUINSMAGUS]), *lore-rich item descriptions* (e.g., [Dark Souls]), and *puzzles designed to fit the theme of a story* (e.g., [I Expect You To Die], [The 7th Guest VR]).

Takeaways: We propose to apply the concept of environmental storytelling to (situated) immersive data stories. There, we see a lack of research on how to balance between collecting data "lore" and presenting the story directly to the user. The risk that critical information is missed is at odds with a structured, complete data story. However, the discoverability of new insights, e.g., by exploring new facets or different points of view of a data story, is a promising field for future research. Additionally, we invite research on how serendipity can improve *replayability*, thus encouraging users to re-experience immersive data stories from different angles.

E. Barriers to Entry for Immersive Data Storytelling

Besides the numerous benefits of immersive data stories, we also see a drawback in their potential lack of inclusiveness and accessibility. An important task during the design of any data story is identifying the intended **audience**. Specifically for immersive systems, however, not only the data and visualization literacy of the target audience has to be considered, but also the audience's level of expertise in working in immersive environments (DS: *Traits (expertise)*). Some of the systems we looked into successfully address a broad target group, like casual games (e.g., [Increment] and [Angry Birds VR: Isle of Pigs]), and journalistic data stories that appeal to the general public, e.g., [Oscars 2019: Experience memorable costumes, from every angle]. This is also exemplified by Hans Rosling's successful use of [physical artifacts] and [immersive media] in data storytelling to reach large audiences. On the other hand, we find successful games for niche target communities. For instance, "souls-like" games target players who enjoy (at times unreasonably) challenging gameplay. Similarly, data stories may also find success in targeting expert users.

Still, in regard to **technology**, the supported platforms in the examples of our scoping review show a large focus on HMD-based VR (e.g., [42, 47]) and, to a lesser extent, AR (e.g., [4]) systems. While development for AR/VR headsets and hand-held devices is widely supported by existing tool chains, non-standard solutions, e.g., projection-based systems [36], can be more challenging. While most examples of immersive data storytelling in journalism that we looked into can also be experienced as non-immersive web apps (e.g., [Tokyo Olympics Athletes]), only a few research systems, such as Flow Immersive [23], support multiple different platforms. In fact, the immersive version of several journalistic data stories required specific hardware that not all of our co-authors had access to, thus revealing an entry barrier. We see supporting many device classes and heterogeneous device ensembles (e.g., for multi-user systems) as a prominent challenge (DS: *Presence (representation, cardinality, space, time)*). In particular, as suggested in [41], systems should be designed to equally empower users, by leveraging the technological differences of the devices.

Finally, the **accessibility** of data stories specifically concerns immersive systems, for which there are still no established assistive technologies available (e.g., screen readers). A recent trend encourages accessibility and inclusiveness in mixed reality, as shown by workshops at ACM CHI and IEEE ISMAR (e.g., [53]), although so far none consider data storytelling specifically. We see an opportunity related to the accessibility of immersive data stories in their potential for multi-modal input and multi-sensory output (DS: *Interaction (modality)*). While some existing works already support multiple output channels (e.g., [42, 46]), most focus on visual output and do not use the rich sensory modalities available. We encourage going beyond visual output to make data stories more engaging and accessible for everyone.

Takeaways: To target specific audiences, it is necessary to assess immersive technology literacy and user types. Furthermore, systems should be designed to support (1) broad device classes instead of specific hardware and (2) heterogeneous device ensembles that do not favor specific devices over others. Lastly, we encourage leveraging the unique features of immersive technologies in favor of accessibility, and support the growing trend to design for inclusiveness.

F. Adaptiveness of Immersive Aspects of Data Stories

Adaptiveness refers to the ability of visualizations to change aspects of their representation, encoding, etc. based on circumstances and user preferences [34, 69]. This concept extends to the visualizations and other aspects of data-driven stories. Specifically for immersive systems, the adaptations should also consider aspects such as infinite display space or placement of digital content in real (dynamic) environments.

An example of an aspect subject to adaptation is the **choice of perspective** (and the user's control over it as captured by DS: *Camera*). Scripted perspective changes can convey author intentions [83] (DS: *Traits (author intention)*), but these intentions may be at odds with user preferences or conditions (e.g., cybersickness proneness). Thus, the user is typically allowed to decide when to trigger the adaptations. For example, in the game franchises of [Another Fisherman's Tale], and [Paranormal Detective: Escape from the 80's], the player must manually switch between different perspectives to solve puzzles. In contrast, [Freedom Riders] transitions automatically between exocentric and egocentric views, since it's less likely to trigger cybersickness with mobile AR. In this vein, we confirmed that **platform-specific adaptations** are well-received by players, as they increase accessibility. From our survey, [Cards & Tankards], [Kismet], and [Falcon Age] have distinct desktop and VR versions.

Another observed aspect which may benefit from adaptation is the use of **guides or companions** (DS: *Navigation (guidance)*). On our query, we found examples of immersion by means of engaging pet companions (e.g., [Falcon Age] and [Ziggy's Cosmic Adventures]). [Sensorium Galaxy] takes this concept further, exemplifying a *metaverse* inhabited by AI-driven "virtual beings", for players to converse with, in a social setting. We believe immersive environments provide a uniquely adequate setting to study and develop (adaptive) virtual beings, because of their potential for emotion triggering (e.g., empathy, environmental awareness [4, 43]).

Lastly, and in particular for AR, the **spatiality of the narration** (see also Section V-A and DS: *Spatiality*) should adapt to environment conditions, like the size of the room and the density of furniture inside. This includes adapting the *content layout* for multi-user systems (e.g., [23, 81, 84], [Curatours]), where the number of participants, their locations, and their actions may all influence the optimal spatial distribution of visualization, narrative, and even virtual environment components of the data story. This challenge is not in the focus of our scoping review results, but we consider it a natural and exciting venue for research. For instance, bystanders could be employed as points of reference for story content (DS: *Traits (role)*).

Takeaways: It remains unclear how to effectively yet safely manipulate the perspective in HMD immersive environments with minimal risk of inducing cybersickness. We also highlight how suitable immersive environments are for the study and development of virtual beings that meaningfully react to users. Lastly, we encourage investigating how to adapt the spatiality of the narration to arbitrary (dynamic) spaces, and how and when it is ethically and technically feasible to employ people (i.e., bystanders) as reference points.

G. From Data Stories to Immersive Data Games

Immersion is expected to improve fact retention and spatial understanding in data stories. *Gamification* and *serious games* similarly employ fun game mechanics to enhance retention and understanding. Thus, we believe that data stories should harness game design to create *immersive data games*, and we found evidence of this in our search. The usage of **real-world data in games** is illustrated e.g., by Oblivion [35], where the game world is in itself a visualization of climate data from the island state Tuvalu (see Figure 5A). Likewise, [Guilford Castle VR] recollects (and recreates) historical data in a museum-like experience switching between two time periods in the same location (DS: *Environment (semantic coupling)*).

Beyond simple mechanics, modern games seamlessly **blend various types of gameplay with visualizations**, narrative, and immersive technologies [86]. For instance, the *diegetic interface* of [Dead Space] embeds visualizations in the game world while enhancing the realism and immersion. Said game inspired the VR title [Cosmodread] (see Figure 6B), which shows how natural interaction with diegetic interfaces contributes to the immersion into the horror experience. This relates to DS: *Interaction (level, modality)* and *Visualization (presentation, complexity)*. Another, more complete example of this blend is [Assassin's Creed Nexus VR]. The franchise is known for weaving abundant (factual) historical data into its predominantly fantastical narratives, broadening the audience's interest in locations and events across time and space. The immersive technology makes the locations, traversal mechanics, and combat encounters feel much more visceral. To further enhance the memorability and familiarity with locations and artifacts, *escape room puzzle games* like [I Expect You To Die] and [A Rogue Escape], facilitate intimate knowledge of small locations, by making the player deeply inspect artifacts while exploring the surroundings through natural interaction. Likewise, directly experiencing the data is possible through exergames like [Space Dance Harmony], where both the choreographies and the music (visually reflected in the environment) act as the data. Formulating ways to directly experience the data was also illustrated by Casamayou et al. with their histogram-shaped roller coasters [15] (see Figure 3A).

Another lesson taught by modern gaming is how players find sense of community and impact through practices like *data-driven game development*, where games are continuously improved based on feedback and **player modeling** [28] from data collected during e.g., online multiplayer interactions. Most games in our survey confirm this, displaying active involvement of the developers with the

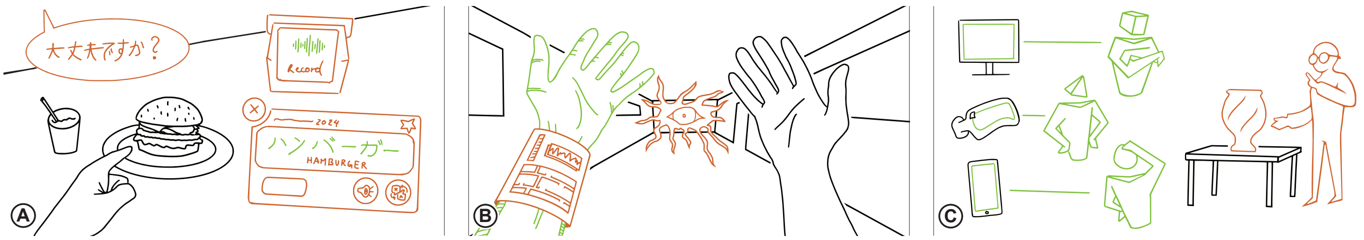

Fig. 6. Three sketches inspired by reviewed games: (A) [Noun Town: VR Language Learning] places players in a foreign country so they can inspect objects in the environment and have conversations with characters in a target language to learn by exposure. (B) [Cosmodread] illustrates a diegetic user interface as part of the space suit worn by the player. (C) [Curatours] exemplifies a multi-user and multi-platform museum tour experience.

player communities. Such models can shape the behavior of *dynamic characters*, as illustrated by [Return to Northbury Grove], [STRANGER], and [Shadow of Valhalla]. Furthermore, player models, behavior, and interactions can be used as data sources for game content. (DS: *Dataset (source)*, *Visualization*, and *Delivery*). For example, games like [Dark Souls], [Death Stranding], and [NieR:Automata] use player data and actions to create content for other players to experience (e.g., ghost animations, community-built structures). However, the spatial tracking and physiology sensors of immersive technologies may enhance player modeling and enable more intricate data-driven game content creation.

Takeaways: We propose to continue blending game mechanics, visualization, and narrative into fully immersive data games. This enables unique research opportunities on how to employ natural interaction to create *intuitive* and *fun* mechanics that enhance retention and understanding. It also motivates the combination of factual and surreal elements in data stories, which promises to improve fact retention (but carries risks of misinformation). Lastly, immersive technologies may enhance player modeling by incorporating spatial tracking and physiological reactions (e.g., heart rate), which in turn can be used as data sources for dynamic character behaviors and (procedural) game content generation.

H. Purpose of Immersive Data-driven Stories

Data stories can simultaneously serve multiple purposes, such as informing, explaining, persuading, and entertaining (DS: *Traits (author intention)*). Immersive technologies can heighten these purposes by enhancing data comprehension and more **easily evoking empathy and emotion** [6, 43] (DS: *Environment (virtuality, representation)*). For example, [Sensations of Sound] can trigger empathy for people with hearing impairments, while simultaneously informing the audience. Similarly, AR waste accumulation visualizations [4] inform the audience about the impact of humans on the environment while prompting them to take action or question their behavior. Likewise, besides entertainment, immersive games can integrate (data-driven) narratives to promote movement (e.g., [Eye of the Temple]), teach new skills, as shown in [Noun Town: VR Language Learning] (see Figure 6A), as well as inform about and question human behavior, as illustrated by [Curatours] (see Figure 6C).

Immersive environments provide unique possibilities to serve these purposes, such as **materializing the data** in the user surroundings (e.g., [35], [The World in 2070]). One can also revert data abstractions, using *visceralization* [43], or related context, like in [88] and [Augmented Reality shows water cost of beef] (see Figure 3C). This technique allows audiences to experience phenomena that are not feasible in real life or traditional storytelling (e.g., seeing air pollution particles in [See How the World's Most Polluted Air Compares With Your City's]). *Including the audience* in the story can also help them connect to the data by, e.g., experiencing it in their own surroundings (DS: *Environment (semantic coupling)*. For instance, in [No mask? Here's how far your germs can travel], the audience can see in AR how far germs can travel in their vicinity. Along with guiding the audience (see Section V-D), *spatial audio* can also contribute to experiencing the data in an immersive environment [6]. These techniques also relate to DS: *Delivery*, *Navigation (guidance)*, and *Interaction (modality)*. Moreover, *metaphors* (see Section V-B, also [21]) are used in some immersive data stories to improve data comprehension and engagement [15, 75]. For instance, Wen et al. [75] immersed students in a driving experience to enhance their comprehension of the underlying stories and insights hidden within the data.

Takeaways: Future research should study the most effective techniques in immersive data stories for various purposes. Immersion is a powerful tool for persuading data story audiences towards positive behavior and increasing awareness (e.g., [4]), which implies a risk in its misuse. Deeply immersive stories could become dangerous instruments for propagating misinformation or encouraging negative behavior. Consequently, we propose comprehensive studies on dark patterns [40] in immersive data storytelling and the development of strategies to enforce responsible and ethical use of immersive technologies in data communication.

VI. Further Research Opportunities

Section V's themes encapsulate the main actionable aspects of immersive data-driven stories. However, there remain other topics that did not have enough visibility in our review results, which we discuss in this section.

a) Evaluation: While evaluation was not part of our codebook, we collected notes regarding the evaluation methods employed in the papers, and included them in our supplementary material. Our findings included unstructured interviews (e.g., [20, 26]) and measurements of the impact of transferring from traditional to immersive environments (e.g., [47, 76]). Immersive scenarios can motivate study participants, allow for flexible virtual study setups (e.g., VR scene backgrounds), and have shown potential for the in-situ and embodied analysis of study data [29, 48]. Unfortunately, these benefits remain underused for research on data stories. In journalism too, the "evaluation" relies on expert judgment exclusively (e.g., OJA). However, once more we learn from the gaming scene where *community-based reviews* provide a continuous source feedback that both research and journalism could benefit from. We saw a single research example comparable to this, in a type of "in-the-wild" qualitative evaluation using social media comments [23]. We would be thrilled to see future research and journalism systems subjected to openly (and continuously) available review platforms as well as new evaluation metrics covering the whole storytelling experience.

b) Tool Support & Empowerment of Authors: Section V-E discusses accessibility from the perspective of the audience users. However, we also notice a lack of support for authors interested in creating immersive data stories. Although Flow Immersive [23] and XRCreator [57] are steps towards this, much more tool support for immersive data stories is needed. We find particular challenges in live storytelling for spatial streaming data (since e.g., the outcome may be unknown) and collaborative systems for heterogeneous device ensembles. We also advocate for easier-to-use authoring tools for users without a programming or design background to create stories using their data and from their perspectives.

c) Digital Humans & Automatic Content Generation: Generative AI models and the subsequent easy access to automatically created content will certainly influence aspects discussed in all of our themes. We are specially interested in automatic content layout suggestions and natural language user guidance or companionship. In this regard, [Sensorium Galaxy] and [NVIDIA's digital human suite of technologies] are initiatives that employ conversational AI along with 3D model generation and animation. In particular for the endless challenges of adaptiveness, AI presents itself as a viable option. However, AI has yet to reach the level of effectiveness and reliability that hand-crafted content can achieve.

VII. Conclusion

Current examples of immersive data-driven storytelling illustrate a young topic brimming with potential for research, development, and content creation. With our reviews, structural design space, and, especially, our discussion of emerging themes, we covered the main aspects that constitute this promising area while also encouraging future research in a multitude of directions. However, we invite more research that integrates games and journalism as sources of knowledge to inform the creation of immersive data-driven storytelling systems. Furthermore, we encourage the employment of emerging AI technologies to broaden the authoring, adaptiveness, and evaluation of such experiences. Doing so will enable a true democratization of immersive data stories. In this vein, we are also fascinated by the prospect of immersive data-driven games that blend multiple purposes, technologies, and creativity in a truly synergistic way. With this work, we hope to have laid the foundations for further advancing this exciting field.

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References

[1] R. Alharbi, O. Strnad, L. R. Luidolt, M. Waldner, D. Kouřil, C. Bohak, T. Klein, E. Gröller, and I. Viola. Nanotilus: Generator of immersive guided-tours in crowded 3d environments. *IEEE Trans. Visual Comput. Graphics*, 29(3):1860–1875, 2023. doi: 10.1109/TVCG.2021.3133592

[2] F. Amini, N. H. Riche, B. Lee, A. Monroy-Hernandez, and P. Irani. Authoring data-driven videos with dataclips. *IEEE Trans. Visual Comput. Graphics*, 23(1):501–510, 2017. doi: 10.1109/TVCG.2016.2598647

[3] H. Arksey and L. O'Malley. Scoping studies: towards a methodological framework. *Int. J. Soc. Res. Methodol.*, 8(1):19–32, 2005. doi: 10.1080/1364557032000119616

[4] A. Assor, A. Prouzeau, P. Dragicevic, and M. Hachet. Augmented reality waste accumulation visualizations. *ACM J. Comput. Sustain. Soc.*, 2(2):1–29, article no. 11, May 2024. doi: 10.1145/3636970

[5] B. Bach, Z. Wang, M. Farinella, D. Murray-Rust, and N. Henry Riche. Design patterns for data comics. In *Proc. CHI*, p. 1–12. ACM, New York, 2018. doi: 10.1145/3173574.3173612

[6] J. Bastiras and B. H. Thomas. Combining virtual reality and narrative visualisation to persuade. In *Proc. BDVA*, pp. 1–8. IEEE, 2017. doi: 10.1109/BDVA.2017.8114623

[7] D. Bormann and T. Greitemeyer. Immersed in virtual worlds and minds: Effects of in-game storytelling on immersion, need satisfaction, and affective theory of mind. *SPPS*, 6(6):646–652, 2015. doi: 10.1177/1948550615578177

[8] B. Bowman, N. Elmqvist, and T. Jankun-Kelly. Toward visualization for games: Theory, design space, and patterns. *IEEE Trans. Visual Comput. Graphics*, 18(11):1956–1968, 2012. doi: 10.1109/TVCG.2012.77

[9] M. Brehmer, B. Lee, B. Bach, N. H. Riche, and T. Munzner. Timelines revisited: A design space and considerations for expressive storytelling. *IEEE Trans. Visual Comput. Graphics*, 23(9):2151–2164, 2017. doi: 10.1109/TVCG.2016.2614803

[10] N. Bressa, H. Korsgaard, A. Tabard, S. Houben, and J. Vermeulen. What's the situation with situated visualization? a survey and perspectives on situatedness. *IEEE Trans. Visual Comput. Graphics*, 28(1):107–117, 2022. doi: 10.1109/TVCG.2021.3114835

[11] M. Bujić and J. Hamari. Immersive journalism: Extant corpus and future agenda. In *Proc. GamiFIN*, pp. 136–145. CEUR-WS, Aachen, 2020.

[12] W. Büschel, J. Chen, R. Dachselt, S. Drucker, T. Dwyer, C. Görg, T. Isenberg, A. Kerren, C. North, and W. Stuerzliner. *Interaction for Immersive Analytics*, vol. 11190 of *LNCS*, pp. 95–138. Springer International Publishing, Cham, 2018. doi: 10.1007/978-3-030-01388-2_4

[13] W. Büschel, A. Mitschick, and R. Dachselt. Here and now: Reality-based information retrieval: Perspective paper. In *Proc. CHIIR*, p. 171–180. ACM, New York, 2018. doi: 10.1145/3176349.3176384

[14] R. Cao, J. Walsh, A. Cunningham, M. Kohler, R. T. Smith, and B. H. Thomas. Examining computer–supported 3d event recreation for enhancing cognitive load, memorability, and engagement. *Multimodal Technol. Interact.*, 4(3), article no. 37, 2020. doi: 10.3390/mti4030037

[15] V. Casamayou, Y. Jansen, P. Dragicevic, and A. Prouzeau. Ride your data: Raise your arms, scream, and experience your data from a roller coaster cart. In *alt.VIS*, 2022.

[16] T. Chandler, M. Cordeil, T. Czauderna, T. Dwyer, J. Glowacki, C. Goncu, M. Klapperstueck, K. Klein, K. Marriott, F. Schreiber, and E. Wilson. Immersive Analytics. In *Proc. BDVA*, pp. 1–8. IEEE, 2015. doi: 10.1109/BDVA.2015.7314296

[17] S. Chen, J. Li, G. Andrienko, N. Andrienko, Y. Wang, P. H. Nguyen, and C. Turkay. Supporting story synthesis: Bridging the gap between visual analytics and storytelling. *IEEE Trans. Visual Comput. Graphics*, 26(7):2499–2516, 2020. doi: 10.1109/TVCG.2018.2889054

[18] F. Chevalier, M. Tory, B. Lee, J. van Wijk, G. Santucci, M. Dörk, and J. Hullman. *From analysis to communication: Supporting the lifecycle of a story*, pp. 151–183. AK Peters/CRC Press, USA, 2018. doi: 10.1201/9781315281575

[19] S. Cooper, R. Cant, M. Kelly, T. Levett-Jones, L. McKenna, P. Seaton, and F. Bogossian. An evidence-based checklist for improving scoping review quality. *Clin. Nurs. Res.*, 30(3):230–240, 2021. doi: 10.1177/1054773819846024

[20] A. Cunningham, J. Walsh, and B. Thomas. Immersive visualisation of geo-temporal narratives in law enforcement. In *Proc. BDVA*, pp. 1–8. IEEE, 2018. doi: 10.1109/BDVA.2018.8533896

[21] R. Dachselt. Action spaces - a metaphorical concept to support navigation and interaction in 3d interfaces. In *Proc. 'Usability Centred Design and Evaluation of Virtual 3D Environments'*, pp. 1–11. Shaker Publishing, Aachen, 2000.

[22] K. de Bruin, Y. de Haan, S. Kruikemeier, S. Lecheler, and N. Goutier. A first-person promise? a content-analysis of immersive journalistic productions. *Journalism*, 23(2):479–498, 2022. doi: 10.1177/1464884920922006

[23] M. DiBenigno, M. Kosa, and M. C. Johnson-Glenberg. Flow immersive: A multiuser, multidimensional, multiplatform interactive covid-19 data visualization tool. *Front. Psychol.*, 12, 2021. doi: 10.3389/fpsyg.2021.661613

[24] T. Dwyer, K. Marriott, T. Isenberg, K. Klein, N. Riche, F. Schreiber, W. Stuerzlinger, and B. H. Thomas. *Immersive analytics: An introduction*, pp. 1–23. Springer International Publishing, Switzerland, 2018. doi: 10.1007/978-3-030-01388-2_1

[25] F. El Outa, M. Francia, P. Marcel, V. Peralta, and P. Vassiliadis. Towards a conceptual model for data narratives. In *Conceptual Modeling*, pp. 261–270. Springer International Publishing, Cham, 2020. doi: 10.1007/978-3-030-62522-1_19

[26] B. D. Hall, L. Bartram, and M. Brehmer. Augmented chironomia for presenting data to remote audiences. In *Proc. UIST*, article no. 18. ACM, New York, 2022. doi: 10.1145/3526113.3545614

[27] D. Hayatpur, H. Xia, and D. Wigdor. Datahop: Spatial data exploration in virtual reality. In *Proc. UIST*, p. 818–828. ACM, New York, 2020. doi: 10.1145/3379337.3415878

[28] D. Hooshyar, M. Yousefi, and H. Lim. Data-driven approaches to game player modeling: A systematic literature review. *ACM Comput. Surv.*, 50(6), article no. 90, 19 pages, 2018. doi: 10.1145/3145814

[29] S. Hubenschmid, J. Wieland, D. I. Fink, A. Batch, J. Zagermann, N. Elmqvist, and H. Reiterer. ReLive: Bridging In-Situ and Ex-Situ Visual Analytics for Analyzing Mixed Reality User Studies. In *Proc. CHI*, pp. 1–20. ACM, New York, 2022. doi: 10.1145/3491102.3517550

[30] J. Hullman and N. Diakopoulos. Visualization rhetoric: Framing effects in narrative visualization. *IEEE Trans. Visual Comput. Graphics*, 17(12):2231–2240, 2011. doi: 10.1109/TVCG.2011.255

[31] P. Isenberg, B. Lee, H. Qu, and M. Cordeil. *Immersive visual data stories*, pp. 165–184. Springer International Publishing, Switzerland, 2018. doi: 10.1007/978-3-030-01388-2_6

[32] T. Ito and C. A. Hidalgo. Biodigital: transform data to experience, beyond data visualization. In *ACM SIGGRAPH 2019 Posters*, article no. 25. ACM, New York, 2019. doi: 10.1145/3306214.3338542

[33] A. Ivanov, K. Danyluk, C. Jacob, and W. Willett. A walk among the data. *IEEE Comput. Graphics Appl.*, 39(3):19–28, 2019. doi: 10.1109/MCG.2019.2898941

[34] A. Jameson. *Adaptive Interfaces and Agents*, pp. 105–130. AK Peters/CRC Press, USA, 2009. doi: 10.1201/9781420088861.ch6

[35] S.-y. Jang, J. Park, and H. Hong. In visible climate change: Exploring immersive data visualisation to promote climate change awareness in a vr game. In *Proc. CHI PLAY EA*, p. 146–152. ACM, New York, 2022. doi: 10.1145/3505270.3558335

[36] M. Kim, J. Lee, W. Stuerzlinger, and K. Wohn. Holostation: Augmented visualization and presentation. In *SA '16: SIGGRAPH ASIA 2016 Symposium on Visualization*, article no. 12. ACM, New York, 2016. doi: 10.1145/3002151.3002161

[37] N. W. Kim, N. Henry Riche, B. Bach, G. Xu, M. Brehmer, K. Hinckley, M. Pahud, H. Xia, M. J. McGuffin, and H. Pfister. Datatoon: Drawing dynamic network comics with pen + touch interaction. In *Proc. CHI*, p. 1–12. ACM, New York, 2019. doi: 10.1145/3290605.3300335

[38] R. Kosara and J. Mackinlay. Storytelling: The next step for visualization. *Computer*, 46(5):44–50, 2013. doi: 10.1109/MC.2013.36

[39] M. Kraus, K. Klein, J. Fuchs, D. A. Keim, F. Schreiber, and M. Sedlmair. The value of immersive visualization. *IEEE Comput. Graphics Appl.*, 41(4):125–132, 2021. doi: 10.1109/MCG.2021.3075258

[40] V. Krauss, P. Saeghe, A. Boden, M. Khamis, M. McGill, J. Gugenheimer, and M. Nebeling. What makes xr dark? examining emerging dark patterns in augmented and virtual reality through expert co-design. *ACM Trans. Comput.-Hum. Interact.*, 2024.

[41] K. Krug, J. Méndez, W. Luo, and R. Dachselt. Don't leave me out: Designing for device inclusivity in mixed reality collaboration. In *CHI 2024 Workshop on Designing Inclusive Future Augmented Realities*. ACM, 5 2024.

[42] S. Latif, H. Tarner, and F. Beck. Talking realities: Audio guides in virtual reality visualizations. *IEEE Comput. Graphics Appl.*, 42(1):73–83, 2022. doi: 10.1109/MCG.2021.3058129

[43] B. Lee, D. Brown, B. Lee, C. Hurter, S. Drucker, and T. Dwyer. Data visceralization: Enabling deeper understanding of data using virtual reality. *IEEE Trans. Visual Comput. Graphics*, 27(2):1095–1105, 2021. doi: 10.1109/TVCG.2020.3030435

[44] B. Lee, N. H. Riche, P. Isenberg, and S. Carpendale. More than telling a story: Transforming data into visually shared stories. *IEEE Comput. Graphics Appl.*, 35(5):84–90, 2015. doi: 10.1109/MCG.2015.99

[45] R. Leroy. Immersion, flow and usability in video games. In *Proc. CHI EA*, article no. 483. ACM, New York, 2021. doi: 10.1145/3411763.3451514

[46] R. R. Lin, Y. Ke, and K. Zhang. Urban symphony: An ai and data-driven approach to real-time animation for public digital art. In *Proc. VINCI*, article no. 31. ACM, New York, 2023. doi: 10.1145/3615522.3615553

[47] R. Liu, H. Wang, C. Zhang, X. Chen, L. Wang, G. Ji, B. Zhao, Z. Mao, and D. Yang. Narrative scientific data visualization in an immersive environment. *Bioinformatics*, 37(14):2033–2041, 2021. doi: 10.1093/bioinformatics/btab052

[48] W. Luo, Z. Yu, R. Rzayev, M. Satkowski, S. Gumhold, M. McGinity, and R. Dachselt. Pearl: Physical environment based augmented reality lenses for in-situ human movement analysis. In *Proc. CHI*, article no. 381. ACM, New York, 2023. doi: 10.1145/3544548.3580715

[49] A. B. Marques, V. Branco, and R. Costa. Narrative visualization with augmented reality. *Multimodal Technologies and Interaction*, 6(12), article no. 105, 2022. doi: 10.3390/mti6120105

[50] S. McKenna, N. Henry Riche, B. Lee, J. Boy, and M. Meyer. Visual narrative flow: Exploring factors shaping data visualization story reading experiences. *Comput. Graphics Forum*, 36(3):377–387, 2017. doi: 10.1111/cgf.13195

[51] J. Meira, J. Marques, J. Jacob, R. Nóbrega, R. Rodrigues, A. Coelho, and A. A. de Sousa. Video annotation for immersive journalism using masking techniques. In *Proc. EPCGI*, pp. 1–7. IEEE, 2016. doi: 10.1109/EPCGI.2016.7851189

[52] Z. Munn, M. D. Peters, C. Stern, C. Tufanaru, A. McArthur, and E. Aromataris. Systematic review or scoping review? guidance for authors when choosing between a systematic or scoping review approach. *BMC Med. Res. Methodol.*, 18:1–7, 2018. doi: 10.1186/s12874-018-0611-x

[53] M. Nebeling, M. Oki, M. Gelsomini, G. R. Hayes, M. Billinghurst, K. Suzuki, and R. Graf. Designing inclusive future augmented realities. In *Proc. CHI EA*, article no. 466, pp. 1–6. ACM, New York, 2024. doi: 10.1145/3613905.3636313

[54] A. Ojo and B. Heravi. Patterns in award winning data storytelling. *Digital Journalism*, 6(6):693–718, 2018. doi: 10.1080/21670811.2017.1403291

[55] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, and D. Moher. The prisma 2020 statement: An updated guideline for reporting systematic reviews. *Int. J. Surg.*, 88:105906, 2021. doi: 10.1016/j.ijsu.2021.105906

[56] F. Pallavicini and A. Pepe. Comparing player experience in video games played in virtual reality or on desktop displays: Immersion, flow, and positive emotions. In *Proc. CHI PLAY EA*, p. 195–210. ACM, New York, 2019. doi: 10.1145/3341215.3355736

[57] D. Ren, B. Lee, and T. Höllerer. Xrcreator: Interactive construction of immersive data-driven stories. In *Proc. VRST*, article no. 136. ACM, New York, 2018. doi: 10.1145/3281505.3283400

[58] P. Ren, H. Tao, W. Ma, Y. Han, W. Cui, and Y. Li. Application of natural interaction in narrative presentation in museum exhibition. In *Proc. IEEE ICVR*, pp. 598–603. IEEE, 2023. doi: 10.1109/ICVR57957.2023.10169234

[59] K. Rogers, S. Karaosmanoglu, M. Altmeyer, A. Suarez, and L. E. Nacke. Much realistic, such wow! a systematic literature review of realism in digital games. In *Proc. CHI*, article no. 190. ACM, New York, 2022. doi: 10.1145/3491102.3501875

[60] D. Saffo, S. Di Bartolomeo, T. Crnovrsanin, L. South, J. Raynor, C. Yildirim, and C. Dunne. Unraveling the design space of immersive analytics: A systematic review. *IEEE Trans. Visual Comput. Graphics*, 30(1):495–506, 2024. doi: 10.1109/TVCG.2023.3327368

[61] E. Segel and J. Heer. Narrative visualization: Telling stories with data. *IEEE Trans. Visual Comput. Graphics*, 16(6):1139–1148, 2010. doi: 10.1109/TVCG.2010.179

[62] D. Seyser and M. Zeiller. Scrollytelling – an analysis of visual storytelling in online journalism. In *Proc. IV*, pp. 401–406. IEEE, 2018. doi: 10.1109/iV.2018.00075

[63] D. Shi, X. Xu, F. Sun, Y. Shi, and N. Cao. Calliope: Automatic visual data story generation from a spreadsheet. *IEEE Trans. Visual Comput. Graphics*, 27(2):453–463, 2021. doi: 10.1109/TVCG.2020.3030403

[64] Y. Shi, T. Gao, X. Jiao, and N. Cao. Breaking the fourth wall of data stories through interaction. *IEEE Trans. Visual Comput. Graphics*, 29(1):972–982, 2023. doi: 10.1109/TVCG.2022.3209409

[65] Y. Shi, X. Lan, J. Li, Z. Li, and N. Cao. Communicating with motion: A design space for animated visual narratives in data videos. In *Proc. CHI*, article no. 605. ACM, New York, 2021. doi: 10.1145/3411764.3445337

[66] S. Shin, A. Batch, P. W. S. Butcher, P. D. Ritsos, and N. Elmqvist. The Reality of the Situation: A Survey of Situated Analytics. *IEEE Trans. Visual Comput. Graphics*, pp. 1–19, 2023. doi: 10.1109/TVCG.2023.3285546

[67] X. Shu, A. Wu, J. Tang, B. Bach, Y. Wu, and H. Qu. What makes a data-gif understandable? *IEEE Trans. Visual Comput. Graphics*, 27(2):1492–1502, 2021. doi: 10.1109/TVCG.2020.3030396

[68] C. D. Stolper, B. Lee, N. Henry Riche, and J. Stasko. Emerging and recurring data-driven storytelling techniques: Analysis of a curated collection of recent stories. Technical Report MSR-TR-2016-14, Microsoft, 2016.

[69] M. Tatzgern, V. Orso, D. Kalkofen, G. Jacucci, L. Gamberini, and D. Schmalstieg. Adaptive information density for augmented reality displays. In *Proc. IEEE VR*, pp. 83–92. IEEE, 2016. doi: 10.1109/VR.2016.7504691

[70] W. Tong, K. Shigyo, L.-P. Yuan, M. Fan, T.-C. Pong, H. Qu, and M. Xia. Vistellar: Embedding data visualization to short-form videos using mobile augmented reality. *IEEE Trans. Visual Comput. Graphics*, pp. 1–13, 2024. doi: 10.1109/TVCG.2024.3372104

[71] A. C. Tricco, E. Lillie, W. Zarin, K. K. O'Brien, H. Colquhoun, D. Levac, D. Moher, M. D. J. Peters, T. Horsley, L. Weeks, S. Hempel, E. A. Akl, C. Chang, J. McGowan, L. Stewart, L. Hartling, A. Aldcroft, M. G. Wilson, C. Garritty, S. Lewin, C. M. Godfrey, M. T. Macdonald, E. V. Langlois, K. Soares-Weiser, J. Moriarty, T. Clifford, Ö. Tunçalp, and S. E. Straus. Prisma extension for scoping reviews (prisma-scr): Checklist and explanation. *Ann. Intern. Med.*, 169(7):467–473, 2018. PMID: 30178033. doi: 10.7326/M18-0850

[72] T. Uskali, A. Gynnild, S. Jones, and E. Sirkkunen. *Immersive journalism as storytelling: Ethics, production, and design*. Taylor & Francis, London, UK, 2021. doi: 10.4324/9780429437748

[73] Z. Wang, H. Romat, F. Chevalier, N. H. Riche, D. Murray-Rust, and B. Bach. Interactive data comics. *IEEE Trans. Visual Comput. Graphics*, 28(1):944–954, 2022. doi: 10.1109/TVCG.2021.3114849

[74] S. Webber, R. M. Kelly, G. Wadley, and W. Smith. Engaging with nature through technology: A scoping review of hci research. In *Proc. CHI*, article no. 521. ACM, New York, 2023. doi: 10.1145/3544548.3581534

[75] L. Wen, M. Zhuang, A. P. K. Kwok, and M. Yan. Beyond charts: A mixed-reality system for visualizing and experiencing data. In *Proc. ICoMS*, p. 85–90. ACM, New York, 2023. doi: 10.1145/3613347.3613360

[76] M. Whitlock, D. A. Szafir, and K. Gruchalla. Hydrogenar: Interactive data-driven presentation of dispenser reliability. In *Proc. ISMAR*, pp. 704–712. IEEE, 2020. doi: 10.1109/ISMAR50242.2020.00101

[77] D. Wilcox-Netepczuk. Immersion and realism in video games - the confused moniker of video game engrossment. In *Proc. CGAMES*, pp. 92–95. IEEE, Louisville, KY, USA, 2013. doi: 10.1109/CGames.2013.6632613

[78] A. Wu, Y. Han, Z. Zhao, and Y. Yang. Hierarchical memory decoder for visual narrating. *IEEE Trans. Circuits Syst. Video Technol.*, 31(6):2438–2449, 2021. doi: 10.1109/TCSVT.2020.3020877

[79] K. Wu and D. Karwas. The metamorphosis of storytelling: Time-based interactivity in virtual reality filmmaking. In *Proc. CHI EA*, article no. 423, pp. 1–5. ACM, New York, 2024. doi: 10.1145/3613905.3648672

[80] S. Wu. Journalism's immersive shift: Uncovering immersive journalism's adherence to traditional news values, norms, routines and roles. *Journalism Practice*, pp. 1–16, 2022. doi: 10.1080/17512786.2022.2133779

[81] N. Xu, Y. Liu, Z. Zhang, and L. Yu. Timequestar: Unfolding cultural narratives via situated visualizations. In *Proc. ISMAR-Adjunct*, pp. 86–91. IEEE, 2023. doi: 10.1109/ISMAR-Adjunct60411.2023.00026

[82] X. Xu, L. Yang, D. Yip, M. Fan, Z. Wei, and H. Qu. From 'wow' to 'why': Guidelines for creating the opening of a data video with cinematic styles. In *Proc. CHI*, article no. 599. ACM, New York, 2022. doi: 10.1145/3491102.3501896

[83] L. Yang, A. Wu, W. Tong, X. Xu, Z. Wei, and H. Qu. Understanding 3d data videos: From screens to virtual reality. In *Proc. PacificVis*, pp. 197–206. IEEE, 2023. doi: 10.1109/PacificVis56936.2023.00029

[84] E. Yoo and J. Yu. Evaluating the impact of presentation on learning and narrative in ar of cultural heritage. *IEEE Access*, 12:25876–25887, 2024. doi: 10.1109/ACCESS.2024.3365696

[85] Y. Zhao, P. Guo, C. Liu, and W. Song. Design and implementation of battlefield situation visualization system based on osg. In *Proc. ICCC*, pp. 2286–2291. IEEE, 2022. doi: 10.1109/ICCC56324.2022.10065972

[86] Z. Zhao and N. Elmqvist. The stories we tell about data: Surveying data-driven storytelling using visualization. *IEEE Comput. Graphics Appl.*, 43(4):97–110, 2023. doi: 10.1109/MCG.2023.3269850

[87] X. Zhou, Y. Yang, F. Ortega, A. Batmaz, and B. Lee. Data-driven storytelling in hybrid immersive display environments. In *Proc. ISMAR-Adjunct*, pp. 242–246. IEEE, 2023. doi: 10.1109/ISMAR-Adjunct60411.2023.00056

[88] Q. Zhu, L. Yuan, Z. Xu, L. Yang, M. Xia, Z. Wang, H.-N. Liang, and X. Ma. From reader to experiencer: Design and evaluation of a vr data story for promoting the situation awareness of public health threats. *Int. J. Hum.-Comput. Stud.*, 181:103137, 2024. doi: 10.1016/j.ijhcs.2023.103137

[89] Y. Zhu, M. Liu, Z. Lou, R. Li, Z. Tie, W. Huang, and Q. Diao. Vitalizing cultural memory with immersive data storytelling. In *Proc. IEEE VRW*, pp. 468–473. IEEE, 2023. doi: 10.1109/VRW58643.2023.00101