Generative Artificial Intelligence for Immersive Analytics

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Abstract: Generative artificial intelligence (GenAI) models have advanced various applications with their ability to generate diverse forms of information, including text, images, audio, video, and 3D models. In visual computing, their primary applications have focused on creating graphic content and enabling data visualization on traditional desktop interfaces, which help automate visual analytics (VA) processes. With the rise of affordable immersive technologies, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), immersive analytics (IA) has been an emerging field offering unique opportunities for deeper engagement and understanding of complex data in immersive environments (IEs). However, IA system development remains resource-intensive and requires significant expertise, while integrating GenAI capabilities into IA is still under early exploration. Therefore, based on an analysis of recent publications in these fields, this position paper investigates how GenAI can support future IA systems for more effective data exploration with immersive experiences. Specifically, we discuss potential directions and key issues concerning future GenAI-supported IA applications.

1 INTRODUCTION

Visual analytics (VA) stems from information and scientific visualization and other areas like data mining, which allows humans to explore complex data using interactive visual digital interfaces (Wong and Thomas, 2004) and address complex data-driven tasks. Professionals can gain a deeper understanding of data and explore different questions and patterns using VA processes and tools. The emergence of Extended Reality (XR), encompassing technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR), has brought up widely available immersive environments (IEs) in various applications and holds great potential (Fortune Business Insights, 2024).

With three-dimensional (3D) visualization spaces, XR provides a new medium to present complex data visualizations and enables immersive analytics (IA). IA is an emerging research field that relies on IEs for various data visualization and analytic tasks (Klein et al., 2022). Combining IA with multisensory features, such as haptics or sound, can further enhance analysis options for the user (Kraus et al., 2021) or personalize the user needs (McCormack et al., 2018).

While IA systems have shown advantages in many interactive data exploration and decision-making scenarios, the development processes can be time-consuming and have a high requirement for expert knowledge. Understanding data visualizations in IEs also requires expertise in interactive techniques and analytical methods. On the other hand, generative artificial intelligence (GenAI) has unleashed great potential across many fields with its content multimodal generation capabilities. According to a recent report by Gartner, Inc. (Gartner, 2024) more than 80% of companies will have used GenAI APIs or deployed GenAI applications by 2026. Therefore, this paper is motivated to investigate how IA applications can benefit from GenAI models.

Starting by reviewing the state-of-the-art research on relevant topics across VA, XR and IA, this position paper aims to identify promising trends for future GenAI-supported IA. The rest of the paper is organized as follows. Section 2 presents relevant research directions that could impact the development of future GenAI-supported IA applications. Here, the work is categorized into three main areas: (1) GenAI for Non-Immersive Visual Analytics, (2) GenAI and XR, and initial previous work on (3) GenAI for IA. Section 3 brings the trends together in a deeper discussion and

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highlights interesting future directions for GenAI in IA applications, while Section 4 concludes the work.

2 CURRENT TRENDS

As IA is an emerging field with deep roots in conventional VA, the investigation starts by reviewing breakthroughs in several relevant research fields, including GenAI for non-immersive data visualization, GenAI for XR applications, and a potential transition toward GenAI for immersive data analysis. We acknowledge that prior research on GenAI for visualization has identified key issues and challenges in general data visualization tasks. GenAI has been integrated into visualization tasks with different capabilities, such as enhancing creativity, automating visualization, or assisting human reasoning processes in a general perspective (Basole and Major, 2024). Ye et al. have also provided a broad overview of GenAI in visualization and highlighted challenges such as data limitations and evaluation methods (Ye et al., 2024). However, both works leave the integration of GenAI with VA in IEs an under-explored field. As real-time interactions and spatial awareness are essential characterizations of data visualization tasks in IEs (Marriott et al., 2018), whether widely adopted GenAI techniques fit those tasks still needs to be assessed. Thus, this paper revisits recent emerging research efforts toward integrating GenAI in IA fields, intending to explore the latest trends.

2.1 GenAI for Non-Immersive VA

Although IA is an emerging field that performs VA with multisensory interfaces in XR, the mainstream workflow is still coined with conventional 2D VA as immersive visualization is the fundamental component for IA (Kraus et al., 2021). Conventional VA workflows, including data processing, visual mapping, and visual perception procedures, can be adapted in IA. Therefore, insights from the state-of-the-art combinations between GenAI, conventional data visualization, and VA may be transferred into IEs, always considering the potential adaptations needed in a different media such as XR.

GenAI and VA have been applied in various research domains across smart healthcare, industrial data communication, and laboratory training. GenAI models, especially pre-trained LLMs (e.g., OpenAI's ChatGPT), support these applications' visual understanding and reasoning processes by generating additional guiding information or automatically summarizing insights in text formats. For example, ChatGPT has been employed in many VA applications to generate textual descriptions based on either data input or information graphs (Gandee et al., 2024). Deep Neural Networks (DNNs) have also been employed in VA systems to transform the graphs into narratives (Shrestha et al., 2022). Meanwhile, the LLM model BART (Lewis et al., 2020) was applied to simplify lengthy textual details, as excessive information may cause information overload for users. Additionally, procedural diagrams such as flowcharts are essential visual tools in iterative design processes. GenAI can update and manage these visualizations with designers' instructions (Balhorn et al., 2024; Alshareef et al., 2024).

One key direction of using GenAI for general visualization tasks is to enhance the interpretability of data visualization. While research on data visualizations focuses heavily on innovative ways to present patterns and insights in an abstract, visual format, making complex information more accessible to users, users may still struggle to understand these visualizations without the necessary domain context. Therefore, data storytelling has been an active research field that can complement abstract information graphs with narrative context, enhancing visual understanding (Shao et al., 2024; Dykes, 2015). GenAI has increasingly automated the creation of data narratives (Lo Duca., 2023; Strömel et al., 2024; Lo Duca., 2024). This narrative generation capability helps users interpret data patterns with minimal cognitive load, clearly explaining data findings and their implications. Researchers have evaluated and confirmed that data narratives enhance visual understanding in fitness analysis (Strömel et al., 2024) by providing complementary qualitative data and more reflective engagement. In learning analytics, the idea of using LLMs to automate data narratives has also been adopted (Pinargote et al., 2024; Yan et al., 2024). Whereas GenAI-based data storytelling expands the information for better visual understanding, visual summarization of raw data input may function in another way to enable users to grasp the overview quickly. GenAI has been applied to create visual summarization (*charts* and *text*) for any data inputs in natural language formats such as audio, video, voice, and text datasets (Nath and Ethirajan, 2023).

Ye et al. have assessed various GenAI techniques tailored for visualization in a non-immersive context (Ye et al., 2024). These techniques include data enhancement, automatic visualization generation, stylization, and supporting user interactions. However, the automatic generation of data visualizations with precise numerical awareness remains a phase with great potential. Several works are emerging toward generating data visualizations with stylizations and numerical awareness. For example, *ChartSpark* (Xiao et al., 2024) has proposed a text-to-image generative approach to create the so-called pictorial visualizations, in which data charts guided the numerical representations. A modern visualization style with semantic context that, in some scenarios, can help enhance visual understanding for key data insights. Another work, *ChartMimic* (Shi et al., 2024), can generate similar axis-based data visualizations using proprietary and open-weight LLMs based on structured text commands. Despite the novelty, the results indicate limitations in generating data visualizations concerning chart inputs. Moreover, limitations in current visualization datasets and issues in effectively integrating GenAI models with VA workflows remain significant concerns.

2.2 GenAI and XR

GenAI and XR are converging to create innovative applications across various fields, such as architectural design, smart healthcare, and interactive learning. Most applications leverage the strengths of IEs in visual presentations along with the capabilities of GenAI in multimodal reasoning, enhancing natural interactions and personalization. For instance, in *CogXR* (Yan and Zhang, 2024), researchers developed a graphical tool that offers visual cues for long text in the XR space, enabling users to navigate and comprehend the reading material swiftly. Beyond providing real-time assistance and feedback in immersive learning experiences, these GenAI techniques have also enhanced personalized experiences in virtual stores (Wang et al., 2024a) and virtual exhibitions (Constantinides et al., 2024; Vasic et al., 2024) by generating recommendations based on individuals' preferences.

Natural interaction techniques are key components for immersive experiences and have been facilitated by many GenAI models. In architectural design, for instance, while XR is advantageous in presenting architectural visualizations, GenAI enables non-experts to design, modify, and explore XR spaces seamlessly, fostering accessibility and innovation across sectors by integrating natural language processing with image generation (Le et al., 2023; Drogemuller et al., 2023; Chen et al., 2024). This research field often intersects with 3D object generation by GenAI technology in XR. Users can create and edit architectural spaces and objects with speech and gesture-based interactions supported by text-to-image GenAI, such as Stable Diffusion (Rombach et al., 2022) and ControlNet (Zhang et al., 2023). Besides, inspired by text-to-3D (Tang et al., 2023) or text-guided image-to-3D (Gao et al., 2022) GenAI approaches, interior designers can easily create 3D models of architectural objects via natural language prompts (Yeo et al., 2023).

The convergence of GenAI and XR has led to transformative advancements in virtual conversational agents that provide real-time instructional guidance and support complex cognitive tasks such as training (Ayre et al., 2023; Chan and Liu, 2024), interactive learning (Hara, 2024; Cheng et al., 2024; Kapadia et al., 2024; Wang et al., 2024a; Hara et al., 2024; Salehi et al., 2024), and therapeutic engagement (Wang and Zhang, 2024). In healthcare scenarios, the combination of GenAI and XR has been employed to rehabilitate cognitive impairments and facilitate behavioral training. Multimodal GenAI models, particularly ChatGPT, have been used for generating auditory (Yamauchi et al., 2023) or visual image content (Wang and Zhang, 2024) for rehabilitation. Moreover, LLM-based chatbots in VR and AR enable users to undergo repeatable training more naturally while reducing the risk of privacy exposure (Li et al., 2024).

GenAI also plays a fundamental role in social XR scenarios by assisting in complex decision-making or promoting communications. LLMs such as ChatGPT are still the majority of GenAI-based approaches in these applications to simulate human behaviors such as natural conversation via voice and gestures (Numan et al., 2023; Si et al., 2023; Shoa et al., 2023). Although IEs have been applied to present immersive scenes to users, the visual content generation is still based on 2D image generation models. For example, in applications such as a virtual interview (Si et al., 2023), a stable diffusion model has been adopted to generate tiled texture images based on users' voice and gesture input. Moreover, creating LLM-based chatbots in XR follows a similar idea of assisting human cognitive processes through real-time interactions.

2.3 GenAI for IA

The field of GenAI for IA has significantly fewer prior examples compared to non-immersive VA tasks and XR applications. While *GazePointAR* (Lee et al., 2023; Lee et al., 2024) has demonstrated the capabilities of pre-trained LLMs in addressing situated analytic tasks, it focuses on enhancing interaction methods in AR by incorporating eye-tracking and speech interactions with ChatGPT, rather than focusing on complex information visualization and analytic tasks. The cross-modal reasoning capabilities of current LLMs may fall short of addressing complex VA tasks and may even be limited to IEs. For instance, generating 3D data visualizations may be challenging as it demands precise spatial accuracy to ensure meaningful interpretations. Even though existing work such as *ChartMimic* (Shi et al., 2024) has shown the capability of generating axis-based data charts, other data visualization types are less explored, such as rational-based data visualizations (e.g., networks, volumetric data visualization). Therefore, we envision the great potential of transforming it into IEs and assessing its usability, which can be a good starting point for further exploration.

Research efforts have also been identified to propose insightful perspectives on evaluating the visual content in conventional visualization mediums and IEs. Typically, evaluations in these fields combine quantitative and qualitative methods to capture a comprehensive view, while quantitative analysis of human factors with specific metrics (e.g., task accuracy, completion time, comprehension, and understanding) is the primary method for evaluating the IA properties (Jamaludin et al., 2023). For instance, the *AIsop* study employed a human-centered evaluation approach to measuring the effects of AI-generated imagery and VR-based data storytelling on user experience (Gatti et al., 2024). In addition to standard metrics, novel factors such as visual aesthetics and emotional impacts are gaining recognition in the assessment of XR applications, as they provide deeper insights into user engagement and satisfaction (Stacchio et al., 2023). When integrating GenAI into IA applications, though quantitative metrics are widely adopted in the AI community, there is a need for further exploration into combining these with human-centered factors for a more comprehensive evaluation.

3 DISCUSSION

The integration of GenAI holds significant potential for addressing conventional VA tasks and enhancing XR applications separately. While research in these two areas has yet to spark extensive dialogue on the effective implementation of GenAI in IA, we anticipate that integrating GenAI into IA could significantly enhance immersive experiences, foster creativity and new knowledge generation, and broaden the accessibility of IA systems. To advance this integration, we outline key areas for further exploration, including GenAI for multisensory IA, 3D data representations for GenAI training, GenAI for prototyping IA, and ethical considerations. Although not exhaustively, addressing these challenges could open the door to more GenAI-supported IA applications.

3.1 GenAI for Multisensory IA

Although immersive data visualizations remain a central focus of IA systems, these systems ultimately strive to engage multiple senses to enhance information perception and interaction (McCormack et al., 2018). Research has shown that multisensory components such as haptic feedback, spatial audio, and olfactory cues can significantly enhance user immersion and understanding in IEs. For example, haptic and auditory feedback can improve spatial awareness and heighten the sense of presence (Wagener et al., 2022; Kern and Ellermeier, 2020), and olfactory cues can evoke deeper emotional engagement (Cowan et al., 2023; Dal Bò et al., 2024; Wang et al., 2024b). These findings suggest that multisensory approaches could be valuable in IA systems.

GenAI could further enhance these multisensory experiences by generating realistic sensory outputs in IA based on user interactions. For instance, auditory cues could alert users when they navigate to outliers within a data cluster in an IA system, providing a sensory guide without adding visual clutter. GenAI has also expanded the potential for novel interaction techniques in XR, which can be adapted to IA. For example, recent work like *SonoHaptic* (Bonada et al., 2016) has shown how audio and haptic feedback can enhance the selection and understanding of data representations in IEs, suggesting similar applications could improve user comprehension during immersive data exploration in IA.

Using GenAI technologies to support multisensory IA experiences also makes sense in scenarios where visual information alone is insufficient or impractical. GenAI's capabilities in generating adaptive, context-aware sensory outputs can reduce the chances of visual overload, enabling users to focus on important visual elements while still gaining a comprehensive understanding of complex data. While visual perception is often the most effective way, using GenAI to provide non-visual data representations, such as olfactory and auditory cues, can enhance accessibility for visually impaired users.

3.2 3D Data Representations for GenAI Training

While some success has been achieved in generating and enhancing basic visualizations using GenAI, current applications remain limited in IA. One reason is that most current GenAI models generate information in textual format, realistic 2D images or videos, and

3D models. However, generating and understanding abstract data visualizations, whether in 2D or 3D, is more challenging as their numerical meanings should be maintained by the visual encoding.

Bridging this gap will require innovative approaches in creating, training, and evaluating 2D and 3D data visualization generative models. A critical first step is the development of comprehensive data representations to serve as training datasets. While within the visualization community, 3D data representations for abstract data in 2D media have been historically and justly criticized since they cause issues e.g., in terms of occlusions and perspective distortion (Munzner, 2014), the use of 3D representations in immersive media should not be automatically discarded regardless of their application, even for abstract data, especially with a spatial embedding (Marriott et al., 2018; Kraus et al., 2022). For example, in situated analytics, 3D data representations can blend more naturally in IEs and provide better immersion to the user (Shin et al., 2024). Moreover, 3D data representations have been adopted and studied for different abstract data types in IEs, e.g., node-link graphs, scatterplots, and parallel coordinate plots (Kraus et al., 2022).

Collecting 3D data representations for future GenAI models may help solve complex data analysis tasks in IEs. Moreover, new approaches could advance the capturing and rendering of spatial relationships to transform how we analyze complex datasets in IA systems.

3.3 GenAI for Prototyping IA

While existing experience from GenAI applications in VA can be leveraged to enhance IA, developing an IA system remains time-consuming, and collecting meaningful user feedback poses additional challenges. Despite these obstacles, the success of GenAI in various fields—including procedural flowchart correction (Alshareef et al., 2024; Balhorn et al., 2024), visual object generation (Nath and Ethirajan, 2023; Numan et al., 2023; Ye et al., 2024), and human behavior simulation (Bharti and Sharma, 2024; Si et al., 2023)—suggests a potential for supporting rapidly prototyping IA applications.

An interesting workflow of GenAI-supported IA prototyping could involve an iterative cycle including design, development, and evaluation phases. In the *design* phase, developers would specify key parameters such as data types, preferred visualization techniques, interaction methods, XR devices, and evaluation protocols in natural language, allowing for easy adaptation to project needs. During the *development* phase, GenAI models, particularly text-to-code generators, could automatically translate specifications into corresponding visualizations within IEs, allowing developers to focus more on the high-level design of IA applications. In the *evaluation* phase, GenAI could simulate participant behaviors and generate feedback based on user studies, with input from psychologists and cognitive experts to ensure realistic behavior modeling. These GenAI-driven evaluations could be automatically analyzed, generating reports for subsequent design iterations.

Despite its potential, we also envision several challenges in applying this human-GenAI collaborative IA prototyping approach. First, GenAI models trained on general visualization types or domain datasets may struggle to generate or adapt highly domain-specific visualizations accurately. This issue is compounded by the evolving nature of XR hardware and software, as updates or new devices may require recalibration of the GenAI-generated visualizations to ensure compatibility and optimal performance. A standardized protocol for future XR devices may help address these problems. Furthermore, as immersive experiences often involve real-time data integration, maintaining synchronization between the GenAI model and live data feeds can be challenging. Addressing these challenges will require GenAI models that are flexible and capable of continuous learning and adaptation to different data streams and IA environments, which currently remains a significant hurdle for practical deployment.

3.4 Ethical Issues of GenAI for IA

The integration of GenAI into IA may introduce new ethical challenges while the widely discussed ethical concerns in AI and XR remain. Recently, Hu et al. have proposed metrology for ethics and data privacy issues in AI-enriched human-centered XR systems (Hu et al., 2024), suggesting most data privacy issues and ethical concerns should be considered in GenAI-supported IA systems. We highlight ethical issues regarding data privacy and interoperability of GenAI-supported IA systems and propose possible solutions from the perspectives of IA researchers and developers.

Some IA applications may continuously learn and adapt based on real-time user data for personalized experiences, which may threaten data privacy. Large pre-trained GenAI models applied to IA may increase the risk as user data is often processed in cloud centers rather than locally (Gupta et al., 2023). The guidance from the research communities in AI, XR, and interdisciplinary topics can be adapted to address data privacy concerns in GenAI-supported IA systems. When continuous user data collection is necessary, developers should keep in mind that all user data collected through IA systems can be linked to individual identification, which should be protected as other private data (Carter and Egliston, 2023). A group of tools and technologies for enhancing data privacy in XR can be adapted in GenAI-supported IA systems, such as self-sovereign identity frameworks, decentralized identifiers and verifiable credentials specifications, and privacy-focused blockchain technologies (Alkaeed et al., 2024).

As the method of data visualization in IEs directly impacts user understanding and interaction (Whitlock et al., 2020), data visualizations automatically generated by GenAI may manipulate user focuses, leading to potential biases or misinterpretations of data. Therefore, an ethical need is to examine how much control GenAI should exert over users' attention in IEs. On the other hand, even though GenAI can potentially guide data exploration in XR, users might need to fully understand how GenAI arrived at certain conclusions. Possible solutions might be to add "explanation layers" within the design spaces that provide insights into the AI's decision-making process and ensure users can evaluate the AI-generated outputs.

3.5 Summary

Despite the overall potential of combining GenAI into IA applications, four future directions with key issues are highlighted. This work first highlights that using GenAI to enhance multisensory IA experiences would benefit immersive data exploration and gaining insights. Besides, the less-explored 3D data representations for GenAI training are spotted as a critical research area. Meanwhile, considering the design spaces of IA, integrating GenAI agents into IA design and prototyping processes may improve the efficiency of IA system development. For actual deployment phases, addressing ethical concerns, particularly regarding data privacy, bias, and transparency, is crucial for responsible deployment. By addressing these key issues, the synergy can provide both technical advancements and novel user-centric designs to both GenAI and IA research communities.

4 CONCLUSIONS

This position paper adds XR as another dimension of the integration of GenAI into visualization and presents an overview of how they have been combined in various applications. Our work illustrates how GenAI intersects with VA and XR, highlighting the transformative potential of these integrations in the IA domain. We envision that GenAI will reshape IA applications by enabling multisensory experiences and automating complex 3D data visualizations, fostering more immersive and personalized data analytics. However, achieving this vision requires advancements in user-centric design, spatially aware model training, and ethical practices. Specifically, considerations around data privacy and interoperability of GenAI models in IA systems are essential. Additionally, we discuss some tools and methods to help address these challenges, positioning GenAI as a driving force for innovative, powerful, and ethically grounded future IA applications.

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REFERENCES

Alkaeed, M., Qayyum, A., and Qadir, J. (2024). Privacy preservation in artificial intelligence and extended reality (ai-xr) metaverses: A survey. *Journal of Network and Computer Applications*, page 103989.

Alshareef, A., Keller, N., Carbo, P., and Zeigler, B. P. (2024). Generative ai with modeling and simulation of activity and flow-based diagrams. In Guisado-Lizar, J.-L., Riscos-Núñez, A., Morón-Fernández, M.-J., and Wainer, G., editors, *Simulation Tools and Techniques*, pages 95–109, Cham. Springer Nature Switzerland.

Ayre, D., Dougherty, C., and Zhao, Y. (2023). Implementation of an artificial intelligence (ai) instructional support system in a virtual reality (vr) thermal-fluids laboratory. In *IMECE2023*, Volume 8: Engineering Education.

Balhorn, L. S., Caballero, M., and Schweidtmann, A. M. (2024). Toward autocorrection of chemical process flowsheets using large language models. In Manenti, F. and Reklaitis, G. V., editors, *34th European Symposium on Computer Aided Process Engineering / 15th International Symposium on Process Systems Engineering*, volume 53 of *Computer Aided Chemical Engineering*, pages 3109–3114. Elsevier.

Basole, R. C. and Major, T. (2024). Generative AI for Visualization: Opportunities and Challenges . *IEEE Computer Graphics and Applications*, 44(02):55–64.

Bharti, P. and Sharma, V. K. (2024). Enhancing decision-making: The significance of humanized avatars in complex scenarios (short paper). In Soto, A. and Zangerle, E., editors, *Joint Proceedings of the ACM IUI 2024 Workshops co-located with the 29th Annual ACM Conference on Intelligent User Interfaces (IUI 2024), Greenville, South Carolina, USA, March 18, 2024*, volume 3660 of *CEUR Workshop Proceedings*. CEUR-WS.org.

Bonada, S., Veras, R., and Collins, C. (2016). Personalized views for immersive analytics. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*, ISS '16 Companion, page 83–89, New York, NY, USA. Association for Computing Machinery.

Carter, M. and Egliston, B. (2023). What are the risks of virtual reality data? learning analytics, algorithmic bias and a fantasy of perfect data. *New Media & Society*, 25(3):485–504.

Chan, A. and Liu, J. A. (2024). Board 24: Development of multi-user-enabled, interactive, and responsive virtual/augmented reality-based laboratory training system. In *2024 ASEE Annual Conference & Exposition*.

Chen, X., Gao, W., Chu, Y., and Song, Y. (2024). Enhancing interaction in virtual-real architectural environments: A comparative analysis of generative ai-driven reality approaches. *Building and Environment*, 266:112113.

Cheng, A. Y., Guo, M., Ran, M., Ranasaria, A., Sharma, A., Xie, A., Le, K. N., Vinaithirthan, B., Luan, S. T., Wright, D. T. H., Cuadra, A., Pea, R., and Landay, J. A. (2024). Scientific and fantastical: Creating immersive, culturally relevant learning experiences with augmented reality and large language models. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, CHI '24, New York, NY, USA. Association for Computing Machinery.

Constantinides, N., Constantinides, A., Koukopoulos, D., Fidas, C., and Belk, M. (2024). Culturai: Exploring mixed reality art exhibitions with large language models for personalized immersive experiences. In *Adjunct Proceedings of the 32nd ACM Conference on User Modeling, Adaptation and Personalization*, UMAP Adjunct '24, page 102–105, New York, NY, USA. Association for Computing Machinery.

Cowan, K., Ketron, S., Kostyk, A., and Kristofferson, K. (2023). Can you smell the (virtual) roses? the influence of olfactory cues in virtual reality on immersion and positive brand responses. *Journal of retailing*, 99(3):385–399.

Dal Bò, E., Cecchetto, C., Callara, A. L., Greco, A., Mura, F., Vanello, N., Di Francesco, F., Scilingo, E. P., and Gentili, C. (2024). Emotion perception through the nose: how olfactory emotional cues modulate the perception of neutral facial expressions in affective disorders. *Translational Psychiatry*, 14(1):342.

Drogemuller, A., Sakhaei, H., Cunningham, A., Yu, R., Gu, N., and Thomas, B. H. (2023). Envisioning paramersive design: An immersive approach to architectural design and review. In *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 261–265.

Dykes, B. (2015). Data storytelling: What it is and how it can be used to effectively communicate analysis results. *Applied Marketing Analytics: The Peer-Reviewed Journal*, 1.

Fortune Business Insights (2024). Extended Reality (XR) Market Size, Share & Industry Analysis, By Type (Virtual Reality, Augmented Reality, and Mixed Reality), By Industry (Healthcare, Education, Retail & E-commerce, Gaming, Automotive, Media & Entertainment, and Others), and Regional Forecast, 2024-2032. https://www.fortunebusinessinsights.com/extended-reality-market-106637. [Online; accessed 12-November-2024].

Gandee, T. J., Glaze, S. C., and Giabbanelli, P. J. (2024). A visual analytics environment for navigating large conceptual models by leveraging generative artificial intelligence. *Mathematics*, 12(13).

Gao, J., Shen, T., Wang, Z., Chen, W., Yin, K., Li, D., Litany, O., Gojcic, Z., and Fidler, S. (2022). Get3d: A generative model of high quality 3d textured shapes learned from images. In *Advances In Neural Information Processing Systems*.

Gartner (2024). Gartner says more than 80% of enterprises will have used generative ai apis or deployed generative ai-enabled applications by 2026. https://www.gartner.com/en/newsroom/press-releases/2023-10-11-gartner-says-more-than-80-percent-of-enterprises-will-have-used-generative-ai-apis-or-deployed-generative-ai-enabled-applications-by-2026. [Online; accessed 13-November-2024].

Gatti, E., Giunchi, D., Numan, N., and Steed, A. (2024). Aisop: Exploring immersive vr storytelling leveraging generative ai. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 865–866. IEEE.

Gupta, M., Akiri, C., Aryal, K., Parker, E., and Praharaj, L. (2023). From chatgpt to threatgpt: Impact of generative ai in cybersecurity and privacy. *IEEE Access*.

Hara, T. (2024). Enhancing vr customer service training: A system for generating customer queries and evaluating trainee responses. In *ACM SIGGRAPH 2024 Posters*, SIGGRAPH '24, New York, NY, USA. Association for Computing Machinery.

Hara, T., Maeda, H., Komatsubara, S., Taniqawa, T., and Hirose, M. (2024). Autonomous avatar for customer service training vr system. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 835–836.

Hu, Y., Tutschku, K., Boeva, V., Goswami, P., Abghari, S., and Sundstedt, V. (2024). Towards an ethical and data privacy metrology for ai-enriched human-centered xr systems. In *IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering – IEEE MetroXRAINE 2024, 21-23 October, St Albans, London, UK*. IEEE.

Jamaludin, N. A., Mohamed, F., Chan, V. S., Sunar, M. S., Selamat, A., Krejcar, O., and Iglesias, A. (2023). Answering why and when?: A systematic literature review of application scenarios and evaluation for immersive data visualization analytics. *Journal of Cases on Information Technology (JCIT)*, 25(1):1–29.

Kapadia, N., Gokhale, S., Nepomuceno, A., Cheng, W., Bothwell, S., Mathews, M., Shallat, J. S., Schultz, C., and Gupta, A. (2024). Evaluation of large language model generated dialogues for an ai based vr nurse training simulator. In Chen, J. Y. C. and Fragomeni, G., editors, *Virtual, Augmented and Mixed Reality*, pages 200–212, Cham. Springer Nature Switzerland.

Kern, A. C. and Ellermeier, W. (2020). Audio in vr: Effects of a soundscape and movement-triggered step sounds on presence. *Frontiers in Robotics and AI*, 7:20.

Klein, K., Sedlmair, M., and Schreiber, F. (2022). Immersive analytics: An overview. *it - Information Technology*, 64(4-5):155–168.

Kraus, M., Fuchs, J., Sommer, B., Klein, K., Engelke, U., Keim, D., and Schreiber, F. (2022). Immersive analytics with abstract 3d visualizations: A survey. *Computer Graphics Forum*, 41(1):201–229.

Kraus, M., Klein, K., Fuchs, J., Keim, D. A., Schreiber, F., and Sedlmair, M. (2021). The value of immersive visualization. *IEEE Computer Graphics and Applications*, 41(4):125–132.

Le, M.-H., Chu, C.-B., Le, K.-D., Nguyen, T. V., Tran, M.-T., and Le, T.-N. (2023). Vides: Virtual interior design via natural language and visual guidance. In *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 689–694.

Lee, J., Wang, J., Brown, E., Chu, L., Rodriguez, S. S., and Froehlich, J. E. (2023). Towards designing a context-aware multimodal voice assistant for pronoun disambiguation: A demonstration of gazepointar. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, UIST '23 Adjunct, New York, NY, USA. Association for Computing Machinery.

Lee, J., Wang, J., Brown, E., Chu, L. G. P., Rodriguez, S. S., and Froehlich, J. E. (2024). Gazepointar: A context-aware multimodal voice assistant for pronoun disambiguation in wearable augmented reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*.

Lewis, M., Liu, Y., Goyal, N., Ghazvininejad, M., Mohamed, A., Levy, O., Stoyanov, V., and Zettlemoyer, L. (2020). BART: Denoising sequence-to-sequence pre-training for natural language generation, translation, and comprehension. In Jurafsky, D., Chai, J., Schluter, N., and Tetreault, J., editors, *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 7871–7880, Online. Association for Computational Linguistics.

Li, Z., Babar, P. P., Barry, M., and Peiris, R. L. (2024). Exploring the use of large language model-driven chatbots in virtual reality to train autistic individuals in job communication skills. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*, CHI EA '24, New York, NY, USA. Association for Computing Machinery.

Lo Duca., A. (2023). Towards a framework for ai-assisted data storytelling. In *Proceedings of the 19th International Conference on Web Information Systems and Technologies - WEBIST*, pages 512–519. INSTICC, SciTePress.

Lo Duca., A. (2024). Using retrieval augmented generation to build the context for data-driven stories. In *Proceedings of the 19th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - IVAPP*, pages 690–696. INSTICC, SciTePress.

Marriott, K., Chen, J., Hlawatsch, M., Itoh, T., Nacenta, M. A., Reina, G., and Stuerzlinger, W. (2018). Immersive analytics: Time to reconsider the value of 3d for information visualisation. *Immersive analytics*, pages 25–55.

McCormack, J., Roberts, J. C., Bach, B., Freitas, C. D. S., Itoh, T., Hurter, C., and Marriott, K. (2018). Multisensory immersive analytics. *Immersive analytics*, pages 57–94.

Munzner, T. (2014). *Visualization Analysis and Design*. A K Peters Visualization Series, CRC Press, 1;1st; edition.

Nath, M. and Ethirajan, L. (2023). Infographics generator: A smart application for visual summarization. In *2023 16th International Conference on Developments in eSystems Engineering (DeSE)*, pages 630–635.

Numan, N., Giunchi, D., Congdon, B., and Steed, A. (2023). Ubiq-genie: Leveraging external frameworks for enhanced social vr experiences. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 497–501.

Pinargote, A., Calderón, E., Cevallos, K., Carrillo, G., Chiluiza, K., and Echeverría, V. (2024). Automating data narratives in learning analytics dashboards using genai. In *LAK Workshops*, pages 150–161.

Rombach, R., Blattmann, A., Lorenz, D., Esser, P., and Ommer, B. (2022). High-resolution image synthesis with latent diffusion models. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pages 10684–10695.

Salehi, P., Hassan, S. Z., Baugerud, G. A., Powell, M., Cano, M. C. L., Johnson, M. S., Røed, R. K., Johansen, D., Sabet, S. S., Riegler, M. A., and Halvorsen, P. (2024). Immersive virtual reality in child interview skills training: A comparison of 2d and 3d environments. In *Proceedings of the 16th International Workshop on Immersive Mixed and Virtual Environment Systems*, MMVE '24, page 1–7, New York, NY, USA. Association for Computing Machinery.

Shao, H., Martinez-Maldonado, R., Echeverria, V., Yan, L., and Gasevic, D. (2024). Data storytelling in data visualisation: Does it enhance the efficiency and effectiveness of information retrieval and insights comprehension? In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, CHI '24, New York, NY, USA. Association for Computing Machinery.

Shi, C., Yang, C., Liu, Y., Shui, B., Wang, J., Jing, M., Xu, L., Zhu, X., Li, S., Zhang, Y., Liu, G., Nie, X., Cai, D., and Yang, Y. (2024). Chartmimic: Evaluating lmm's cross-modal reasoning capability via chart-to-code generation. *arXiv preprint arXiv:2406.09961*.

Shin, S., Batch, A., Butcher, P. W. S., Ritsos, P. D., and Elmqvist, N. (2024). The reality of the situation: A survey of situated analytics. *IEEE Transactions on Visualization and Computer Graphics*, 30(8):5147–5164.

Shoa, A., Oliva, R., Slater, M., and Friedman, D. (2023). Sushi with einstein: Enhancing hybrid live events with llm-based virtual humans. In *Proceedings of the 23rd ACM International Conference on Intelligent Virtual Agents*, IVA '23, New York, NY, USA. Association for Computing Machinery.

Shrestha, A., Mielke, K., Nguyen, T. A., and Giabbanelli, P. J. (2022). Automatically explaining a model: Using deep neural networks to generate text from causal maps. In *2022 Winter Simulation Conference (WSC)*, page 2629–2640.

Si, J., Yang, S., Kim, D., and Kim, S. (2023). Metaverse interview room creation with virtual interviewer generation using diffusion model. In *2023 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE)*, pages 1–4.

Stacchio, L., Scorolli, C., Marfia, G., et al. (2023). Evaluating human aesthetic and emotional aspects of 3d generated content through extended reality. In *CREAI@ AI* IA*, pages 38–49.

Strömel, K. R., Henry, S., Johansson, T., Niess, J., and Woźniak, P. W. (2024). Narrating fitness: Leveraging large language models for reflective fitness tracker data interpretation. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, CHI '24, New York, NY, USA. Association for Computing Machinery.

Tang, J., Wang, T., Zhang, B., Zhang, T., Yi, R., Ma, L., and Chen, D. (2023). Make-it-3d: High-fidelity 3d creation from a single image with diffusion prior. In *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)*, pages 22819–22829.

Vasic, I., Fill, H.-G., Quattrini, R., and Pierdicca, R. (2024). Llm-aided museum guide: Personalized tours based on user preferences. In *Extended Reality: International Conference, XR Salento 2024, Lecce, Italy, September 4–7, 2024, Proceedings, Part III*, page 249–262, Berlin, Heidelberg. Springer-Verlag.

Wagener, N., Ackermann, A., Savino, G.-L., Dänekas, B., Niess, J., and Schöning, J. (2022). Influence of passive haptic and auditory feedback on presence and mindfulness in virtual reality environments. In *Proceedings of the 2022 International Conference on Multimodal Interaction*, ICMI '22, page 558–569, New York, NY, USA. Association for Computing Machinery.

Wang, W.-S., Lin, C.-J., Lee, H.-Y., Huang, Y.-M., and Wu, T.-T. (2024a). Integrating feedback mechanisms and chatgpt for vr-based experiential learning: impacts on reflective thinking and aiot physical hands-on tasks. *Interactive Learning Environments*, pages 1–18.

Wang, Y., Li, Y., Yuan, M., Fei, X., Ma, S., and Hansen, P. (2024b). Scentclue: Enhancing story engagement in virtual reality through hedonically varied olfactory hints. *International Journal of Human–Computer Interaction*, pages 1–20.

Wang, Y. and Zhang, Y. (2024). Enhancing cognitive recall in dementia patients: Integrating generative ai with virtual reality for behavioral and memory rehabilitation. In *Proceedings of the 2024 6th International Conference on Big-Data Service and Intelligent Computation*, BDSIC '24, page 86–91, New York, NY, USA. Association for Computing Machinery.

Whitlock, M., Smart, S., and Szafir, D. A. (2020). Graphical perception for immersive analytics. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 616–625.

Wong, P. C. and Thomas, J. (2004). Visual analytics. *IEEE Computer Graphics and Applications*, 24(5):20–21.

Xiao, S., Huang, S., Lin, Y., Ye, Y., and Zeng, W. (2024). Let the Chart Spark: Embedding Semantic Context into Chart with Text-to-Image Generative Model . *IEEE Transactions on Visualization & Computer Graphics*, 30(01):284–294.

Yamauchi, Y., Ino, K., and Zempo, K. (2023). Auditory vr generative system for non-experts to reproduce human memories through natural language interactions. In *SIGGRAPH Asia 2023 Posters*, SA '23, New York, NY, USA. Association for Computing Machinery.

Yan, L., Zhao, L., Echeverria, V., Jin, Y., Alfredo, R., Li, X., Gaševi'c, D., and Martinez-Maldonado, R. (2024). Vizchat: enhancing learning analytics dashboards with contextualised explanations using multimodal generative ai chatbots. In *International Conference on Artificial Intelligence in Education*, pages 180–193. Springer.

Yan, Y. and Zhang, W. (2024). Cogxr: An ai/xr powered graphic tool enhancing human rationality. In Stephanidis, C., Antona, M., Ntoa, S., and Salvendy, G., editors, *HCI International 2024 Posters*, pages 245–252, Cham. Springer Nature Switzerland.

Ye, Y., Hao, J., Hou, Y., Wang, Z., Xiao, S., Luo, Y., and Zeng, W. (2024). Generative ai for visualization: State of the art and future directions. *Visual Informatics*, 8(2):43–66.

Yeo, J. Q., Wang, Y., Tanary, S., Cheng, J., Lau, M., Ng, A. B., and Guan, F. (2023). Aicrid: Ai-empowered cr for interior design. In *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 837–841.

Zhang, L., Rao, A., and Agrawala, M. (2023). Adding conditional control to text-to-image diffusion models. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pages 3836–3847.