Interactive Extended Reality Techniques in Information Visualization

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***Abstract*—Immersive techniques, such as virtual reality, augmented reality, and mixed reality, take immersive displays as carriers to provide immersive experience. A large number of approaches focus on the visualization of scientific data in immersive environments while just a few methods concentrate on interactive information visualization (InfoVis) in an immersive environment, although InfoVis has been extended to the 3-D space for a long time. In the era of data explosion, the traditional 2-D space is unable to convey large amounts of abstract information in an intuitive way. Meanwhile, desktop-based 3-D InfoVis generally leads to visual conflict and confusion owing to limited display size and field of vision. In this survey, we search for the interactive techniques in immersive InfoVis and summarize their commonalities and discuss their differences and potential trends. The data types of abstract information in InfoVis can be categorized into graph/network data, high-dimensional and multivariate data, time-varying data, and text and document data. Besides, the visual presentation of information in immersive environments is also summarized, especially for charts, plots, and diagrams, which are some basic components of InfoVis techniques. We also described the immersive applications of InfoVis techniques, including the tools or frameworks on immersive analytics and infographics. The discussion about the traditional nonimmersive and the immersive methods in data visualizations show that the latter one has the potential to become an alternative to explore massive information in the future.**

***Index Terms*—Extended reality (XR), immersive environment, information visualization (InfoVis), virtual reality (VR).**

Manuscript received 23 February 2022; revised 23 May 2022 and 7 September 2022; accepted 28 September 2022. Date of publication 21 October 2022; date of current version 15 November 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 61702271 and Grant 61972010 and in part by the Open Research Fund of Beijing Key Laboratory of Big Data Technology for Food Safety under Project BTBD-2021KF04, Beijing Technology and Business University. This article was recommended by Associate Editor Giuseppe Serra. *(Corresponding authors: Siming Chen; Yi Chen.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/THMS.2022.3211317.

Digital Object Identifier 10.1109/THMS.2022.3211317

I. Introduction

THE design of interactive information visualizations (InfoVis) on traditional desk-top PCs is challenging due to the limited display size, especially in the linked-view visualizations or multiple coordinated visualizations [1]. One of the potential solutions to the display size limitation is to use large or wall-sized displays [2], [3], [4]. They can visualize a large amount of data or provide several visualization views at once which are often linked to each other [1]. The linked views are useful to help users understand multivariate data by highlighting links between views through brushing and linking; however, they also leads to awareness and perception issues regarding the peripheral areas of the display [1], [5], [6]. Besides large or wall-sized displays, the recent research field of immersive visualizations has proven to help improve data analysis [7]. Immersive environment aims to solve the problems between users, their data, and the approaches used for analysis and decision making [8], and spatial immersion [2] has great potential in helping users understand complex data. They can wear a head-mounted display (HMD), which is used to overlay the screen with additional user-specific information [1], [9].

With the popularity of immersive devices and development platforms, the immersive techniques have attracted attention from the communities of visualization, human computer interaction. The extended reality (XR) is often considered as consisting of virtual reality (VR), augmented reality (AR), and mixed reality (MR), which combines reality and virtual to increase the content of the world. Immersive interfaces, such as immersive displays and input devices, support more intuitive interaction and data exploration strategies.

There are a large number of scientific visualization (SciVis) approaches that are applied in an immersive environment because the data presentation space in SciVis and immersive visualization is similar, while much less immersive InfoVis techniques were proposed and developed. Besides, "avoiding 3-D" is a well-known rule of the design of data presentations and interactions for InfoVis techniques due to the inherent interaction ambiguities, visual clutter, and 3-D occlusions derived from its additional depth information. Thus, the navigation, selection and occlusion are still the remaining issues of desktop-based 3-D InfoVis. The traditional screen of desktop-PC with a keyboard and mouse cannot provide enough presentation space for 3-D InfoVis and the sense of intuitive immersion is missing. In view of the above considerations, we collect the recent immersive visualization work on InfoVis and categorize, summarize, and discuss them in order to inspire more future work.

The generation of immersive experience is also dependent on hardware devices, mainly display devices and input devices. According to the size, display devices can be divided into two types, i.e., the HMD [62], [63], [64] and the cave automatic virtual environments (CAVE) [25], [27], which have their own advantages and disadvantages. The CAVE is an immersive VR display system based on projection, which is characterized by high resolution, strong immersion, and good interactivity. However, a large number of devices, such as displays, sensors, speakers, along with synchronization of multiple devices mean that they are usually expensive and bulky. The HMD is much smaller and more delicate and can be worn directly on the user's head. It just needs to control the view of each eye and does not need to draw the whole scene. In addition, mobile devices, such as phones and tablets, can support AR in daily life to display additional abstract information. In terms of input devices, the HMD is usually equipped with handlers while the CAVE is fixed with a whole set of controllers. Post-WIMP including touch, gesture, speech, and sketch can also be considered as input to provide natural interactions [65]. To extend the visualization space of 2-D displays on mobile devices, an AR-based visualization framework, named MARVIS [66], was proposed to augment the space around, above, and between 2-D displays. Except for the interactions around the visualization contents, physical objects, such as the mobile devices themselves or even the nearby planar objects, can be exploited to integrate into the AR interaction design among mobile devices.

We searched for relevant papers on the IEEE Xplore, the ACM digital library, Wiley online library, etc. We found that a large number of visualization papers on VR/AR/MR are more like SciVis papers or graphics-related papers, and just a few papers focus on InfoVis, which often cover visualizations for abstract or unstructured data, for example, network, graph, hierarchical trees, charts, diagrams, maps, and high-dimensional structures.

A. Related Surveys

There have been a few surveys on immersive analytics (IA) [67] in recent years. Fonnet et al. [67] described how technologies, interactions, collaborations, data, and sensory mapping have been utilized to construct IA systems and how to assess an IA system from different perspectives. It is worth mentioning that the survey [67] focused more on immersive devices and immersive environments instead of visualization techniques. Marriott et al. [68] explored the benefits of 3-D visualizations in IA systems and identify possible applications of depth cues for visualizing abstract data. We believe that the 3-D space in an immersive environment is both an opportunity and a challenge. Whether the third dimension is to be utilized should depend on specific application scenarios. For example, 2-D is still suitable for AR-based personal InfoVis. Besides, Ens et al. [69] proposed 17 key research challenges in IA. These challenges aim to coordinate future work by providing a systematic roadmap of current directions and impending hurdles to facilitate productive and effective applications for IA. Ratclife et al. [70] further summarized XR-based approaches on remote experiments and discuss their drawbacks and opportunities. To our best knowledge, there is no comprehensive summary of InfoVis techniques in immersive environments at present.

Fig. 1. Six major categories of the survey visualized by an interactive tool named BubbleSets [60]: immersive charts, diagrams, and plots (purple bubble), graph/network data visualization (flesh-colored bubble), high-dimensional data visualization (light green bubble), time-varying data visualization (pink bubble), text and document data visualization (dark green bubble), and applications of InfoVis techniques in immersive environments (blue bubble).

B. Taxonomy of the Survey

According to abstract data types, we divided the papers related to InfoVis techniques in VR/AR environments into the following categories: *graph/network* data visualization, *high-dimensional and multivariate* data visualization, *time-varying* data visualization, and *text and document* data visualization. In addition, we summarized and discussed the most related work about *charts, diagrams, and plots* in immersive environments and some *applications of InfoVis techniques* in immersive environments. The detailed classification categories can be seen in Table I.

Specifically, each category has been divided into different subcategories. In immersive charts, diagrams, and plots, different novel raw data mappings have been listed and multiple coordinated views (MCV) summarize how they are laid out and linked. Besides, some immersive authoring tools that decrease learning curves of nonexpert programmers are illustrated. In immersive graph/network visualization, uncommon spherical layouts and user interactions offer great visibility and flexible manipulations. Three immersive methods adapted from traditional versions, i.e., scatter plot method, parallel coordinated plot method, and dimension reduction (DR) method, have been concluded to depict high-dimensional and multivariate data. Time-varying data visualization introduces how two types of data (time-series data and sequential data) are presented in VR/AR space. Text input and reading are regions of interest in text and document visualizations in virtual environments. In terms of applications of InfoVis, IA designed for InfoVis, especially for the combination of AR and infographics, is helpful for users to understand extra information.

We employed an interactive tool named BubbleSets [60] (see Fig. 1) and further developed a set data visualization tool named BalloonVis [61] (see Fig. 2) to explore the literature in a focus+context exploration scheme. Figs. 1 and 2 show the major six categories by bubbles and balloons with different colors, respectively. All the nodes in an identical color represent

TABLE I
OVERVIEW OF THE RELATED WORK ON IMMERSIVE INFOVIS TECHNIQUES

Category	Literature	Device	Method/Tech	Task
Immersive charts, plots, and diagrams	3-D bar/pie chart [10]	HMD	VR	Virtual museum
	3-D scatter plot [11]	HMD, Leap	VR	Collaborative analysis
	Immersive bubble chart [12]	HMD, handlers	VR	Semantic data analysis
	ART [13]	HMD, handlers	VR	Multidimensional data analysis
	Tilt Map [14]	HMD, handlers	VR	Geological data analysis
	3-D radar chart [15]	HTC Vive, Leap Motion	VR	Time-oriented data analysis
	Small-multiple shelf [16]	HMD, handlers	VR	Multiples data analysis
	DXR [17]	-	VR/AR	Unity-based toolkit
	PapARVis [18]	-	AR	Augment static visualization
	Glance [19]	-	VR/AR	GPU-acceleration framework
	WebVR [20]	HMD	VR	Build VR applications for multiple devices
Graph/Network visualization	Spherical layouts [21] [22]	HMD	VR	Graph layouts
	Ring graph [23]	HMD	VR	Graph analysis
	SIM [24]	HMD	VR	Geospatial network analysis
	iCAVE [25]	CAVE/stereoscopic glasses	VR	Biomolecular network analysis
	VR-based 3-D network [26]	HTC Vive	VR	Mental maps study
	Network connection analysis [27]	HMD/CAVE	VR	Collaborative analysis
	Graph analysis [28]	Leap Motion	VR/AR	Network connectivity visualization
	Genome3-DExplorer [29]	LIMSI	VR	Genomic network analysis
	GraphiteVR [30]	Holojam	VR	Collaborative social network analysis
Time-varying data visualization	STC [31] [32]	HMD	VR	Trajectory visualization
	TUI [33]	HMD	VR	Temporal visualization
	HANNAH [34]	HMD	VR/AR	Immersive process data visualization
	ImWeb [35]	Hololens	AR/Web	3-D neuron exploration
Text and document data visualization	Screen [36]	CAVE	VR	Reading
	cAR [37]	transparent display	AR	Reading
	TranslatMR [38] [39]	HMD	MR	Reading and translation
	TranslatAR [40]	phone	AR	Translation
	HeadsetsVR [41]	HMD	VR	Reading
	Imsovision [42] [43]	CAVE	VR	Software development
	Information Cube [44]	HDM	VR	Displaying a unix directory
	QWERTY [45]	Oculus Quest	VR	3-D word-gesture text entry
	HawKEY [46]	HMD	VR	Text Entry
	Virtual Notepad [47]	HMD	VR	Mandwriting
Multidimensional data visualization	A prototype for immersive infovis [48] [49]	-	AR	Multidimensional InfoVis
	ImAxes [50]	HMD	VR/AR	Immersive parallel coordinates
Applications of InfoVis techniques in immersive environments	mARGraphy [51]	mobile	AR	Dynamic 3-D information display
	IATK [52]	HMD	VR/AR	Development of an IA toolkit
	FIESTA [53]	HMD	VR	Immersive collaborative data visualization
	Dataspace [54] [55],EPICylinder [56]	HMD, TDW	AR	Collaborative exploratory data analysis
	IA for DICE [57]	HMD	VR	Immersive visualization of DICE
	ART [13]	AR HMD	VR/AR	3-D parallel coordinates
	NiwViw [58]	AR HMD, iPad	AR	Immersive analytics authoring tool
	VRIA [59]	HMD	VR/Web	Immersive Web-based interaction

that the corresponding papers are in the same category. The links are used to connect the papers in the same category. The vertical positions of the nodes represent the citation of the literature. The brown balloons represent immersive charts, plots, and diagrams data visualization (#01), and the balloons in pink belong to immersive graph/network visualization (#02). High-dimensional data visualization (#03) is mapped to jade-green while time-varying data visualization (#04) is encoded in dark green. The blue and purple balloons represent text/document data visualization (#05) and applications of immersive InfoVis techniques (#06), respectively.

II. IMMERSIVE CHARTS, DIAGRAMS, AND PLOTS

Charts, diagrams, and plots are basic visualization components of InfoVis. Charts include line charts, bar charts, heat maps (choropleths), area charts, pie charts, and treemaps. Diagrams include arc diagram, sankey diagram, and chord diagram, while plots include parallel coordinates plots, star plots, scatter plots, box plots, etc. They are indispensable for complex large-scale visualization systems. We divided charts, diagrams, and plots into three categories: raw data mapping, layout of multiple views, and existing authoring tools. AR is potentially better in designing face-to-face interaction and remote collaboration than VR due to the naturality [71].

A. Immersive Raw Data Mappings

To visualize raw data, designers should follow two design principles: expressiveness and effectiveness [42]. The mapping and visual encoding from raw data to visual components requires selecting appropriate visual elements and white space. In this section, we will summarize novel raw data mapping approaches in immersive environments. Although many methods utilize 3-D graphics, they are all displayed on nonimmersive computer monitors, i.e., 2-D displays. One of the advantages of the technique is that the immersive visualizations is capable of providing better spatial understanding through depth cues and reviewing 3-D visualization and interaction methods.

B. Charts, Diagrams and Plots

Pie charts are relatively rarely used in immersive environments, even though they are useful for displaying proportions. In virtual museums based on VR, pie charts showed visitor

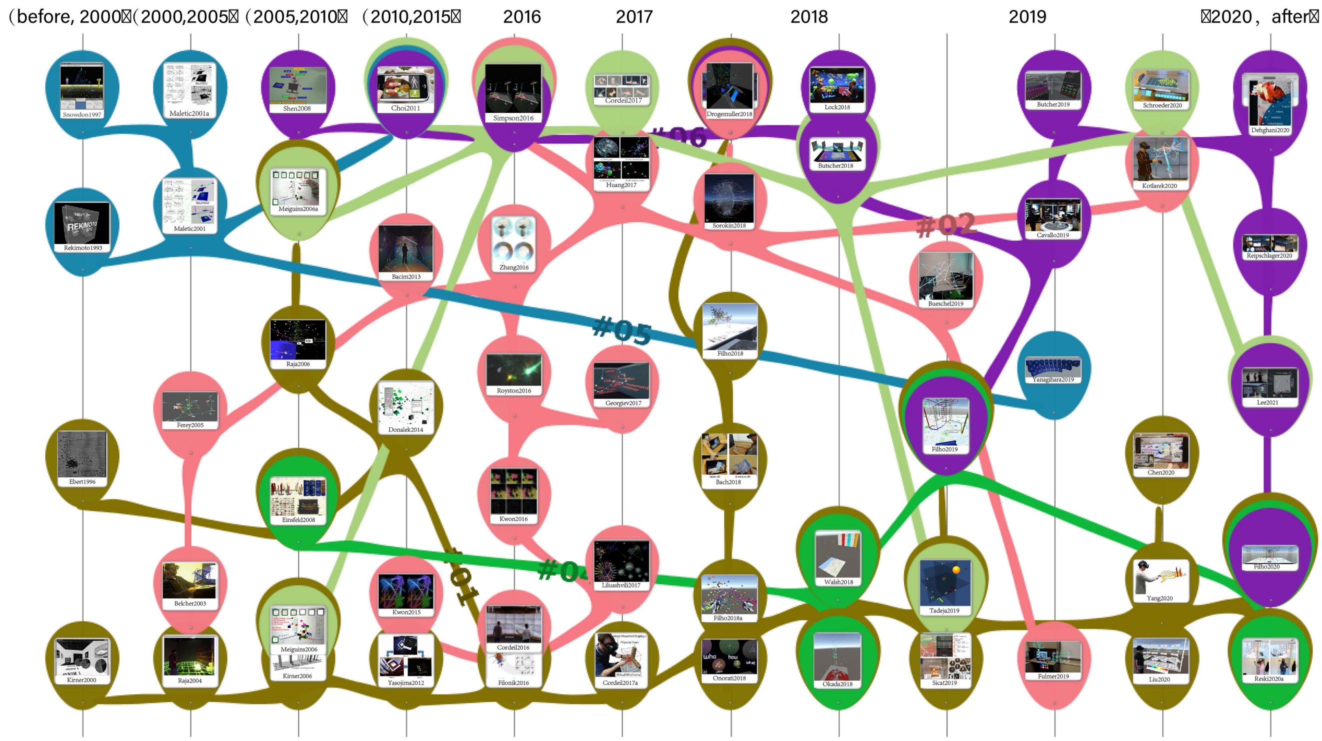

Fig. 2. Overview of the representative papers in six categories visualized by balloons. We have designed an interactive tool named BalloonVis [61] to visualize the relationships of literatures. Each node represents a paper. All the nodes in an identical color represent that the corresponding papers are in the same category. The links are used to connect the papers in the same category. The vertical positions of the nodes represent the citation of the literature. Nodes wrapped by different colored balloons indicate that the paper covers more than one category while each colored balloon represents one category. The brown balloons represent immersive charts, plots, and diagrams data visualization (#01), and the balloons in pink belong to immersive graph/network visualization (#02). High-dimensional data visualization (#03) is mapped to jade-green while time-varying data visualization (#04) is encoded in dark green. The blue and purple balloons represent text and document data visualization (#05), and applications of InfoVis techniques in immersive environments (#06), respectively.

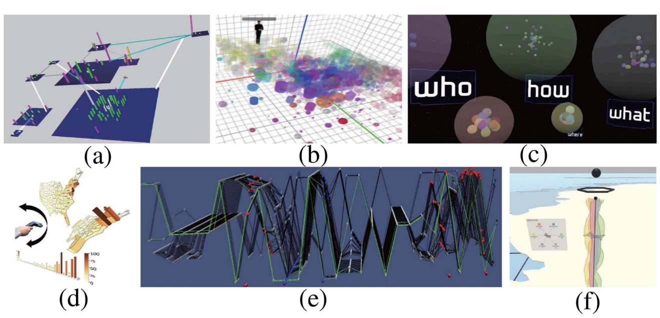

Fig. 3. Raw data mapping in VR space. (a) Bar charts for visualizing software [10]. (b) 3-D scatter plot representing an 8-D data visualization [11]. (c) Immersive bubble chart [12]. (d) Tilt Map combines choropleth map and prism map for geospatial visualization [14]. (e) Immersive parallel coordinate plot [72]. (f) 3-D radar chart in immersive VR [15].

data collected from the corresponding text files [10]. Bar charts were also used in the virtual museum, which were equivalent to the variation of pie charts [10]. 3-D bar charts have one more dimension than 2-D bar charts. A software system [10] was visualized by using bar charts. The size of the blue rectangle at the bottom of bars indicates the size of a class, as shown in Fig. 3(a). Columns of different colors represent different functions. The length and width of the bar and the thickness of the pie are visual attributes that can be utilized, but these characteristics are difficult to distinguish and easy to be ignored.

Visual properties in 3-D scatter plots include: x, y and z coordinates, data point size, shape, color, opacity and texture. Fig. 3(b) is an 8-D data visualization represented by a 3-D scatter plot [11]. They employed scatter plots under three different dimensions and equipment conditions: desktop-based 2-D, desktop-based 3-D and immersive HMD-based 3-D [73]. Results show that the HMD-based condition not only provides higher accuracy and subjective feelings of participation but also needs less effort and navigation to find information. High-dimensional data are often analyzed by reducing dimension, and scatter plots are often used to represent the data after DR for further exploration.

Bubble chart is a kind of diagram with several circles depicted by three dimensions, i.e., x, y coordinates and size. An immersive bubble chart is a 3-D version of a VR space developed by Unity [12], as shown in Fig. 3(c). There are two kinds of bubbles: individual bubbles and category bubbles. Individual bubbles represent specific terms, while category bubbles with transparent textures include individual bubbles and relevant subcategory bubbles. The volume of a category bubble is decided by the number of contained elements. The correlation of the specific term in the data domain determines the volume of an individual bubble. Users are immersed in visualization and they can use gestures to interact with bubbles, such as grabbing and moving the bubbles, throwing them away, knocking two of them apart to create clusters. In this way, users have a deeper understanding of the relationships between different elements in the dataset.

Choropleth map is often employed to display data related to geographical areas. Areas on the map are colored or shaded to indicate relevant values. The prism map is a novel way to show area linked data, in which areas are extruded into a third dimension, thus the height of prism stands for relevant value. Besides, tilt map is an interactive visualization for visually transforming between 2-D and 3-D maps in an immersive environment [14], as shown in Fig. 3(d). Specifically, it generates transitions from 2-D choropleth maps to 3-D prism maps and then to 2-D bar charts to overcome their own limitations. It is easy to find that tilt map has advantages over other alternatives in time, accuracy, and user preference.

Parallel coordinate plots are widely used for interactively visualizing and analyzing multidimensional data in a 2-D environment. Tadeja et al. [72] explored parallel coordinate plots in immersive 3-D virtual environments to support decision making in the engineering design process. Each data item was visualized as a series of unit-size cubes evenly space along the x-axis, as shown in Fig. 3(e). These cubes were connected by lines whose y-axis represents the value of each dimension scaled by the selected range.

Radar charts are established to visualize 2-D multivariate data across different contexts and scenarios. Reski et al. [15] proposed a 3-D radar chart approach in immersive VR to represent time series data, as shown in Fig. 3(f). The black axis with a large start point and a small end point in vertical dimension is the representation of time. According to the conventional concept of radar chart, a single data variable is organized as a single spoke arranged radially around the time axis. The time series data of each variable is visualized as a 2-D frequency polygon and the time axis represents the origin of each spoke. If the value of a data variable is close to zero, it is located closer to the time axis, otherwise a larger value is farther away from it. The spokes of each data variable are color-coded and semitransparent, allowing observers to view all spokes and avoid occlusion. This 3-D arrangement and the stereo function of HMD enable users to obtain a spatial impression of time. Besides, Ye et al. [74] designed a semidonut chart to visualize the statistical data of badminton in immersive environment to assist experts in analyzing badminton trajectory data.

III. Immersive Graph/Network Visualization

Graph/Network data exist in every aspect of modern human society and virtual Internet society, e.g., communication network, social network, biological gene network [25], [29], geospatial network, and text phrase network [75]. The visualization and analysis of graph/network reveals the patterns behind the data, which helps understand the overall situation and assists in management and decision-making. Immersive displays and input devices shed new light on the visualization of graph/network because they offer greater visibility and more flexible interactions.

A. Graph/Network Layouts in Immersive Environments

The challenge of visualizing graph and network data mainly comes from the data scale. A visualization approach may work well with hundreds of vertices but not with thousands or even millions of vertices. Due to the limitation of 2-D screen size, it is difficult to visualize large-scale datasets directly with good layouts.

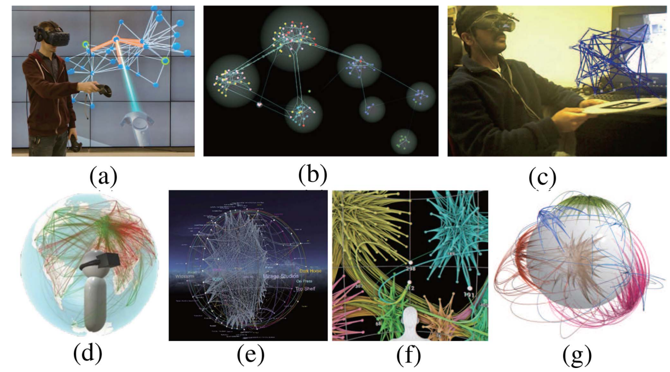

Fig. 4. Graph/network layouts in immersive environment. (a) VR-based environment for large networks [26]. (b) tangible AR interface is well suited to link analysis [76]. There are some VR-based spherical layouts in graph visualizations. (e) Ring graph organizes nodes along the ring according to attributes [23]. (d) Spherical immersive model for exploring geospatial network datasets [24]. (f) Visualization results of a graph can be observed from the inside of a sphere [22]. (g) Space filling curve defined on a cubed sphere for full immersion [21].

The primary principle of the node-link layout in practicality and aesthetics is to avoid edge crossing and node overlapping. On 2-D screens, small world graphs will become visually complex due to poor scalability. Ring graph [see Fig. 4(e)] is a graph visualization technique especially designed for VR, which makes full use of the potential infinite space in VR to solve the layout problem [23]. It organizes graph nodes along the ring according to attributes. Link edges between nodes within the ring are drawn using an edge bundling algorithm.

Spherical immersive model [see Fig. 4(d)] is a VR-based method for exploring geospatial network datasets [24]. Classical geospatial network visualization limits itself to 2-D space by organizing edges and nodes on the surface of a 2-D map or traditional earth model. A parameterized 5-step 3-D edge bundling algorithm and a method designed for avoiding conflicts between network edges and the viewpoint are proposed to reduce visual clutter and reveal the trunk structure of different geospatial networks.

Visualization of biomolecular networks is helpful for exploring system-level data during cellular processes. An open-source software platform, iCAVE [25], is presented to visualize 3-D large and complex biomolecular networks. Several network layouts are provided by iCAVE to solve the problem of how to arrange nodes clearly to get a pleasant and user-friendly network topology in an immersive environment. The variations of the force-directed layout are extended to 3-D, i.e., the classical force-directed algorithm, hybrid force-directed layout, coarsened force-directed layout, and simulated annealing force-directed layout. Two novel layout algorithms are further implemented to take full advantage of features in immersive 3-D space, i.e., semantic levels layout algorithm and hemispherical layout. The above layout algorithms have their own unique superiorities. Specifically, force-directed layouts can capture the essence of large networks. Semantic layouts are often ideal choices for hierarchical networks, while hemispherical layouts bring about clear and clean visualizations with optional edge bundling algorithms.

3-D node-link graph is an important part of immersive visualization, in which the mapping of data attributes and visual variables deserves careful considerations. Büschel et al. [77] focus on the design considerations of edge visualization in 3-D AR graph. In the user study, three visual styles are designed for undirected edges and directed edges, respectively. The results show that edge variants based on shape or geometric methods in AR diagrams are reasonable. Actually, AR brings additional challenges to design, which leads to changes in the suitability of visual variables (e.g., shape, size, color, transparency, focus, and texture). These challenges have to be considered when designers choose visual variables for visualization systems. Meanwhile, there should be more research works for visual encodings in immersive environment to provide reference for designers.

B. Immersive User Interaction

Most immersive visualizations are based on VR equipped with HMDs [see Fig. 4(a)]. The visualization of graph/network will affect the quality of mind maps created by observers to understand the graph/network. Kotlarek et al. [26] study the influence of 3-D VR environment and traditional 2-D desktop environment on understanding network structures. Participants can interpret the network structure more accurately when inspecting the network, especially large networks, in an immersive environment.

AR is also suitable for the visualization of graph/network [see Fig. 4(b)]. Apart from increasing the comprehension of complex link analysis graphs, the integration of virtual and reality is beneficial to real applications, such as circuit and network routing inspection. Belcher et al. [76] compare a tangible AR interface to a desktop-based interface and put forward different ways to view network graphs based on two interfaces. Experiments indicate that a tangible AR interface is good for link analysis. The error generated on AR condition is significantly less than that of the 2-D screen condition. AR is significantly superior to 2-D screens in terms of ease of use, superiority of displaying information, convenience of manipulation, and expression of perception.

By virtue of immersive devices, the exploration and perception of users significantly increase as they are involved themselves into the immersive context when exploring graph/network data. The CAVE is a huge immersive environment, whose driving force of development is cooperative perception. The HMD is considered as an economical alternative to the CAVE. A user study is conducted to explore the relative advantages of HMDs and CAVEs in network connection collaborative analysis [27]. The two conditions have significant differences in task completion time and participants' physical movement in space: participants who use HMD are faster while CAVE introduces asymmetric movement among collaborators. There is no difference between the HMD and the CAVE in accuracy.

Leap Motion and handle controllers are common input devices in immersive environment. The gesture input system for 3-D graph visualization [28] takes Leap Motion as a sensor device to provide an input interface in a VR environment. Users can easily manipulate and analyze graphs with gesture input. When exploring complex graphics, freehand gesture input is more effective than desktop mouse input. Teleportation and One-Handed Flying are the two main navigation technologies in VR, while Two-Handed Flying and Worlds In Miniature are less common. Drogemuller et al. [78] evaluate their performance and effectiveness through a series of tasks.

Many VR systems are designed for uncooperative personal visualization, while data analysis and visualization is usually a process of multiperson cooperation. GraphiteVR is an HMD-based system which allows users to use hands to intuitively generate and inspect large network layouts collaboratively [30]. The system was constructed by combining Holojam architecture and sensory neuron movement suit so as to provide unlimited visual experience for multiple people in the whole room. Semantic network includes words and their semantic relations generated by a concept dictionary or the users' oral/text descriptions. The certain structure of a semantic network can promote the creation of creative concept. Immersive VR systems make it possible for users to walk through semantic networks [75], which supports the inherent characteristics of creative thinking.

IV. High-Dimensional and Multivariate Data Visualization

High-dimensional data refer to data with two or more independent attributes per data object, and the dimensionality refers to the number of data attributes. This kind of data can be found everywhere and is very important in display life. The understanding and analysis of high-dimensional data can play a prominent role in making decisions in daily work life. However, when the dimensionality of data becomes higher or the volume of data becomes larger, the difficulty of analyzing and evaluating high-dimensional data increases dramatically. This is where researchers need the help of visualization tools. Some studies [52], [72], [79] have also shown that immersive environments are potentially better for visualizing such data.

The 3-D interaction, including manipulation, selection, and annotation, becomes increasingly challenging when they are used to visualize complex structures of 3-D data [80]. VR reveals the complex spatial structure behind the 3-D high-dimensional data in an easy way to explore, but it is difficult to navigate in this space with helmet display. A feasible way to control the view is to combine 3-D mouse for camera positioning with HMD head tracking for controlling the view direction. Gray et al. [81] have tested three navigation types: rotation, scaling, and alignment. Although the 3-D mouse makes the viewer "fly around" in the virtual environment, HMD allows slight adjustment of the head to change the visual reality. This is impossible for 3-D projection on 2-D screen. With the advent of MR devices such as the Microsoft HoloLens, developers have faced with the interaction challenges to utilize the third dimension in InfoVis effectively. The methods on stereoscopic devices have shown that 3-D representation can improve accuracy in specific tasks [25], [79].

A. Scatter Plot

Scatter plot is a frequently-used component to visualize high-dimensional data. This method maps the values of individual attributes of an object to different axes and determines the position of individual data points in the coordinate system. The essence is to map abstract data into a coordinate system and reflect its distribution characteristics through location information. As the dimensionality of the data becomes higher, more dimensional information can be represented using various visual codes such as color, size, and shape. Besides, scatter plot matrix is also a good option in visualizing high-dimensional data. In an immersive environment, these approaches are also applicable. Moreover, the virtual immersive space is more feasible in doing various visual coding on high-dimensional data, which can make the high-dimensional data better explored and analyzed.

B. Parallel Coordinates Plots

Parallel coordinate plots can be used to interactively visualize and analyze high-dimensional data in a 2-D environment. Tadeja et al. [72] explored the use of parallel coordinate plots in an immersive 3-D virtual environment to support decision-making in the engineering design process. A qualitative study was conducted to evaluate the potential of VR PCP. The research results indicate that VR PCP may be beneficial compared to 2-D PCP. Some studies have created some toolkits for the convenience of parallel coordinates plots visualization in immersive environments. Cordeil et al. [52] introduced Immersive Analytics Toolkit (IATK), an extensible and expressive visualization toolkit, which can be used to create large-scale and multidimensional data visualizations in VR environment. At the data pre-processing stage, IATK converts attribute data to tabular data for better standardization. IATK is based on a simple grammar of graphics that is expressive enough to handle a wide variety of common data graphics. Based on this, IATK allows users to create a wide variety of data visualization to handle the high-dimensional and multivariate data.

C. Dimension Reduction

DR is one of the commonly used approaches in high-dimensional processing. However, it may also cause the information loss. To deal with this problem, Babaee et al. [82] introduced a novel metric to assess the quality of DRs in terms of preserving the structure of data. They model the DR process as a communication channel model transferring data points from a high-dimensional space (input) to a lower one (output). Whether the DR method will cause the information loss or how the data will be affected by this method has been tried to verify in some studies. Schroeder et al. [79] systematically investigated the differences in user perception between a regular monitor and an MR device. They developed two visualization prototypes to identify how the display technology affects decision making in real-life financial settings.

V. Immersive Time-Varying Data Visualization

Time is a significant attribute presented in data. Data that changes with time and has temporal attributes are called time-varying data. In science, engineering, social, and economic fields, a large amount of time-varying data are generated. Semantically, time-varying data can be broadly classified into two categories, one is time-series data arranged in time axis, and the other is sequential datasets that are not time-invariant but have an intrinsic order of arrangement. They have large volume, dimensions, and variables in practical applications and are rich in types and widely distributed. Therefore, visualization of such data in an immersive environment becomes crucial. At the data level, time-varying data can be divided into two categories, one is time-ordered data, called temporal data, and the other is not time-invariant, but there is a logical internal order, called sequential datasets.

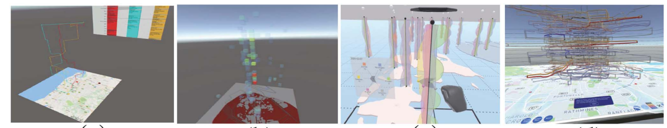
(a) (b) (c) (d)

Fig. 5. Time-varying data visualization in VR space. (a) New tangible user interface and a novel controller for exploring geographic time data [33]. (b) Tweet data visualization in VR devices with location information [83]. (c) Approach to interact with time series data in VR space [15]. (d) Approach to interact with time-series data in VirtualDesk Metaphor [31].

Time-series data are generally arranged in a timeline, i.e., they are strictly ordered in time. There is a large amount of such data in life, such as video sequences captured by personal cameras, social media data of people in a certain region during a certain time period, NBA game schedules, and so on. The traditional method to present such timing data is to use a 2-D line graph to display it, with the x-axis corresponds to the time variable and the y-axis corresponds to the other variables. This approach gives a good representation of how the data change over time. But this 2-D approach can contain few kinds of variables, and the immersive approach shows its advantages when more time-related elements and attributes need to be presented. For example, in the above-mentioned social media data for a region during a certain time period, at least three elements are included: time, location, and social media data. Moreover, the location information itself is 2-D, which makes it difficult for traditional 2-D methods to present this kind of data well. For this reason, many researchers have introduced XR technologies.

Okada et al. [83] presented a method to visualize the tweet data in VR devices with location information, as shown in Fig. 5(b). They took the area near Tokyo Disneyland as an example. The analysis of social media data is helpful to understand people's behaviors. For the datasets that are often related to time and position, this work builds a 3-D time-series visualization system, which is composed of a 2-D map and a timeline. The number of tweets of each coordinate on the map is added up and displayed at the corresponding time coordinates in the form of a cube. Along the same lines, Walsh et al. [33] developed a new tangible user interface and a novel controller for exploring geographic time-series data, as shown in Fig. 5(a). Associated by the principle of radar chart [see Fig. 5(c)], Reski et al. [15] proposed an approach to interact with time series data in VR space. The VR application based on HMD and 3-D gestures allows users to explore data in an immersive environment. It uses the potential advantages of immersive technologies for helping users become more involved in data exploration, better understanding, and interacting with the data. Besides, Filho et al. [31], [32] proposed a concept named space-time cube (STC), as shown in Fig. 5(d). In STC, trajectory datasets are represented by 2-D maps, and an additional third dimension is used to indicate time. They examine the STC in the field of immersive analysis. All data manipulations and queries were implemented through intuitive gestures and tangible controls. The evaluation results show that the immersion implementation based on VirtualDesk exploration metaphor has high usability and low learning curve.

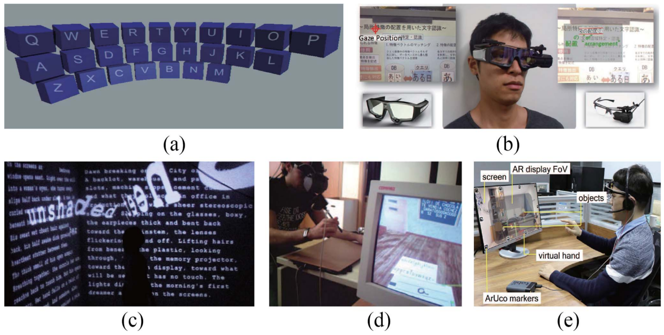

Fig. 6. Some typical approaches on text and document data visualization.

VI. Immersive Text and Document Data Processing

Text information is ubiquitous in our lives, such as in e-mails, news, and work reports. Regarding the explosive growth of text information and the increasing pace of work, people need more interesting methods to read and analyze text, thus text visualization emerges.

With the development of technologies, such as VR, new techniques for combining text visualizations with virtual environments are gradually gaining attention from experts in the field. This section focuses on text input and text and document reading in immersive environments.

A. *Text Input in Immersive Environments*

Gonzalez et al. [84] have summarized different text input techniques in an immersive environment. Speicher et al. [85] also evaluated the performance of different input methods in detail through six comparative experiments. The results show that the best virtual keyboard input method is a key selection on a hovering flat virtual keyboard by using a VR controller with light projection. However, due to the close proximity of the keyboard keys, the position selected by the controller cannot be processed as precisely as direct interaction, which often brings many keystroke errors and, thus, wastes time. In contrast to the flat keyboard, Yanagihara and Shizuki [86] proposed a cubic keyboard. Since this method allows the desired key to be selected by the pause controller, it made a great improvement in input performance. However, the cube layout poses the problem of cognitive difficulties for users. A curved "QWERTY" keyboard [45] showed the function of alleviating arm fatigue and improving input efficiency, as shown in Fig. 6(a). A virtual keyboard, named HawKEY [46], solved the limitation of physical movement in the virtual environment, allowing users to type while standing up, making the typing process more efficient and free. With the development of technology, handwritten input is gradually being electronized. Poupyrev et al. [47] proposed Virtual Notepad, a method that combined handwritten input with a virtual environment to explore new ways of entering text. The method explores where virtual environments can shift from gaining experience to doing real work.

B. *Text and Document Reading in Immersive Environments*

Users extract the desired information by perceiving and discerning the viewable elements [44]. Therefore, the core problem of text visualization is how to assist users in extracting and indirectly visualizing information from text accurately and without errors. Carroll et al. [36] suggested enhancing the interaction between the body and the text, creating a new reading experience by involving the reader's body, as shown in Fig. 6(c). They proposed a tool named Screen [36]. It provided a VR environment (the Brown University Cave) for users to read. The AR-based form of contact AR (cAR) proposed by HincapieRamos et al. [37] was a mobile device with a transparent display that can be placed on the top of an augmented object.

With the development of hardware, HMDs are becoming well known as a new interactive device. The human gaze is used as an effective input interface for wearable displays. Experiments on reading detection and gaze position estimation in wearable displays offered the possibility of enhancing the relationship between managing the virtual and the reality and creating a more cohesive experience for users [39]. Toyama et al. [38] proposed a new approach by using an HMD to combine human eye gaze with text translation, as shown in Fig. 6(b). The method provided a more intuitive and effective OCR input using human eyes. Besides, Lamberti et al. [87] used VR and AR applications built on wearable devices to generate speech-based interfaces automatically. A multimodal interactive system [88] was also proposed to integrate speech into a flexibly configurable AR system. Noting that the use of large screens poses problems due to limited reading in multiple screen windows, Grout et al. [41] explored the possibility of using virtual environments for users performing everyday computing tasks. They conducted user study experiments to analyze the execution of typical reading tasks in a generic computing environment in an immersive VR headset.

Immersive environments allow users to use their stereoscopic vision and are able to disambiguate complex abstract representations to a certain extent. Therefore, combining VR techniques with software visualization can effectively address some of the limitations when studying software in two dimensions. For example, Maletic et al. developed a research platform called Imsovision [42], [43], which provided a VR environment to support software development, maintenance, and reverse engineering, as shown in Fig. 6(d). This approach used CAVE as a vehicle for an immersive environment, providing the user with information not available in UML, such as size metrics, methods, and attribute types.

VII. Applications of InfoVis Techniques in Immersive Environments

Immersive InfoVis has also provided a good chance for many new applications. Two kinds of the typical applications include IA and infographics.

A. *Immersive Analytics*

The concept of IA was defined by Chandler et al. [89] to be "emerging user interface technologies for providing immersive experiences and smooth workflows for data analysis." IA help users understand and analyze data and help them make decisions. It also brings a variety of novel ways for users to interact with data. Thus, the application of IA is very promising. Simpson et al. [57] represented the first step in exploring IAMs in an immersive environment, as shown in Fig. 7(d). They tried to create an immersive analysis tool for exploring the output of

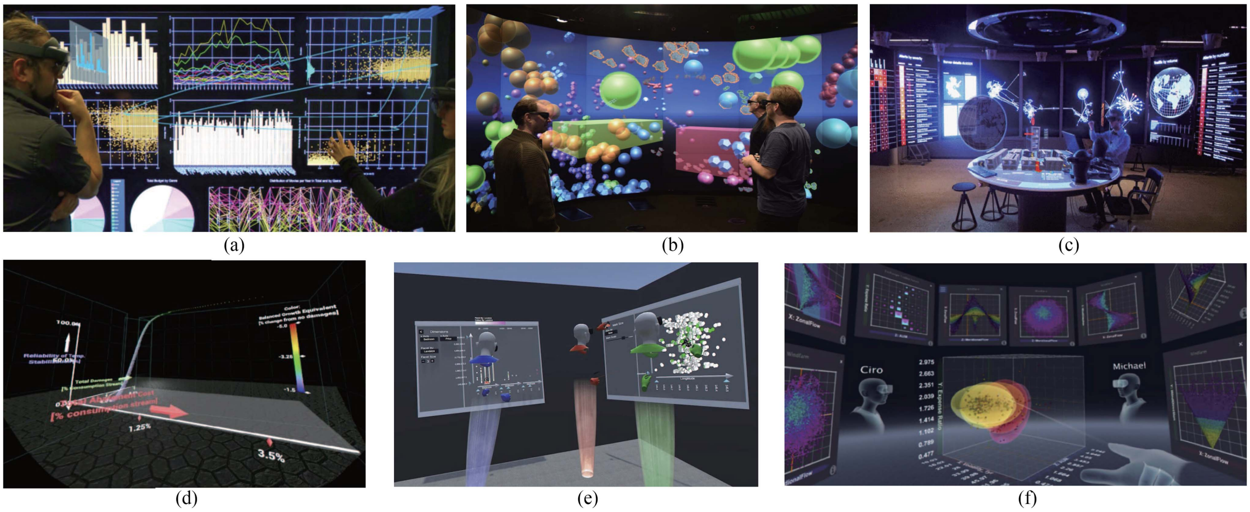

Fig. 7. Some applications of IA. (a) Combination of a large interactive display with personal head-mounted AR for InfoVis [1]. (b) Platform for visualizing cancer cell motility and related parameters [56]. (c) Immersive, collaborative, and eronfigurable environment that combines heterogeneous technologies and hybrid interaction approaches called dataspace [54]. (d) Immersive analysis tool for exploring the output of DICE model [57]. (e) System that supports team-based analysis in an immersive environment called FIESTA [53]. (f) VR multidimensional data mining and visualization system based on browser called WebVR [20].

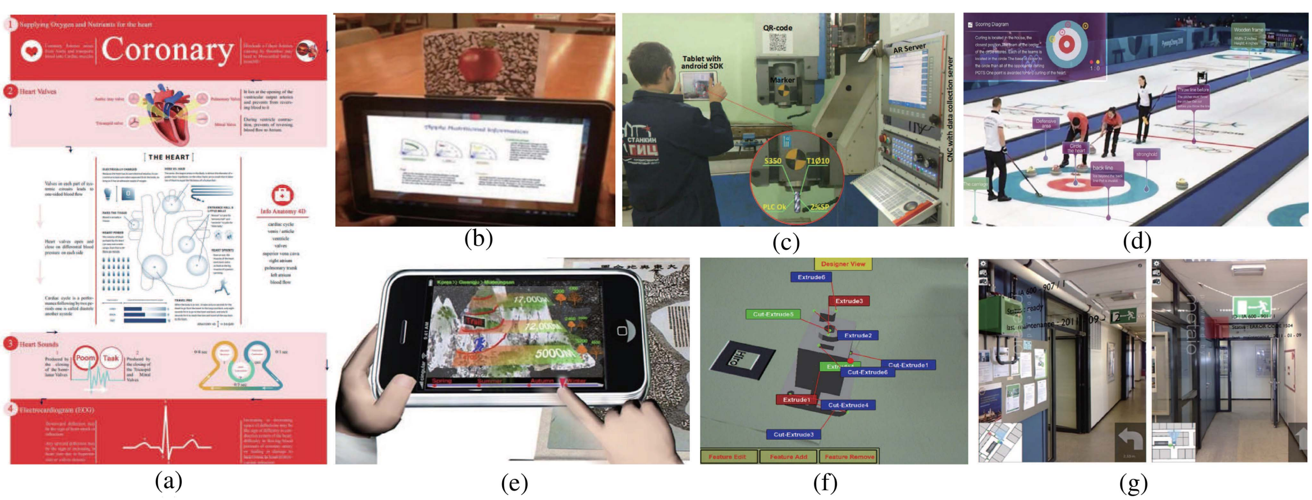

Fig. 8. Augmented infographics in different domains. (a) Teaching of heart and cardiac cycle system [90]. (b) Nutritional information of food [91]. (c) Monitor of machine parameters [92]. (d) Race conditions of ice curling [93]. (e) Altitude of mountains [51]. (f) Annotation of product models [94]. (g) Facility maintenance in a university campus [95].

simulation model. This tool can provide a new way to make these models more easily understood by experts and decision makers.

Some literature works have focused on how IA can better help users understand the data. The tools were designed to help experts as well as users without professional knowledge. For example, Lock et al. [56] designed and developed a visualization platform, which combines the delayed confocal microscope recording of cancer cell movement with image-derived quantitative data across 52 parameters, as shown in Fig. 7(b). In addition, the immersive visualization environment has the ability to enhance the accuracy and ease of data query collaboration supports important interdisciplinary collaboration. It gains transformative insights from the rapidly emerging biological image Big Data. Vira [59] is a customized VR visualization system based on WebVR and various visualization libraries, which provides web-based solutions for immersive analysis. Yim et al. proposed an application called NiwViw [58]. The system was designed to help people who has little programming skill to create IA tools in their own space. It allows nonexpert users as well as those lacking a background knowledge to create immersive visualizations autonomously in a wide range of immersive devices.

Another main problem of IA is how to interact with data. Traditional interactive devices, such as keyboard and mouse, are no longer feasible. Immersive analysis systems require the same immersive interaction. Cordeil et al. developed IATK [52], a Unity-based immersive analysis software toolkit. Filho et al. [31] expanded on the basic principles of the virtual desktop metaphor and analyzed the results of case studies in two different fields. In VirtualDesk Metaphor, users can manipulate a dataset or change the viewpoint through head movement while interacting with mid-air natural gestures and tangible contact with a desk in the real world. The results show that the VirtualDesk Metaphor has

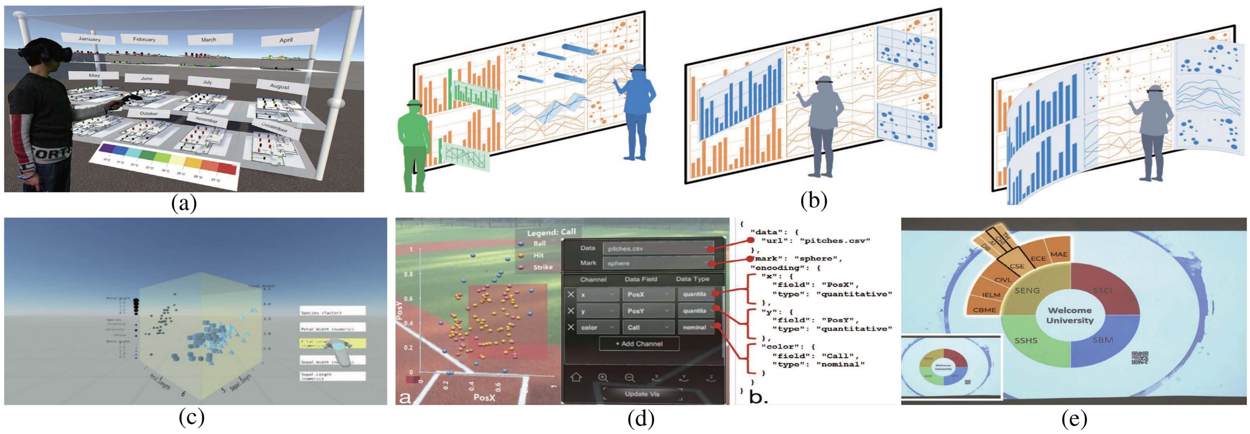

Fig. 9. Layout of multiple views in immersive environments and different authoring tools for creating InfoVis in immersive environments. (a) Shelf of small multiples [16]. (b) Embedded AR visualization [1]. (c) WebAR-based interactive visualization of open health data [20]. (d) DXR: an immersive data visualization toolkit based on Unity [17]. (e) PapARVis: a designer for static visualization of virtual content in AR [18].

consistent visible benefits in terms of user preference, comfort, and engagement. Thus, combining prior knowledge from VR and 3-D user interface research can lead to a more comfortable and efficient way to explore data and improve the acceptability of IA applications in real-world environments. Hadjar et al. [20] proposed a web-based system, which was a multidimensional data mining and visualization system, helping users better understand the data and make decisions, as shown in Fig. 7(f). Butscher et al. studied the potential of AR environment designed in collaborative analysis for multidimensional abstract data. They proposed an AR system based on Tabletop, named ART [13]. ART used multiple scatter plots in AR and created 3-D parallel coordinate visualizations.

Visualization is anchored to a touch-sensitive desktop, making the interaction operations familiar and smooth. In addition, design guidelines and future research directions are provided to promote the development of tools supporting collaborative analysis of multidimensional data. Reski et al. [96] proposed a hybrid immersive analysis system, where multiple peer users can manipulate asymmetrically while exploring data synchronously. The system consists of an immersive VR application and a nonimmersive web application, and the connection between the two was accomplished through a real-time communication interface. Such a design promotes the mutual understanding of collaborators and their ability to make (spatial) references.

IA can help users better support real-world visual analysis tasks and make decisions in immersive environment [89]. There are 11 different interaction tasks in IA, as summarized by Fonnet and Prie [67]. They include navigation, selection, arranging, changing, filtering, and details on demand. [67].

The analysis tasks in all the categories summarized by Fonnet and Prie [67] can be fulfilled by kinds of interactions and operations. For example, the "navigation" task consists of interactions that change the viewpoint of the user. The analysis task can be fulfilled by direct controller, virtual menu [97], and magnifying glass metaphor [98], [99]. "Selection" task include the selection of datapoints. The analysis task can be fulfilled by single-object operations [97], [100] or multiobject operations [98], [101]. "Arranging" aims at organizing visualization elements spatially [67], including datapoints, view components, and visualization views. "Changing" refers to interactive tasks that modify visual encodings. The immersive visual analysis in the task can be fulfilled by highlighting [99] and visual mapping [98]. "Filtering" is to specify inclusion or exclusion dataset for visualizations. The immersive analysis in the task can be fulfilled by direct box selection [98] or other abstract layer operations. "Details on demand" includes interactions to display detailed information. The visual analysis in this task can be fulfilled by pop-up window interactive lens [100].

B. Augmented Infographics

Infographics can convey information intuitively and help understand concepts and meanings in a short time by reorganizing information. InfoVis techniques in AR environments are effective to display infographics. In this survey, we call them as augmented infographics. Augmented infographics have been widely used in nutrition [51], [91], education [90], geology [102], industry [92], [94], sports [93], etc.

The appearance of outdoor AR and mobile GIS offer new ideas and new interfaces for the visual representation of spatial information. Augmented virtual geographic objects on real scenes can enhance and expand users' spatial cognition. Wu et al. [102] put forward the mechanism and method of AR-based outdoor spatial InfoVis. When travelers pass through unfamiliar environments, it can provide additional visual information and help users to discover important points of interest in their field of vision. The annotations and attributes were superimposed on the buildings to show details [102], as shown in Fig. 8(g). Augmented infographics organize the information for different audiences and enhance the real-time and convenient exchange of events and tour information. Guo et al. [93] designed different infographics for the 2022 Beijing Winter Olympics, which relies on mobile terminals and VR glasses. The system included path guidance, information delivery, and popular science education. Fig. 8(d) shows a curling sport with high participation. The complex and abstract information and the hidden interweaving relationships between them can be integrated by the outline of basic visual elements.

In the field of health care, users want to know the nutrition information so as to improve their health. Mobile devices have become the first choice for AR prototype development because of their popularity. An Android application was created to provide users with nutrition information, such as calories and nutrition, and helped them manage their diet [91]. It tracked with the digital camera and detected by scanning the image of the object. Another mobile AR-based application, named mARGraphy, can also prompt nutrition information [51]. The proposed method enables the system to identify dynamic changes of the environment and users in real time and displays the appropriate content according to the identified information. In addition, mARGraphy can identify other information, e.g., the religious characteristics of different regions and the altitude of mountains.

Augmented infographics has great potential in education and teaching, which is manifested by improving the synergistic effect in learning. Dehghani et al. investigated the influence of augmented infographics on learning biology [90]. Participants were divided into three groups, learning with static infographics, augmented infographics, and no infographics (AR-based environments). The results showed that augmented infographics simplifies complex information and has a significant impact on learning. Fig. 8(a) shows the teaching material of heart and cardiac cycle system, which combines infographics with AR techniques.

In industry, the augmented annotation provided by AR brings convenience for designing product models. It is important to get information of complex product models by clearly marking and annotating important components. Shen et al. [94] presented a collaborative system for visualizing and augmenting product information. Product feature information can be displayed by linking virtual annotations to related features. Different users can input annotations through a user interface at the same time. All the annotations were shared in real time. In order to avoid overlap of multiple annotations in the field of view, a greedy algorithm based on clustering was implemented in this work. In modern enterprises, the automation of technological process makes the connection between equipment complicated. The amount of data that must be acquired and analyzed in the working process increases considerably. Meanwhile, the available interface of the control system is often overloaded with information. Chekryzhov et al. [92] proposed a variant of using AR to solve the terminal problem. AR can provide extra information for the ongoing technical processes and help to cut down redundant information. Furthermore, users can observe the virtual machining process, monitor machine parameters and simulate emergency situations without damaging equipment and harming themselves.

VIII. Discussions and Conclusion

InfoVis approaches in immersive environments are summarized in this survey according to data types, including graph/network data, high-dimensional and multivariate data, time-varying data, and text and document data. The presentations and interactions of these abstract data types have upgraded due to increased dimensionality and spaciousness of the immersive environment. Charts, diagrams, and plots are basic elements of InfoVis. Their forms have undergone a series of changes from 2-D to 3-D, and finally to a combination of both in immersive space. Besides, many methods on IA and infographics utilize AR to provide augmented information.

We notice that a limited amount of literature works focus on InfoVis techniques in VR/AR environments. The possible reasons are summarized as follows. First, immersive applications are more difficult to develop as it involves not only language learning but also equipment debugging. This means the developers have to be familiar with both software and hardware. No common development libraries for immersive environments are currently available such as D3 for Web, which are some of frequently-used InfoVis libraries. Second, immersive devices produced by different manufactures are not necessarily compatible even for the same series of products. Third, the creation of a fully virtual environment requires the use of heavy equipments such as HMDs and CAVEs, which are unportable and inconvenient. Consequently, the commercial products, such as Microsoft Hololens 2 and Google Glass as well as the upcoming Apple Glass, will become the popular display devices for MR in the future. Fourth, new input devices, such as leap motion and Kinect, do bring novel experience to users but the related interaction techniques are not accurate and stable enough to support long-term use.

As far as we surveyed, we found that the evaluations of immersive InfoVis techniques often include user study, case study, expert review, and performance study (frame rate for XR rendering, task completion time, response accuracy, scalability, gesture recognition accuracy, etc.). One of the major differences between the evaluations of immersive techniques and nonimmersive techniques is the study process. It is time-consuming to conduct an evaluation for immersive work since they often need to wear an HMD device, operate other immersive devices, or put themselves into immersive environment.

The weakness of applying InfoVis techniques in immersive environments consists of three aspects. 1) Color is particularly difficult to be used in AR due to the color disturbance from the physical background environment [7]. However, the visual channels, such as shape or size, are better choices when design InfoVis tools because they are better perceptible than color [1]. 2) Depth and size in 3-D InfoVis should also be cautiously used in immersive environment because they are often intertwined [7]. 3) Resolution and field of view of many immersive devices are limited; therefore, it is difficult to display detailed information such as small texts.

We summarize and discuss two of potential research trends in interactive immersive information presentations, i.e., MCV in immersive environments and immersive authoring tools.

A. Potential Trend Discussion: MCV in Immersive Environments

A single view often cannot provide a complete image of data. MCV in immersive environments is one of potential research trends, which link multiple raw data mappings together to help improve data perception and data analysis. A typical example is IA using MCV, which combines VR and AR to display data in multiple views within a physical space. This kind of systems often exploit tiled display walls or large display screens, either virtual or reality. Regarding the immersive InfoVis approaches, there are a large number of challenges in combining various physical hardware devices, designing interactions between users and data, and coordinating collaborative interactions between users.

The integration of large display screen and immersive devices: The large display screen is an important component in immersive environments, which can display multiple collaborative views at the same time. Users' areas of interest vary from usage scenarios in a collaborative immersive environment. Many issues affect users' further analysis, for example, the position relative to the display, the distance between a person and the display, and the occlusion caused by peers. A large interactive display together with personal AR HMDs/glasses can display extra information, which meets the exploration needs of teams and individuals at the same time [1], as shown in Fig. 9(b).

There are three AR-based techniques that can solve the perception problem on large displays and provide an overview of the whole dataset [1]. First, embedded AR visualizations display additional data directly situated on the corresponding data object of an existing visualization. Second, hinged visualizations support rotating distant views of the display such as a hinged door. Third, curved AR screen enables an overview of the full display when users are close to the screen.

B. Potential Trend Discussion: Small Multiples in Immersive Space

Small multiples use the same visual encodings to represent a set of different data items in a tiled display space to support simple coordinated comparisons. Liu et al. [16] migrate the 2-D small multiples visualization on a flat screen to a 3-D immersive space. "Shelf" can be considered as a metaphor of the layout of small multiples [see Fig. 9(a)]. The dimension, curvature, aspect ratio, and orientation of the "shelf" can give a description of many possible layouts of small multiples in VR environments. There are three different layouts such as "flat," "half-circle," and "full-circle." According to their user study, the performance of different layouts depend on the number of the small multiples. A flat layout has higher performance when the number is small even if it needs a lot of walking. The half-circle layout is preferred by participants if it needs multiple linked views because it is a good compromise between walking and rotation, and it allows for an overview at a glance by taking a step back.

C. Potential Trend Discussion: Immersive Authoring Tools

Over the past few years, VR, AR, and MR devices are one of the most promising data-aware media for InfoVis. However, creating InfoVis in an immersive environment is challenging, especially for developers who have no experience in 3-D graphics, AR, and VR programming. It usually requires tedious low-level programming of mapping data attributes to geometric markers and visual channels. Immersive authoring tools in combination with domain-specific languages (DSL) are friendly solutions for nonexpert users [103]. For example, DXR [17] is an immersive data visualization toolkit based on DSL. It offers a graphical user interface for easy and quick editing and preview when designing InfoVis, as shown in Fig. 9(d). With the help of DXR, the designers can create customized geometric marks and visual channels to build unique and attractive designs with the wide variety of Unity prefabrication. Besides, an authoring tool named PapARVis [18] [see Fig. 9(e)] was developed to enhance static visualization of virtual content in AR. Visual designers without AR development experience can exploit PapARVis designer to create augmented static visualizations. Although augmented static visualization can take advantage of the best materials in the physical and digital world, its creation often involves a lot of different devices and tools. Few methods can support designing and debugging static and virtual content simultaneously. Thus, building of authoring immersive tools is challenging and potential in immersive data presentations.

To our best knowledge, there is no survey summarizing a literature of InfoVis techniques in immersive environments from the perspective of abstract data types. Overall, we expect that this survey inspires more ideas on InfoVis by using immersive technologies.

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