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ORIGINAL ARTICLE

Visualization in virtual reality: a systematic review

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Abstract

Rapidly growing virtual reality (VR) technologies and techniques have gained importance over the past few years, and academics and practitioners have been searching for efficient visualizations in VR. To date, the emphasis has been on the employment of game technologies. Despite the growing interest and potential, visualization studies have lacked a common baseline in the transition period of 2D visualizations to immersive ones. To this end, the presented study aims to provide a systematic literature review that explains the state-of-the-art research and future trends in visualization in virtual reality. The research framework is grounded in empirical and theoretical works of visualization. We characterize the reviewed literature based on three dimensions: (a) Connection with visualization background and theory, (b) Evaluation and design considerations for virtual reality visualization, and (c) Empirical studies. The results from this systematic review suggest that: (1) There are only a few studies that focus on creating standard guidelines for virtual reality, and each study individually provides a framework or employs previous studies on traditional 2D visualizations; (2) With the myriad of advantages provided for visualization and virtual reality, most of the studies prefer to use game engines; (3) Although game engines are extensively used, they are not convenient for critical scientific studies; and (4) 3D versions of traditional statistical visualization techniques, such as bar plots and scatter plots, are still commonly used in the data visualization context. This systematic review attempts to add a clear picture of the emerging contexts, different elements, and interdependencies to the literature.

Keywords Virtual reality · Visualization · Game technologies · Systematic review

1 Introduction

The word "visualization" has been an overloaded term even before being established as a scientific field and has a prolonged usage with different meanings in different contexts. Since the visualization structures and types that can be presented in immersive environments are very diverse, immersive visualization is placed in the convergence of different research areas. In immersive environments, data can be presented with 3D models, 3D graphs and plots, simulations, and multiple 2D representations. The data source can be statistics, medicine, computer sciences, heritage, and many others. Its scope includes technology-related areas, such as multisensory interfaces, interaction, navigation, collaborative aspects, rendering techniques, and domain-specific subjects. Immersive environments offer distinctive methods to engage with the rapidly expanding digital realm as an immersive computing technology. Over time, various fundamental VR technologies have emerged that collectively allow a person to experience a virtual environment. The technology is specifically tailored to use human information processing systems with an emphasis on presenting information to our senses (Suh and Prophet 2018), and interaction opportunities provide new ways to express ideas and propose new interaction methods for a wide range of research domains and disciplines (Fig. 1). With recent technological advances, the invention of several libraries, tools, and devices, VR facilitates the manipulation and analysis of data by using the advantages of 3D environments. The combinations of VR and haptic or kinesthetic interfaces enable various interaction techniques and maximize efficiency. The generation of immersive visualizations has further improved various domains in terms of practicability, education, and cost-effectiveness. VR technology supports and facilitates

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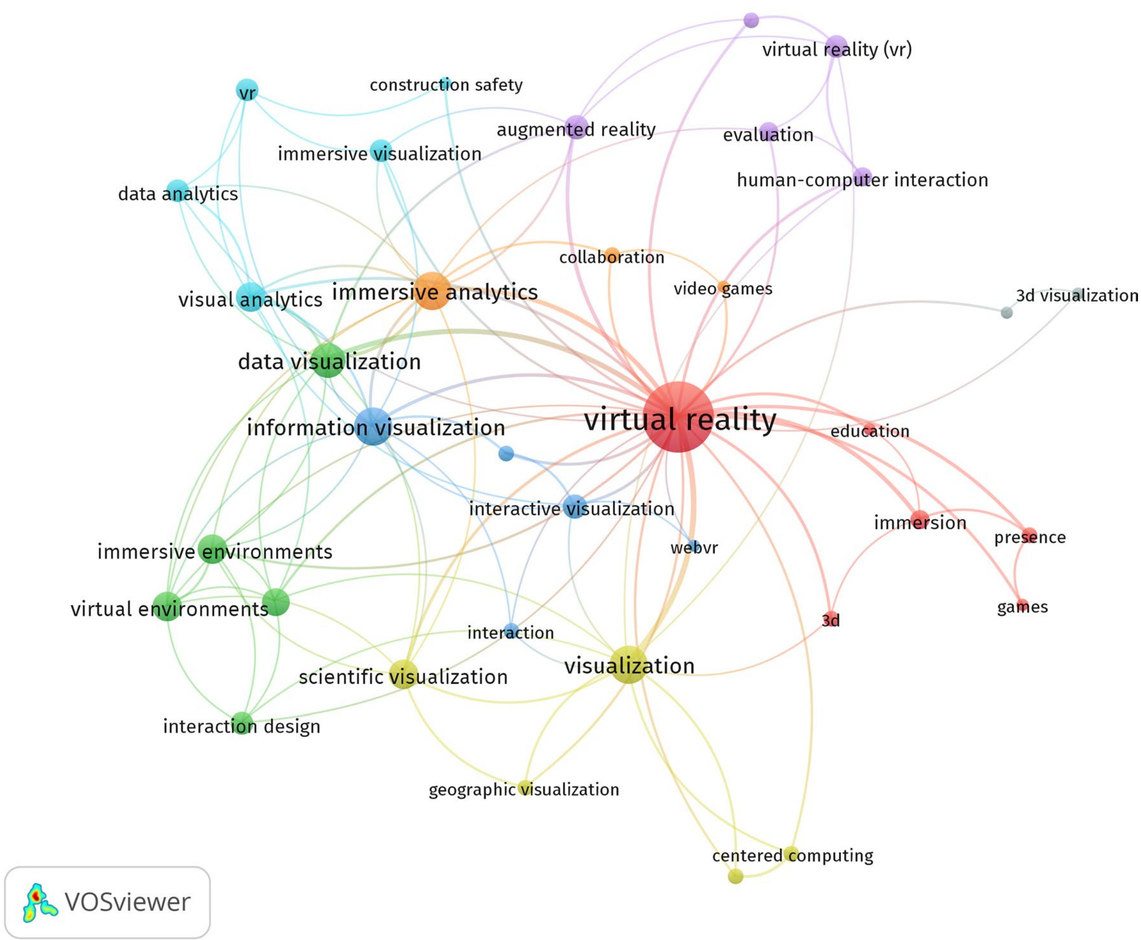

Fig. 1 Co-occurrence Keyword Network of 110 Papers. Produced with VOSviewer

the learning and teaching processes by offering 3D replications of tools and experimental settings. Rather than being a passive spectator, the development of exploration-based learning paradigms requires users' active participation in those learning environments while enhancing memory through interaction (Sauzéon et al. 2012).

The adoption of immersive VR technologies into teaching on a regular basis is essential to teach specific skills, especially those that require declarative and practical knowledge. The potential for enhancing training and learning methodologies through the use of virtual reality settings and game-based learning methodologies is highly encouraging, and this is further supported by the accessibility of software and hardware solutions. Effective teamwork between coworkers and other professionals is a crucial component. Virtual environments have been constructed that can provide sustainable, coordinated, and conjoined activity to counteract the negative effects of the lack of a shared local or distant ideation space. Research on multi-user virtual environments is becoming more prevalent, which indicates a growing trend in distant collaboration. VR has been promoted as a tool to simplify design, engineering, construction, and management for built environments due to its sophisticated immersive and interactive visualization capabilities. For example, digital city technology allows users to create more sustainable and effective solutions for urban environments. Virtual environments provide training in diverse areas and create reusable and safe environments for experiments and education. Over the past few decades, investments in VR-related applications in the architecture, engineering, and construction (AEC) sector have produced a varied and dispersed body of knowledge.

Compared to conventional 2D methodologies on a desktop computer, immersive visualization can be considerably different, forcing scientists to reconsider how they approach the data in some cases. VR and 3D immersive environments are perception-related technologies that need to have their visual language. Therefore, it is necessary to continue building theoretical approaches. An ensemble of studies has the power to lead a groundwork for visualizations. The bidirectional contribution and the influence between games, video games, and VR have propelled the extension of VR into scientific, artistic or informational, and educational domains.

While most VR studies embrace a ludic approach, VR has created an ocean of possibilities that contain new mechanics, narratives, and interactions for the game industry. Zyda (2005) strongly advises VR researchers to study games to improve their design and stay up-to-date.

While a wide range of areas adopts this technology, it is crucial to think critically about the solution for challenges, visualization specifications, and design guidelines. Several sectors are currently utilizing immersive visualization to help decision-making and foster innovation. However, while some domains are well-established, immersive visualization is still in its experimental stage and is not used consistently in all fields. A specific domain or visualization structure is the subject of several existing surveys on visualization in virtual reality. For example, Zimmermann (2008) focused on the automotive industry and design aspects. Seth et al. (2011) explained assembly methods for prototyping, Radianti et al. (2020) focused on higher education, Wang et al. (2018) surveyed construction engineering from education and training perspectives, El Jamiy and Marsh (2018) inspected depth estimation, Caserman et al. (2019) provided studies and analysis on full-body motion reconstruction, and Ferdani et al. (2020) analyzed the studies on archaeology. However, considering the specific requirements of immersive technologies, visualization techniques that are used in different domains are closely interrelated and have the potential to create a mutual relationship to solve the problems of immersive technologies. To fully achieve the visual representation objectives, the construction of visualization methods depends on various areas, from psychology to machine learning. Therefore, we survey techniques from a broader perspective to extract the relations, similarities, and shared problems in visualization in VR. We think this approach can help developers find solutions in other domains and give direction to more concrete guidelines. This paper aims to present an overview of existing literature and discuss the common problems and methods used in different domains to provide a basis for the immersive visualization field to construct a comprehensive and consistent structure.

The remainder of this study is structured as follows. While Sect. 2 presents the background and related concepts, Sect. 3 briefly describes the methodology, Sect. 4 summarizes the results, Sect. 5 discusses the results, Sect. 6 presents the conclusion, and Sect. 7 explains future directions.

2 Background

Without a definitive starting event, the history of visualization includes many discussions collected around design, purpose, or intent themes. Geometric diagrams, astronomical tables, and navigational graphics are considered the first visualization attempts, and prominent subjects of the field differ according to the era's problems and fields of interest. The increase in practical applications in the seventeenth century was closely related to interest in physical measurements, which led to more line graphs, astronomical graphics, and maps. For example, the first known weather map, a theoretical curve relating barometric pressure to altitude by Edmund Halley, and the plot of "life expectancy vs. age" by Christian Huygens were produced in that era (Chen et al., 2014). In addition to the increase in practical applications, with the collection of social data, demographic and economic visualizations were produced within the methods of 'political arithmetic.' The eighteenth century brought new domains and graphic forms, such as abstract graphs and thematic mapping. Joseph Priestley produced a more convenient timeline (1765) and a detailed history chart (1769). With the creative combinations of the fundamental forms, first-line graphs and bar charts (1786), pie charts, and circle graphs (1801) were invented by William Playfair which are graphical representations still commonly used today (Friendly 2007).

Most of the data representations used today took their form in the nineteenth century with the developments in statistical graphs. With the recognition of graphical representation by official and scientific spheres, graphical analyses were used in scientific publications and state planning. Together with the other innovative works of Charles Joseph Minard, his famous visual storytelling, the fate of the armies of Napoleon and Hannibal, are examples of the social and political uses of graphics which later gained the appreciation of most of the important names in the field (Rendgen 2018). Among others, Nightingale's coxcomb plot, Jon Snow's Cholera map to enhance public health, statistical graphics and weather patterns of Francis Galton, and the works of Karl Pearson are also typical examples of historic visualizations. After a fertile period, the early 1900s were defined as the modern dark ages of visualization. Analyses over time in the relational database of Milestone Project show a steady rise in the nineteenth century, followed by a decline in the twentieth century and until 1945, and continued with a steep rise to today (Friendly et al. 2017).

The insufficiency of traditional 2D representations leads the visualization community to search for more effective solutions. Recently, the interest in virtual reality technology and the contribution of interdisciplinary fields created new possibilities for application and implementation. VR is an immersive experience in an artificial environment. Throughout time, different methods and setups have been suggested for VR. Although Ivan Sutherland demonstrated virtual and augmented reality prototypes in the late 1960s, the practical, interactive virtual reality systems had to wait until the 1990s (Dwyer et al. 2018). In 1992, Cruz-Neira et al. (1992) reported the Cave Automatic Virtual Environment (CAVE) system as an early example of an immersive virtual reality system. It is a surround-screen display technology consisting of room-scale projection surfaces to facilitate immersive virtual reality designed for exploration and interaction. The used projection technique allows users to see all directions. Later, Fish Tank VR (Ware et al. 1993) was introduced. The system includes monitors and special glasses for stereoscopic viewing and uses the keyboard as the primary input source—enthusiasm for interaction with virtual content followed by a series of events. Today, immersive systems are primarily used with the help of Head-Mounted Displays (HMDs). HMDs are stereoscopic devices that display two images in front of the eyes to create a sense of depth, providing an opportunity for new data exploration and interaction methods. In parallel with the development of virtual reality software, the content and scale of digital environments have expanded. Recently, game engines Unity and Unreal Engine have been widely used to create large-scale VR environments. Rapid production offered by game engines has allowed many fields to build immersive visualizations. With the increasing hardware and software capabilities, VR devices have become more useful and affordable.

Immersive technologies change data experiences and decision-making processes. It allows users to analyze complex and dynamic datasets and change their passive roles to active ones. As an interactive communication method, visualizations are expected to provide certain features and tasks, such as the presentation of the data and confirmatory and exploratory analysis. Data visualization and exploratory data analysis have gained tremendous importance in recent years due to the increasing amount of data. Extracting information from high dimensional and large volume data requires visualization domain to employ different automation techniques such as machine learning algorithms. Recent advances in immersive technologies and computational power present new possibilities for data exploration methods that aim to provide interaction with high-dimensional data to gain fundamental insights. Condensed information extracted from data needs to be presented in a visual form. This form can be animated, static, or interactive. The definition of data type and selection of visualization and interaction techniques is crucial to create efficient and accurate visualizations. The selection of appropriate presentation techniques depends mainly on the user. Therefore, visualization techniques depend on perception and cognitive theories to convey the data efficiently.

Immersive environments generally refer to specific terms like presence, immersion, and embodiment. Sense of embodiment depends on the spatial components provided for the user, such as awareness of location and virtual body. VR recreates a spatial environment and builds three-dimensional spatial awareness via visual cues and sounds. The presence is related to being in the virtual environment, and immersion can be considered as the result of this presence. The combination of immersion, presence, and embodiment contributes to the user's experience and determines its quality. Therefore, they are widely used to evaluate and develop VR experiences. Most of the studies employ questionnaires to measure presence and immersion.

Depending on the technology used, interaction techniques can vary. Techniques include head tracking, eye tracking, hand tracking, and motion tracking. Due to the limitations of physical spaces, HMDs provide seated configurations, allowing users to move with controllers and room-scale VR. There are also different interaction modes for VR. Users can have only a passive role or, most commonly, move with a pre-defined trajectory. Exploratory VR allows users to locomote themselves. In the interaction mode, users can explore and interact to manipulate the environment, which is the most common interaction mode for immersive visualizations. Head-mounted devices present an opportunity for new data exploration and interaction methods. Degrees of Freedom (DoF) is a term used to describe the moving capabilities of an object. While basic HMDs provide 3 DoF for moving along the x-, y-, and z-axis, more advanced devices offer 6 DoF, including the translational movement in physical space, surge, heave, and sway. Therefore, visualization techniques depend on perception and cognitive theories to convey the data efficiently. In immersive environments, visual signals indicate the existence of a body movement while there is no actual movement, and as a result of this sensory conflict, cybersickness occurs. Different hardware has different frequency requirements to induce cybersickness.

Recent research includes the development of new techniques for visualizations, interaction and collaboration, evaluation of perception and systems, proposals for frameworks and tools definition, and categorization of challenges. For instance, by extending the work of Brehmer and Munzner's (Brehmer and Munzner 2013) What-Why-How framework for immersive analytics, Marriott et al. (2018) propose to use Where-What-Who-Why-How questions as a basis. Besides those common research areas of VR, visualization subfields have domain-specific design problems. The creation of information visualizations includes a decision-making process regarding abstraction methods, visual encoding, and design principles. Scientific visualizations must deal with scalability, accuracy, and precision problems. Visual Analytics (VA) is concerned with activities that can be performed through visualizations, such as decision-making and reasoning. Immersive Analytics (IA) focuses on using display and interface technologies to support better analytical reasoning and decision-making processes.

The emerging field of visual analytics is explained as "the science of analytical reasoning facilitated by interactive visual interfaces" (Keim et al. 2008). With the massive volumes of information waiting for human judgment, it is seen as a critical technology to handle big data (Mehrotra et al.

2017). The urgent need to analyze complex data leads to the integrated work of the user and the computer. For example, visual analytics systems are actively studied in medicine to provide better health care. As part of the Electronic Health Records (EHRs), clinical decision support systems (CDSS) (Moon and Galea 2016), interpretable machine learning for recurrent neural networks (Kwon et al. 2018), supporting comparative studies of patient records (Guo et al. 2020), and applications such as OutFlow (Wongsuphasawat and Gotz 2011), CarePre (Jin et al. 2020) and EventAction (Du et al. 2016) are used. To provide a better understanding, convolutional neural networks (CNNs) were also studied with visual analytics systems (Liu et al. 2016; Jacovi et al. 2018; Chawla et al. 2020). While visual analytics is more concerned with getting insights, detecting interesting patterns, and gaining a deep understanding from visually represented data, a new term has emerged with the development of 3D-based data exploration tools. Chandler et al. (2015) define the phrase "Immersive Analytics" as "the use of engaging embodied analysis tools to support data understanding and decision making." Combining data visualization and visual analytics with technological developments, immersive analytics aims to remove the obstacles between humans and data to make all processes available for everyone.

The increased use of immersive and spatially oriented technologies, including virtual, augmented, and mixed reality (VR/AR/MR) devices, has created new possibilities to explore complex data sets within a collaborative and interactive environment. With the increased accessibility to technology, those devices have started to be used by non-specialists who create a need for the field of Human–Computer Interaction (HCI), where psychology and computer science blend together. Thereby, as a unifying term, immersive analytics had a chance to merge the areas of Immersive Information Visualization, Visual Analytics, virtual and augmented reality, and Natural User Interfaces successfully.

3 Materials and methods

This study offers a systematic literature review of the studies related to immersive visualizations in virtual reality. The research questions of this study are:

RQ1: What are the most preferred visualization types and structures for VR visualization?

RQ2: What methodologies/theories are being used to research VR visualization?

RQ3: What are the research gaps in VR visualization?

RQ4: What are the existing approaches and techniques?

RQ5: Which software and hardware have been selected for different types of visualizations?

We have performed a systematic literature review following the guidelines proposed by Kitchenham and Charters (2007) to answer the above-mentioned research questions. To find relevant research that has been published since 2015, we selected seven primary academic databases: ACM Digital Library, IEEE Xplore, SpringerLink, Science Direct, Google Scholar, Elsevier, and Web of Science. We broke the query down into the major research fields to perform the search. The primary terms were 'virtual reality' and 'visualization.' After considering alternative spellings, search terminology included related areas combined with virtual reality. The resulting search strings were: visualization/visualization AND virtual reality, virtual reality AND ("data visualization" OR "information visualization" OR "information visualization"), immersive visualization, immersive AND visual analytics, and virtual reality AND game. We searched for the title, abstract, and keywords with this query. The search process was carried out between August 2019 and February 2022, and the timeframe for publications was between 2015 and 2022 (Fig. 2).

3.1 Inclusion and exclusion criteria

After performing the searches, due to the importance of the selection phase, each candidate study was subjected to a set of stages composed of inclusion and exclusion criteria. Publications were selected from 2015 onward, and the systematic review included journal articles, conference proceedings, in-progress research, and scientific magazines. Online presentations were excluded. Initially, we assessed

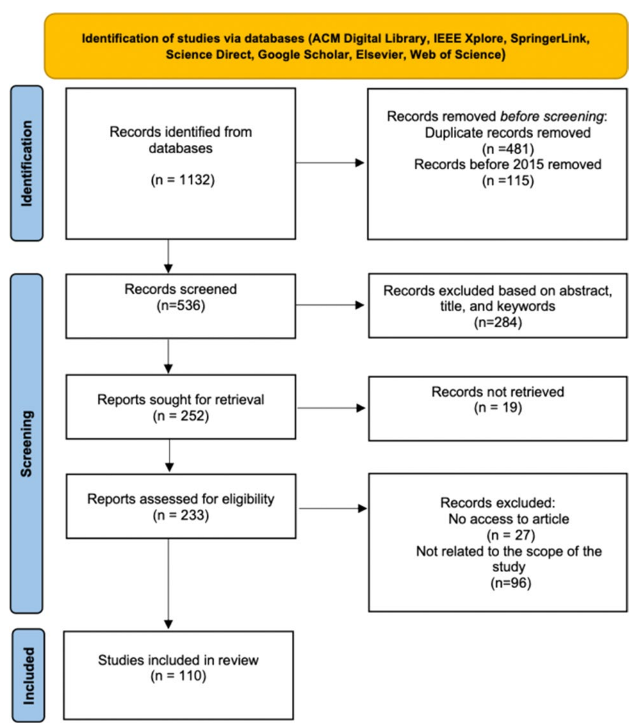

Fig. 2 PRISMA Flow Diagram for systematic records selection

the relevance of the literature according to the titles and the abstracts, looking for papers that described either virtual reality visualization or its indicators. Papers that do not include ques about visualization elements or techniques were excluded. Although we placed particular emphasis on immersive visualization and excluded research focusing on other non-visual stimuli, such as sonification or olfaction, we included studies that combine non-visual stimuli with visualizations. Secondly, we retrieved each study, read it entirely, and critically appraised it based on similar criteria as stated above. Then, validated studies were grouped according to association levels with visualization subfields. Finally, we removed duplicate papers or preliminary versions of works already being analyzed. A total of 1132 papers were obtained by running the query in the databases. Out of these 1132 papers, 536 papers passed the first stage. After removing non-relevant papers, 252 papers contained related studies, and 110 of them were found as primary sources. Additional to those papers, studies published before 2015 were included, which present a theoretical proposal to explain the motivation behind the implementation studies.

3.2 Types of contributions and division

The review distinguished between several types of contributions based on three criteria; connection with visualization background and theory, evaluation and design concerns for virtual reality visualization, and empirical studies based on implementation. Papers that offer a theory, framework, argument, technique, validation, or rebuttal meet the first criteria. The second criterion entails user studies, comparative analysis, and evaluation of prior research. Research that offers new techniques or improvements, tools or toolkits, innovation, creativity, or vision is considered an empirical study. Due to the visualization domain's intricate nature, most studies fulfill more than one criterion. For example, most papers that contributed a theoretical framework included subsequent implementation to validate the proposal.

Author keywords draw attention to the core concepts in academic works; as a result, keyword networks can represent a knowledge domain and provide details about the major research areas as well as their organizational and intellectual relationships. The author keyword is used in this study to examine the keyword co-occurrence of 110 papers. After several experiments, the threshold of keyword occurrences is set to three to be more representative and complete. A total of 36 co-occurrence keywords are thus found, divided into eight clusters, each representing a distinct hue on the distance-based network representation (Fig. 1). The thickness of the line shows the keywords' affinity, while the nodes' size reflects the term's frequency. The thicker line separating them indicates a stronger link between the two words' respective scientific fields. Sections of this survey were constructed according to condensed areas or extensively used terms and based on co-occurrence of keywords. Although in some cases the category of the study is clear or defined by the authors, due to interwoven feature of visualization, a study can belong to more than one section. For such cases, the category of the study was clarified according to definitions of the terms given in the studies of Rhyne et al. (2003) and Kosara et al. (2003). After an extensive literature search and review, the resulting research papers were grouped around ten main categories according to their contribution, domain, and visualization category (Fig. 3).

4 Results and analyses

We systematically reviewed each paper, assigning it to different categories based on the papers found. When it is necessary, these categories were further divided. The following subsections present our results for each of the ten domains considered. The overall distribution of the publications considered for this survey is shown in Fig. 3. In each subsection, we analyze the papers regarding the respective dimension. Subsequently, findings for each section are presented while comparisons and contrasts between methodologies are emphasized.

4.1 Tools, toolkits, and frameworks

Visualization tools can generally be standalone, web-based presentations, web-based development mainly consisting of software libraries (APIs), or programming language modules (e.g., Python or Java module). They can also be categorized in terms of software, visualization structure, operating system, license, scalability, extendibility, or latest release date. According to the criteria above, Caldarola and Rinaldi (2017) reported 36 software tools grouped into four subsections; scientific visualization, data visualization, information visualization, and business intelligence tools. Database-related and GUI-based applications provide a "direct manipulation principle" providing continuous representation, such as Microsoft Excel, Amazon Quicksight, and Microsoft Power BI. Although they are widely used, since they are out of the scope of this article, further detail will not be given. Visualization construction tools are generally criticized for preventing creativity due to fixed properties; however, they are preferred since they provide easy-to-use environments without requiring programming.

Although visualization libraries reduce the complexity of the process, they still require experience. In addition, there are development platforms and existing cross-platform tools whose scope involves multiple areas. The need for easy-to-use and flexible graphical systems to support visual thinking paved the way for further developments.

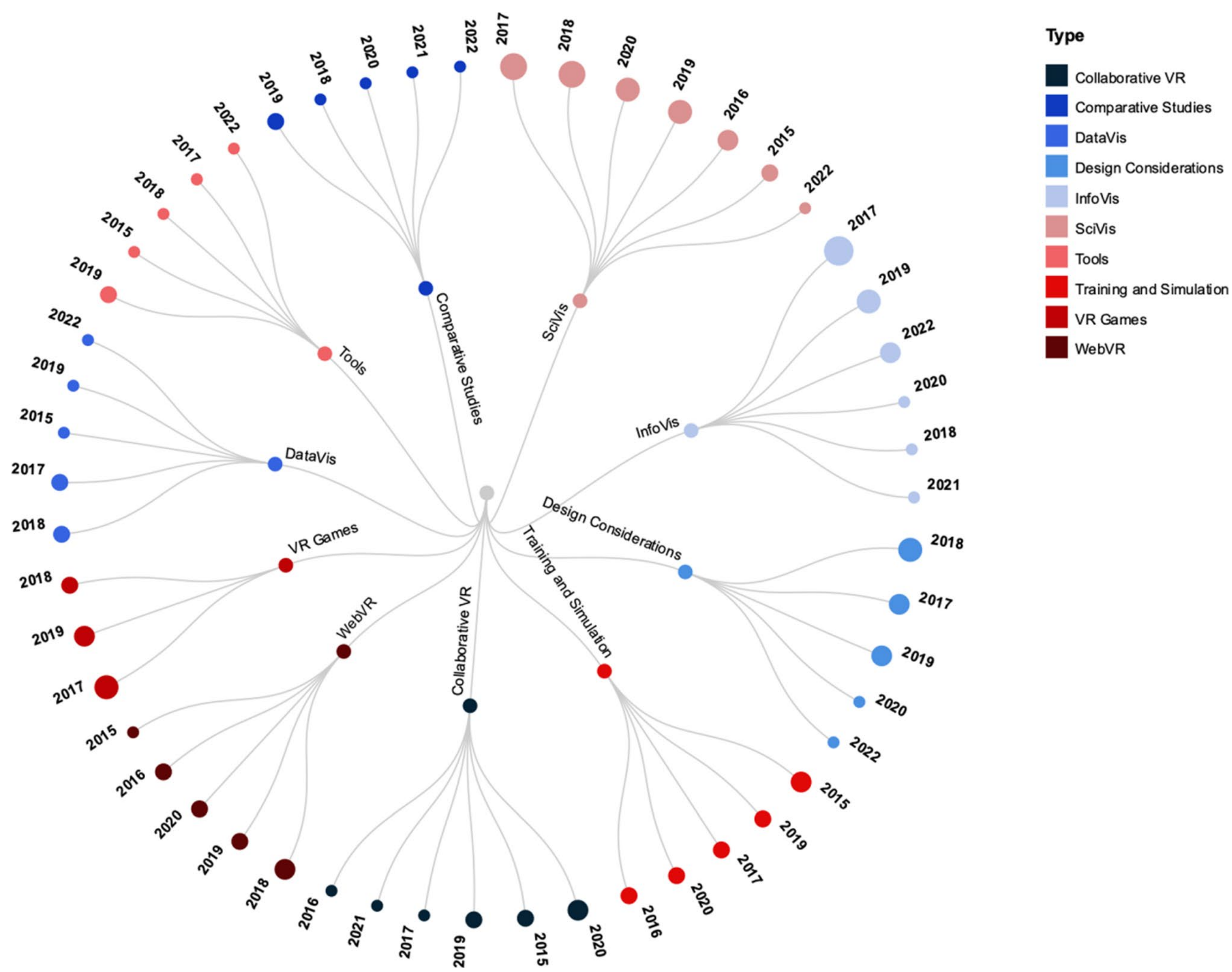

Fig. 3 Distribution of the 110 papers into ten categories. The radius of the circles is proportional to the number of studies. The circular dendrogram was obtained using RAWGraphs

Beginning with Bertin's Semiology of Graphics (Bertin 1983), the formalization of the principles of graphic communication started, which later transformed into structural theories of graphics to establish a bond between computer graphics and information visualization theories. Cleveland and McGill (1984) experimented with retinal variables (position, color, and size). More recently, the ideas and theories of Wilkinson (2012) provide a basis for visualization interfaces, Lyra (Satyanarayan and Heer 2014) and VegaLite (Satyanarayan et al. 2017), and grammar-based systems such as Polaris (Stolte et al. 2002), which extends the pivot table interface. Visualization production tools such as Lyra and iVisDesigner (Ren et al. 2014) enable the creation of various customized graphic visualizations based on conceptual modularity without writing code. Unfortunately, they support only a small set of visual forms and parameters that limit users.

Many visualization grammars, toolkits, and frameworks have been implemented from Wilkinson's grammar with the formalization of the grammar of graphics. The majority of visualization grammars can be described as declarative specifications, which only relive low-level details and allow users to produce a variety of visualizations using a maintainable number of building blocks. Users only need to describe the properties of components, such as data processing, scaling, marking, and encoding, to construct the final visual representation. They are generally grouped into low-level and high-level grammar. While low-level grammars demand specification for each mapping element, high-level languages encapsulate the properties of visualization construction (Tommasini et al. 2019). During the process, the data can be subjected to a set of transforms such as filtering and encoded using multiple visual channels like color, form, or any measurements of a selected shape. Data attributes are mapped to the characteristics of the visual markers according to the encoding. Low-level expressive grammars like D3 (Bostock et al. 2011), Vega (Satyanarayan et al. 2015), and Protovis (Heer 2009) assist designers in generating customized, explanatory graphics. They offer fine-grained control for data display, requiring the user to specify each mapping element. More recently, D3 became very popular, especially for web development. Protovis is an embedded domain-specific language implemented in JavaScript, and defining graphical marks such as bars, lines, and labels helps users specify data bindings to visual properties. Vega is similar to Protovis and D3 but provides transformation with support modules. Users can also share and reuse the product via an interactive connection between input data and mark characteristics. On the other hand, high-level declarative grammars such as Vega-Lite, and ECharts (Li et al. 2018a, b) are better for exploratory visualization. Encapsulating the details and properties, they focus on the rapid production of visualizations. There is also a declarative statistical visualization library that was developed for Python named Altair (Satyanarayan et al. 2017).

Creating visualizations using APIs requires background knowledge, and it can become a grueling process. Therefore, frameworks have been created for rapid and better abstractions. After introducing InfoVis, toolkits that provide a collection of visualization tools similar to Java-based visualization libraries were developed, such as Prefuse (Heer et al. 2005). In addition to provided operators and abstractions of libraries, Prefuse and Flare (Gal et al. 2014) allow users to define new ones with fine-grained monolithic units to provide customization. The graphics processing unit (GPU) powered visualizations that have been widely used in scientific visualization, and their use in information visualization increased in recent years due to improvements in rendering performance. For example, Stardust (Ren et al. 2017) utilizes those improvements. It does not provide a new visualization grammar, but it is complementary work for previous tools with more user-friendly building blocks, enabling the creation of both 2D and 3D visualizations. Pointing out the gap between artists and expert coders, a programmable integrated development environment (IDE) named VisComposer (Mei et al. 2018) has been developed, which uses tree-based visual structures similar to D3. VisAct (Wu et al. 2020) is another interactive visualization system that provides a high-level grammar for semantic actions and guides the users by including a wizard panel and a wide range of visual forms.

The effort to construct interactive toolkits or systems for information visualization had limited itself to more traditional 2D representations. Therefore, with already suitable 3D environments for immersive environments, scientific visualization has led to the development of virtual reality systems. A widely used framework targeted at scientific visualization applications is the Visualization Toolkit (VTK) (Hanwell et al. 2015), an extensive library for displaying and interacting with data. Using VTK in the VR environment became possible with the development of OpenVR. This API supports SteamVR, developed by Valve. Thus, the framework became compatible with Oculus Rift and the HTC Vive.

Researchers have recently paid more attention to exploring immersive environments for non-spatial data. Although designed for gaming applications, the Unity game engine has become a standard platform for developing immersive environments. IATK (Cordeil et al., 2019) and DXR (Sicat et al. 2019) toolkits were developed to build immersive data visualizations based on the Unity game engine. DXR is a toolkit that uses a declarative framework inspired by Vega-Lite and provides interaction and extendable visualizations with additional classes and applications that can be exported to various platforms, including mixed reality (MR) on Microsoft HoloLens, and VR headsets. On the other hand, the API of IATK is similar to D3, and graphics grammar allows easy construction of visualizations. Emerging from previous applications like ImAxes (Immersive Axes) (Cordeil et al., 2017a) and FiberClay (Hurter et al. 2018), IATK allows users to create visualizations by three-dimensional axes, but it does not provide collaboration. Fiberclay, being a flagship example, was evaluated with air traffic controllers, and it displays large-scale spatial trajectory data in 3D, where it provides selections of 3D beams for constructing queries. ImAxes is an open-source information visualization tool that implements scatterplots, histograms, and explorable parallel coordinates based on manipulating reconfigurable axes using natural interactions.

Transitional interfaces (TIs) aim to provide interaction modality to extend the capabilities of a single isolated interactive system and allow users to choose the most appropriate technology for the task within the reality-virtuality continuum. As an example of transitional interfaces, Hubenschmid et al. (2022) provided a framework called Re-Live, where they created a hybrid use between a 2D desktop interface and immersive 3D VR. Synchronization between the ex situ desktop view with the in situ VR visualization facilitates the user experience by combining the advantages of non-immersive and immersive approaches.

4.2 Data visualization

Data visualization represents data or information in a graphical format that enables the audience to identify patterns, pull insights, grasp the true meaning of information, and communicate more quickly and efficiently (Aparicio and Costa, 2015). While diverse areas benefit from the graphic representation of data, data visualization also feeds on several disciplines. Transformation of the data into compact and understandable information in pictorial format became possible with the contribution of psychology, computer sciences, statistics, graphic design, and many other disciplines. Flourishing with knowledge from multiple backgrounds, the adaptability and scalability of the data visualizations have increased. For example, continuously accumulated data in various domains eliminates the traditional methods, which are currently insufficient for large batches of data. Different methods, like machine learning, can be applied to conduct analyses and create more efficient visualizations with varying attributes. Existing 2D methods of data visualization can contain only a small number of correlations between a few metrics. Thus, to perform analyses on high-dimensional data, many individual charts are required for comprehensive presentation, eventually preventing comprehension of correlations and patterns.

Direct conversion to 3D does not offer enough clarity since problems of 3D, such as occlusion and perspective distortion, may lead to wrong interpretation in analytical use cases. Although 3D graphics can be compelling, they can be considered unnecessary according to data and visualization structure. To enhance the data visualization experience, it is necessary to have additional techniques to display information in greater depth. Graph layout algorithms and clustering algorithms are extensively used for complex network visualizations. Clustered data needs to be converted into comprehensible visualizations. Clustering algorithms help users detect patterns quickly and assist them in inspecting high-dimensional datasets. While clustering and data reordering methods are essential for complex data visualizations, various visualization types are used due to their multiple channels to encode data. Pixel-based, matrix, and heatmap visualizations are widely used since they provide color attributes that enhance visual perception. According to a survey (Fonnet and Prie 2021), position and visual channels such as textures, colors, and shapes are commonly used to encode multidimensional data. For example, Drogemuller et al. (2017) preferred spheres for entities, lines for relationships, and circles for cluster nodes to construct a network visualization using a spring embedder layout.

Interactivity is one of those aspects that enhance 3D environments. Virtual reality changes how we interact with and interpret data, and visualizations should support several activities. VR should enable an exploratory analysis to discover the input data and its features, tendencies, and relations. To help the user to reject or accept the constructed hypothesis, it must offer confirmatory analysis. The presentation of data should be given in a structured manner to reveal the hidden features which cannot be presented via other mediums or platforms. In the study of Okada et al. (2018), the visualization system generated two layers for spatiotemporal data. The first layer presents a spatial model with an adjustable scale according to worldview and minimap options. The second layer represents the frequency with cubes with different colors and transparency. The combination of multiple visualization techniques in single VR visualization improves the information flow and creates more engaging experiences.

As a communication medium, another critical element of visualization is interpretation. Design and interpretation choices of visualization can alter the users' ability to comprehend the data or lead to misunderstandings. Therefore, a good visualization should protect the balance between esthetics and functionality. Sun et al. (2019) provided dynamic visualization of the time series along with geographical attributes and made visualizations available to observe the relation between accumulation, wind direction, time, and location. They used an aggregation table, calendar view, day bar graph, and line plots to visualize data coming from air sampling sensors and meteorological data. Recently, three-dimensional techniques widely used for scientific visualizations have provided distinctive cases for more effective data visualizations. Krokos et al. (2018) utilize auto-encoders to create spatiotemporal volumes from non-spatial queries. According to their work, volumetric data can provide more convenient ways to identify anomalies, groups, and patterns in Domain Name System (DNS) data.

Multidimensional data comprise independent dimensions, whereas multivariate refers to the inclusion of dependent elements. The primary objective of visualizing multidimensional data is to minimize the dimensionality while retaining as much of the original data as feasible. Dimensionality reduction methods are frequently used in multidimensional data exploration in machine learning, data science, and information visualization (Zebari et al. 2020). The representation of multidimensional data on a low-dimensional space using projection methods helps preserve specific data collection characteristics. To facilitate users to identify, locate, distinguish, categorize, cluster, rank, compare, associate, or correlate the underlying data, multivariate data visualization seeks to thoroughly understand the data distributions by exploring the interplay between multiple data features. However, utilized algorithms may perform poorly because of dimensionality or noisy data. Therefore, while presenting a refined version of the Immersive Parallel Coordinates Plots (IPCP) system, Bobek et al. (2022) prefer to use a wide range of clustering algorithms for multidimensional datasets. Also, they show the importance of feature selection by testing multiple feature selection methods.

Unlike 2D data visualizations, where the data are always presented from one perspective, VR exhibits potential uses for switching between perspectives. This creates different embodied cognition cases for users to interpret data in new ways. The ability to change perspectives creates more immersive experiences and precise insights. The focal point changes according to the user's movement in a virtual reality environment. Therefore, according to the user's perspective, the perceived distance of contents varies. The layout of the presented data can provide equivalent perception and ensure distribution in spherical space; Kwon et al. (2015) employ a space-filling curve layout together with spherical edge bundling. The perspective-based Observational Tunnels Method is another strategy that is offered by Jamroz (2018). The method combines a parallel projection in conjunction with a local orthogonal projection range that is limited by the tunnel's maximum radius. The observational tunnels approach considers projections of all coordinates taken collectively, producing a graphical image consequently. This solution makes it feasible to observe certain regions of space carrying dense information—which is not possible in the case of orthogonal projection. The ability to achieve a perspective-based view allows for observing several point sets. According to the comparative results of his study, based on artificially produced seven-dimensional data generated, the method provides more readable results and is an effective tool for the qualitative analysis of multidimensional data.

Different strategies, algorithms, alternative ideas, presentations, and the combination of those techniques enhance the visualization. Creating elaborative interpretations of complex data allows users to gain a deep understanding by seeing data in different ways.

4.3 Information visualization

Exploring the design space of spatial mappings for abstract data became a key theme of a new subfield of visualization called Information Visualization (InfoVis). Information visualization was built upon graphic designers, statisticians, human–computer interaction (HCI) researchers, and many others. The interdisciplinary field has been exploring the effective use of computer graphics for abstract data visualization and its interactive exploration (Fig. 4). Information visualization is the process of enhancing human cognition by providing mental models of information. Information from multiple sources is consolidated through visualization to create a single, impactful visual representation. Sustaining easy comprehension depends on the presentation of the data. InfoVis is the investigation of strategies for the intelligent and visual portrayal of complicated information in a way that best features the information structure and associated relations to facilitate understanding and ease during the time spent in its comprehension. Throughout the long term, it has been integrated with immersive settings, which is viewed as an alternative mechanism for both 2D and 3D depictions. The techniques that are used to transform data, information, and knowledge into interactive, computer-based visual representations assist users in understanding the data effectively.

4.3.1 Art, heritage, and architecture

After the first 3D documentation of archeological objects was realized by Leo Biek (Gettens 1964), many artifacts started to be exported to digital environments. With sufficient documentation for transmitting cultural heritage to future generations, which cannot be protected due to natural and artificial disasters, preservation in digital media has become a reliable method. The gaming industry and the recent development of low-cost devices which can provide powerful VR and AR applications propelled the digitalization era of cultural heritage institutions. The digitization process' final products serve not only for archaeological and architectural documentation but also for educational opportunities, exhibitions, virtual tourism, experimental studies on space, and analyses of artifacts. The development of technology that can capture and document heritage sites offers new techniques that substitute human interpretation, which requires more time and workload. According to the complexity, scale, and location of the subject of 3D digital representation, different methodologies can be used, such as laser scanning and photogrammetry. Also, several techniques have been developed to reconstruct an artifact, such as sculptures and paintings. These techniques include image sequencing, volume-based methods, and structured form motion algorithm (Sooai et al. 2017). On the other hand, preparation, presentation, and interaction of 3D digital content require meticulous work. Generated models are generally complex due to graphic requirements of details. Several geometric optimizations and compression methods have been developed to solve technical problems such as managing millions of polygons or processing time, while their main aim is not to comprise details and realism. For example, Fernandez-Palacios et al. (2017) offered a pipeline including many optimization techniques to create an immersive VR experience with digitally reconstructed heritage scenarios. Their work includes normal maps to transmit details to low-resolution models, unwrapping techniques to decrease the texture load, and the use of software tools to decrease the resolution for geometric optimization without reducing visible quality. Choromanski et al. (2019) established a VR system that utilizes terrestrial laser scanning and photographic images that belong to a baroque palace. They also tested various texture mapping algorithms to simplify the mesh geometry of models constructed with data gathered through different methods.

Another way of protecting and maintaining cultural heritage with digitization is through virtual museums. Schweibenz (1998) defines virtual museums as a collection of relevant digital objects to disseminate objects and

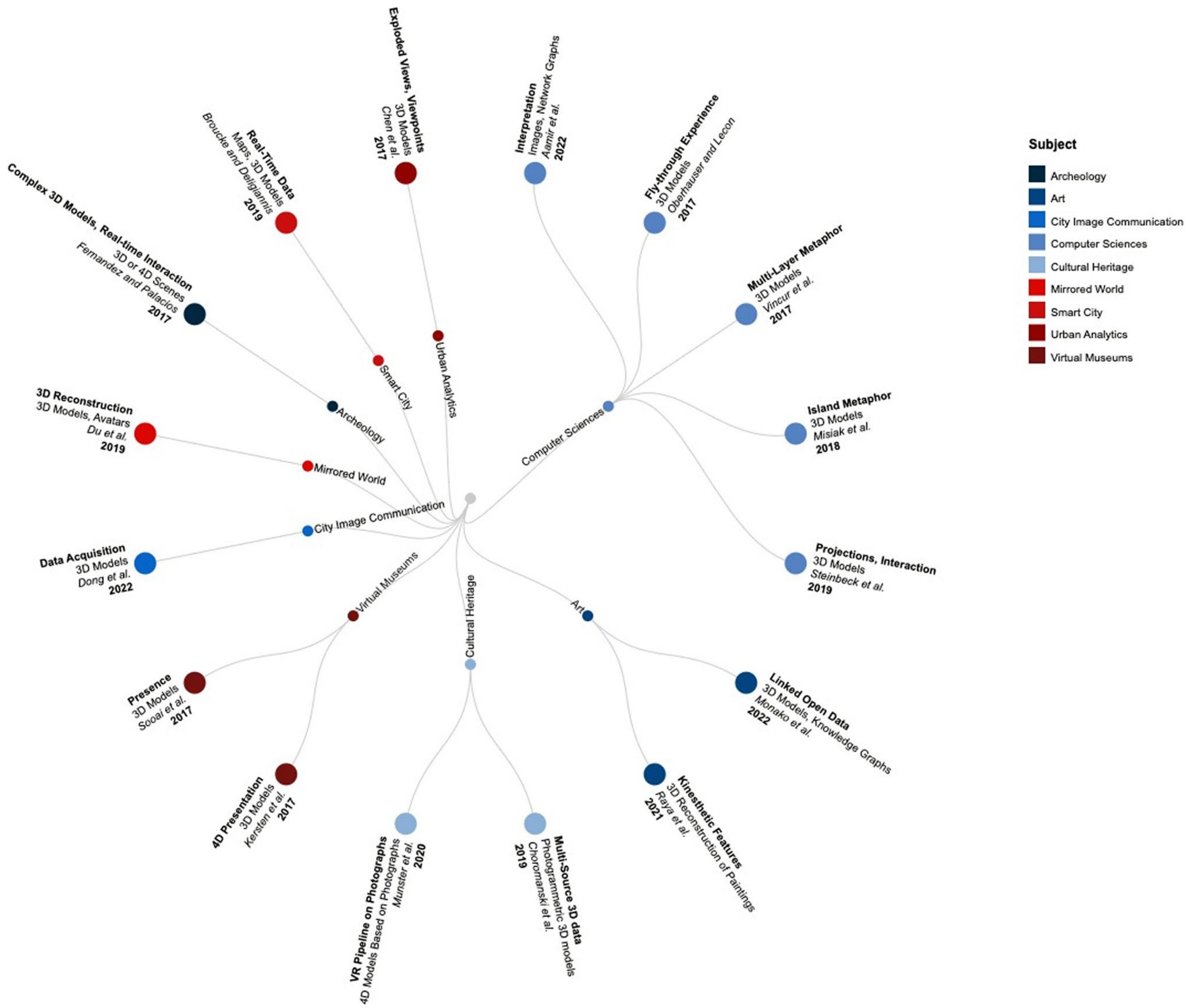

Fig. 4 Distribution of Information Visualization studies by the primary subject. The circular dendrogram was obtained using RAWGraphs

information without real place or space. To make art experiences more accessible, immersive, and engaging, digitally based strategies such as AR, VR, and Web3D have been employed. The construction of virtual museums is challenging due to its requirements, such as user interaction, environment and content, and design of the experience. Recent projects mainly focus on the recreation of an artifact or an entire museum collection with its architectural surroundings in a virtual environment. Even though the results of many studies are promising, the process of implementing an artist's universe is not an easy task. For example, transmitting a 2D art form into VR experience requires developers to add the parts of the painting not included in the original work, and duplication requires every detail to be modeled in 3D. Raya et al. (2021) reconstructed two paintings for VR, where the paintings became available for users to experience kinesthetic textures with an introductory approach.

The museum can be designed in a realistic form, duplicate an actual museum, or alternative methods can be used, but the final product should convey the intended information (Skamantzari 2018). The information can be given in different formats. For example, besides the realistic models, the virtual museum design of Kersten et al. (2017) includes guided viewpoints for essential positions and detailed information menus. Information is a set of entities, properties, and relations between them that can form a graph of nodes and edges, making graph structure a realistic representation of knowledge. Combining virtual exhibitions and graph abstractions enhanced the interactivity and made the complex relations of knowledge understandable in a context that traditional museums cannot present. Monaco et al. (2022)

created a customizable virtual museum where users can have a more active role in virtual exhibitions. Their construction process allows users to select data using Knowledge Graphs (KGs), personalize the museum by changing the layout, and select annotations. They also reported that construction time is highly related to the lighting settings after users' selections since it requires heavy computation. Therefore, they offer alternative lighting options.

According to a review paper (Zhang et al. 2020), VR technologies are employed in architectural domains in safety planning, design interpretation, collaboration, construction project management, education, planning, and human behavior and perception. In recent years, integrating Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools with VR has been promoted to maintain efficient communication and design processes and avoid conflicts in the above-mentioned areas. Architects and engineers use BIM for efficient design, management, construction, and operation stages. For example, on the effects of daylighting, Akin et al. (2020) developed an immersive design tool integrating BIM technology to improve visual perception and awareness during the design process. The 3D CAD models contain a large amount of information in 3D models, 2D drawings, and charts (Ivson et al. 2020). Munster et al. (2020) offer an automated pipeline to construct 4D city models from historical images to create browser-based VR applications for mobile, where the fourth dimension here is time. Utilizing CNN architecture, they generated models of buildings from images based on their floor plans. Attempts to engraft different fields also led to a wide range of subfields, such as immersive urban analytics. For example, Chen et al., 2017 proposed a method to apply visual analytics in the urban context using the exploded views and principles explained by Li et al. (2008).

The assemblage of VR technology and geographic information system (GIS) generated a new information system called VRGIS. VRGIS can support spatial data query, processing, storage, and analysis functions. Combining multiple technologies, such as Internet of Things (IoT) technology, VR, and 3D geographic information system (3D GIS), provides new ways for producing sustainable urban environments. Compound use of visual analytics and GIS systems allows an understanding of essential features, such as betweenness, closeness, centralities, and shortest paths in the urban design domain. However, the city scale and components generate graphs that are not workable to explore or understand. One way to solve this clutter problem is simplification and division of graphs. For example, Huang et al. (2016) generated a visual analytics system called TrajGraph to study and plan urban networks. They applied a graph partitioning algorithm to divide graphs into several chunks while conserving the necessary relations for objectives. Geollery (Du et al. 2019) is one of the studies that point out real-time challenges of the virtual representation of geospatial data and propose a method based on 2D maps. Instead of using expensive computational methods such as image-based modeling and the extrusion operation of 2D polygons and textures in real time, they allow a progressive creation of a mirrored world where they combine spatial resources with social media.

The smart city concept is proposed to optimize urban systems and form sustainable and efficient environments. According to Lv et al. (2016), a smart city's construction comprises information, digitization, and intelligence stages. Broucke and Deligiannis (2019) propose a VR platform on Brussels' smart city data, which shows a reduction in frustration level in the exploratory experiences of participants. Dong et al. (2022) conducted a detailed analysis to understand virtual reality requirements for multilayered data of cities. In parallel to the results of their analysis, they constructed a digital city simulation model based on multiple components and subsystems, such as model editing and restructuring models (MERM) and scene creation and roaming system (SCCM). Their process starts with the data collection and convolves into different formats to create a consistent platform. Most smart city projects aim to improve urban life and create environments to support efficient and effortless interaction for urban dwellers. The smart city concept also can be helpful in urban construction. In the construction process, it is crucial to foresee practical issues. It is also essential to understand spatial order, functions that are applicable, technical requirements, and production process. Considering the parameters and scale of a city, 3D visualizations and simulations can orient the decision-making process.

4.3.2 Computer sciences

Different visualization techniques have been offered to better understand software architectures, various algorithms, and computer science concepts. Studies focus on interpreting complex structures to understand different features and concepts related to the field. For example, visualization techniques have been employed to better understand and explain artificial intelligence (AI). Explainable Artificial Intelligence (XAI) is a recently developed technology aiming to enhance the understanding of AI from the eyes of humans. As part of this study, Selvaraju et al. (2017) offered to use Gradient-weighted Class Activation Mapping (GradCAM), which is a visualization method that benefits from the gradient of the target and produces localization maps on Deep Reinforcement Learning (DRL) algorithms. With the analysis of their study on Atari Games that includes visualizations of input states and selected output action, the role of the CNN layer can be understood. Another study that focuses on visualizing neural networks is Caffe2Unity (Aamir et al. 2022).

Combining the Caffe framework with the Unity game engine provides real-time interaction with the neural network on the image classification task. Their interaction method allows users to gain better insight into the complex structures of neural networks.

An essential constituent in computer sciences is the use of metaphors. High-dimensional visualizations with 3D representations benefit from metaphors that make knowledge more accessible and understandable. The assessment of the metaphor is related to the properties of the visualized field and the approximation of the notions of the related field. The design of the components related to specific features is crucial in this approach. One of the extensively used metaphors in computer sciences is the city metaphor. For example, the EvoStreets technique (Steinbeck et al. 2019) uses a city metaphor that visualizes hierarchical relations as streets. VR City (Vincur et al. 2017) consists of different layers to hold various entities using a layout algorithm. It includes connection layers for relationships, an authors' layer to show recent activities with waypoints, a city layer to represent classes, a code space layer to scan codes, and a UI space layer for possible actions. Oberhauser and Lecon (2017) provide space, terrestrial, and custom metaphors for fly-through experiences to encourage exploratory, analytical, and descriptive cognitive processes on code information. In IslandViz, Misiak et al. (2018) utilize an island metaphor to visualize the software architecture of a software system based on the Open Service Gateway Initiative (OSGI) in VR.

4.4 Scientific visualization

The recognition of graphics as a distinct field actualized with the achievements of powerful computers and photorealistic renderings has made scientists to use available visualization for scientific studies (Fig. 5). Visualizing scientific data are crucial for experts working on scientific domains and

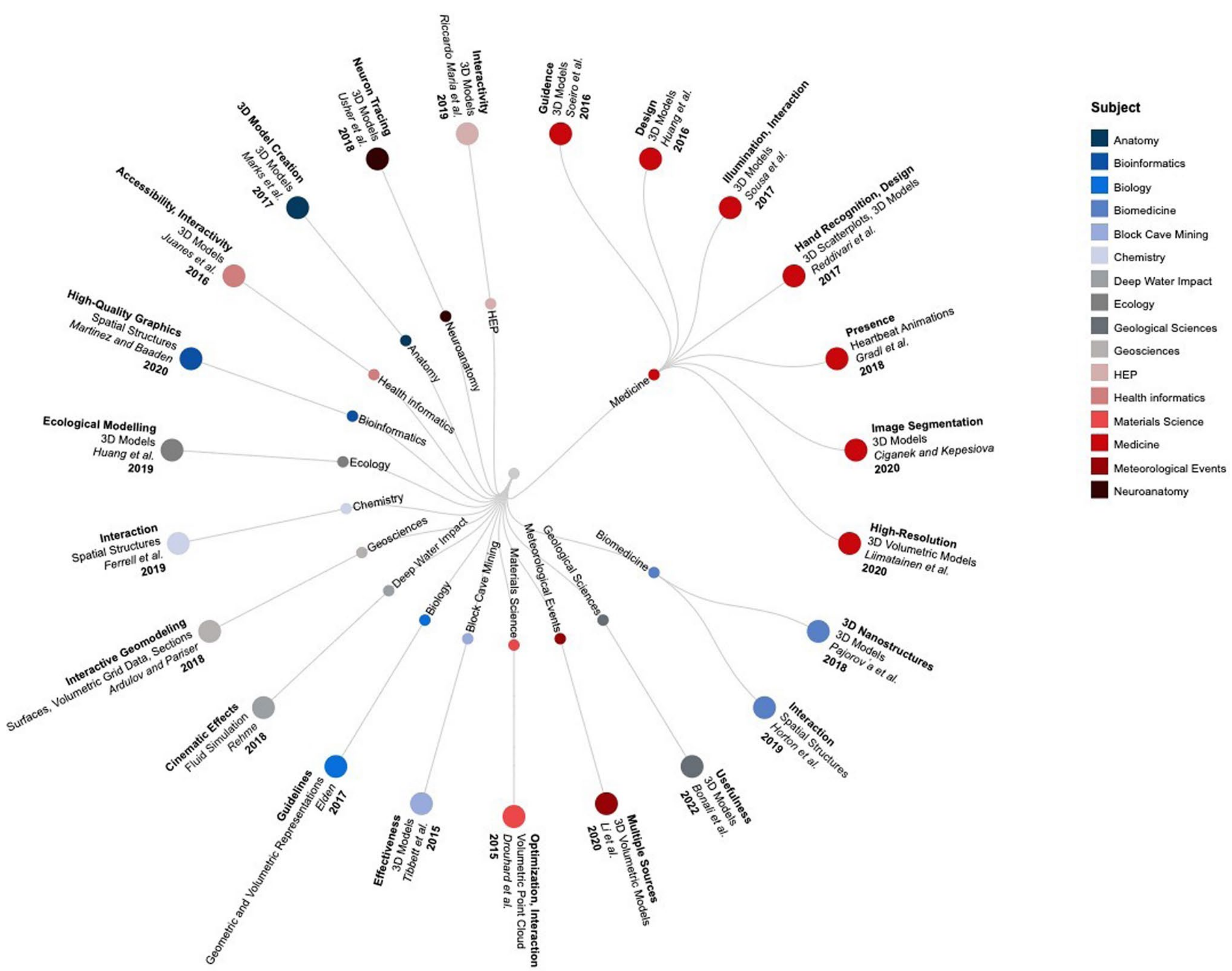

Fig. 5 Distribution of Scientific Visualization studies by their primary subject. The circular dendrogram was obtained using RAWGraphs

communicating with a general audience and students. Digital scientific visualizations were limited to two-dimensional representations. The development of rendering techniques made it possible to visualize and interact with scientific data in a 3D virtual world. This allows users to explore and interact with real-like representations that improve the comprehension capabilities of students and enhance public engagement.

Scientific visualizations can be complex and hard to compute according to the dataset due to high-dimensional and abstract data. They might require exclusive visualizations instead of traditional computer ones. Different 2D sections implemented with a conventional desktop and mouse may not be sufficient to construct a 3D understanding, which also differs according to the user.

4.4.1 Meteorology and earth sciences

Geospatial data are predominantly three-dimensional and/or time-varying. Consequently, traditional map-based geographic information science and technologies are complemented with other visualization techniques due to geospatial data's 3D and time-varying nature to collect, manage, and display global environmental data. Virtual reality environments offer space for visualizations of geospatial data at all scales, from local to global, and navigational methods that are practical and operational. To incorporate observational data into process-based models, efficient algorithms that can handle global-scale information extraction and spatial-temporal techniques are required. Virtual environments promise to enable scientists worldwide to communicate their data and research findings in an intuitive perspective, providing embodied experiences. Helbig et al. (2014) used VR to visualize atmospheric cloud data. Heterogeneous data in different dimensions are hard to convey by only showing the numbers. Using virtual environments and layering techniques, they illustrated the interactions between variables and correlations between different elements that can affect the data. Advancing over prior meteorological visualization systems, MeteoVis (Li et al. 2020) offers concurrent spatiotemporal meteorological data streams from multiple sources with a wide range of manipulation and exploration features. Challenges in geosciences are generally related to visual requirements such as size, shape, and structure. The shader interface provided by game engines is used to visualize the terrain within the geophysical context. This allows rendering higher resolution meshes in the field of view to give details and conserve the extended view with low-resolution meshes. Bonali et al. (2022) reconstructed selected geological environments using photogrammetry techniques. According to their extensive user tests, most students and academics agreed on the usefulness of VR technology. They also draw attention to the accessibility of data and experience by promoting immersive technologies.

Planetary-related models are inherently multilayered; therefore, maintaining a holistic approach for one-to-one 3D models may not be adequate. VRGE (Ardulov and Pariser 2017) addresses this problem with surface viewing, volumetric grid data, cross-sectional viewing, and surface editing. Presenting various species under climate change scenarios, Huang et al. (2019) provide perspective views from different heights and filters to retrieve information. Unlike a monocular system like traditional 2D screens, binocular systems in virtual reality display provide a true sense of depth perception and spatial relations. Thus, many industries have adopted these systems to test real-life scenarios in training. Serving for the mining industry software module, the block cave mining system visualizer was developed to contribute to the block cave's management cycle and operation. Allowing a collaborative environment and converting the complex context of the mining system into a graphical representation improves the understanding of seismic data (Tibbett et al., 2015). Interactive 3D data visualizations are also used in High Energy Physics (HEP) experiments. ATLASrift project (Riccardo Maria et al., 2019) aims to create an immersive experience for the atlas detector and experiment site. Utilizing Unreal Engine, they offer three levels with different modes of interaction. Although game engines are widely used for visualization when there is a need for an external library, as in the ATLASrift project, external libraries can be challenging.

Subjectivity, artistic elements, and the use of ornaments have always been burning questions in the visualization sphere. Especially for scientific visualizations, the presentation must preserve the data's accuracy, integrity, and credibility. On the other hand, some examples used argumentative elements without spoiling the data's essence, contrarily enriching it by engaging. For instance, Rehme (2018) employed artistic and cinematic elements such as shaders, shadows, camera movements, and slow-motion, which bring new functionalities to the end product.

4.4.2 Nanosciences

With the development of advanced techniques, nanoscience has proliferated. In the context of nanosciences, virtual reality has been employed for chemistry (Ferrell et al. 2019), materials sciences (Drouhard et al. 2015), biomedicine (Pajorov´a et al., 2018), bioinformatics (Martinez and Baaden 2020; Sommer et al. 2018), solution finding for medicine, and health care (Gradl et al. 2018). Visualization and transfer of the structural properties of nanostructures require different techniques.

Being an advanced approach, scanning electron microscopy (SEM) is one of those techniques in which the obtained data can be transferred to virtual environments. Several approaches that convert scientific knowledge to interactive 3D VR environment formats exist. Conversion can consist of artistic representations, direct visualization of data using technologies like electron microscopy, or simplified 3D models. As in the case of geosciences, different artistic features provided by game engines are employed to amplify certain features of small-scale structures. GEARS (Horton et al. 2019) utilizes surface shader properties to emphasize selected features of confocal microscopy data. There are also different rendering techniques available for rendering. For instance, while ray-traced volumetric rendering composes the object via simulating the light, geometric rendering takes advantage of 2D sections to construct a 3D model.

Material sciences extensively rely on volume rendering. Therefore, to overcome latency, optimized rendering algorithms are employed. To create intuitive interaction and natural controls before transmitting volumetric point cloud representation to a game engine, Drouhard et al. (2015) offered the use of extraction methods to reduce the size and provide better optimization.

4.4.3 Medicine and biology

Medical visualizations are generally composed of 2D mediums such as cross-sectional images and magnetic resonance imaging (MRI) scans. Therefore, 3D geometric models are reconstructed from individual slices (Reddivari et al. 2017; Soeiro et al. 2016; Juanes et al. 2016). Another method is image segmentation, which helps separate the pixels of the specified parts from the overall image. Ciganek and Kepesiova (2020) propose a segmentation and 3D model reconstruction method based on machine learning algorithms. Visualizations of medical or anatomical models consist of many complex subparts (Liimatainen et al. 2020). Thus, studies designed interfaces that include different features such as labeling, highlighting (Marks et al. 2017), distinct colors, selective visualization (Soeiro et al. 2016), and navigators (Juanes et al. 2016). Also, to solve depth perception problems in rendering photography effects, depth-of-field (Martinez and Baaden 2020) and gradient shading (Usher et al. 2017) are used to sustain depth cues. Virtual reality can assist the diagnosis process by providing appropriate conditions. To reduce diagnostic errors in radiology, Sousa et al. (2017) designed a virtual reading room where the reader can adjust the illumination and ambient light while displaying luminance.

Some studies include different approaches and subjects, such as medical education (Huang et al. 2016), hand recognition (Reddivari et al. 2017), smartphone applications for anatomy (Juanes et al. 2016; Soeiro et al. 2016), and biofeedback (Gradl et al. 2018). Although game engines are employed by most of the studies due to graphics performance, physics, and ease of deployment to VR, game engines may not be proper for scientific visualizations, as examined in the study of Elden (2017). Elden (2017)'s study includes three demos; artery, rat brain, and genome. According to the requirements of the demos, different representation techniques were chosen. Thereby, the study became convenient for constructing guidelines. As reported by the study, game engines are designed for geometric visualizations, and their priority is not accuracy but speed, which makes game engines unreliable.

4.5 Collaborative VR

Collaborative Virtual Environments (CVEs) provide remote and collaborative interaction on various data representations independent of the users' physical location. Within a comprehensive spatial environment, users can train, review and discuss using different information channels (Churchill and Snowdon, 1998). Previous CVEs included information visualization, teleconferencing, simulation, and social events. To design CVEs, the most commonly employed technologies were large spatial immersion displays and Virtual Environments (VEs), such as CAVEs and HMDs. These technologies have many differences, such as resolution, presence, and freedom of movement. Cordeil et al. (2017b) conducted a user study consisting of a series of tasks on 3D network visualizations to compare those in VR platforms. According to the results, while there is no major difference in accuracy and experience, HMDs offer faster interaction. Therefore, modern HMDs are preferable for immersive visualizations instead of expensive CAVE-style facilities. CVEs aim to provide enjoyment, social interaction, and presence, which provide cognitive benefits.

Collaborative environments aim to connect multiple users more naturally and increase users' awareness to break down the isolation. The environment can require participants to be co-located or remote and present different interaction levels, such as symmetric or asymmetric. Co-located studies are preferable due to network limitations. However, they enhance people's interactions within a single space and limit VR opportunities. Asymmetric applications do not offer the same interaction possibilities to all participants. For example, while one user interacts using a VR head-mounted display, another user might experience the VR through traditional screens. The interdependence of users is inextricably linked to the special demands of visualization. Therefore, different degrees of asymmetry can be used in the setup depending on the visualization and collaboration mechanics. The use of different devices has already produced an asymmetry in terms of visualization. According to the roles of the participants, this asymmetry arising from hardware differences can be a conscious design choice. For instance, ShareVR (Gugenheimer et al. 2017a) presents an experience where Non-HMD and HMD users can interact with each other and the environment together. They implemented several cases to construct guidelines for co-located asymmetric VR experiences. According to the results of their study, shared physical space and physical interaction enhance the experience and enable novel interaction methods for VR and VR games.

Another important interaction decision is the determination of viewpoint. This decision can be divided into two parts for collaborative environments. The first step is determining where a user is looking in the scene, and the second is deciding independence between users. Although the general tendency is to use the "what I see is what you see" principle with only one shared view, the environment can require or provide multiple views for different users, either synchronously or asynchronously. For example, PlottyVR (Brunhart-Lupo et al. 2020) is composed of various statistical tools and libraries and offers a myriad of visualizations. Providing multiple viewpoints for different users enables each user to utilize different types of visualization. In some cases, the environment facilitates asymmetric collaboration and multiple viewpoints. Pointing out this requirement in design and architecture, Ibayashi et al. (2015) propose a system named Dollhouse VR that consists of a multi-touch tabletop device to manipulate the environment and HMDs to provide an internal view. Xia et al. (2018a) created a scene-editing tool to support collaborative workflow. The tool, Spacetime, introduces three interaction concepts to enable users to easily manipulate the environment: container, parallel object, and avatar objects.

Companies that use the advantages of remote working have also implemented virtual reality to benefit from interaction possibilities that existing communication tools cannot offer. Therefore, commercial virtual tools for teamwork have emerged, such as VISIONxR (Xia et al. 2018b). It allows multiple users in multiple locations and on multiple devices. These virtual platforms aim to improve quality and effectiveness and create easily adaptable environment options and interfaces. Virtual collaboration is still less effective than sharing the same physical location in terms of expressive communication, including voice gaze, gestures, facial expressions, or full-body movements. According to Fussell and Setlock (2014), visual actions are way more important than speaking for communication in virtual environments. Therefore, to convey messages and provide more effective and efficient communication, avatars and hand gestures were started to be used in virtual environments to replace the expressions belonging to the physical world. To increase the sense of physical co-presence, Amores et al. (Amores et al. 2015) present an immersive mobile platform, ShowMe. Using depth sensors and cameras enables users to see their hand gestures and hands, making it easier to work collaboratively on a physical task. Orts-Escolano et al. (2016) present a system to improve the audio-visual quality of communication and interaction with remote users for AR and VR interaction. Holoportation uses depth cameras to create high-quality, real-time 3D reconstructions of an entire space, including people and objects. The system allows for the real-time transmission of 3D models to remote users, creating a sense of being in the same physical space as other participants.

HMDs require users to have their hardware equipment; thus, collaborative environments are composed of not one but several worlds, each for one user. This situation creates two types of users; authorized users and connected users. While the authorized user has direct control over the world with local machines, the world of the connected user is continuously synchronized. Also, having multiple users share a virtual space requires virtual representations of individuals. Using the ability to distinguish users as an opportunity, Hoppe et al. (2021) presented ShiSha, which uses shifted but shared perspective modification for the remote virtual environment. Therefore, it enables users to observe from the same point of view while seeing other's virtual avatars in their virtual worlds. CollaboVR (He et al. 2020) provides both co-located and distant interactions and enables users to share the same viewpoint. The system allows users to collaborate on drawing and creating 3D models and procedural animations in real-time, offering multi-user communication. It includes various layouts and interaction modes that enable users to arrange themselves and their input in different ways, including a "physical side-by-side white-boarding" layout, a "face-to-face communication" layout, and a "lecture with a presentation" layout. With the changes in layouts, the system offers both different and shared viewpoints. Having multiple users share a virtual space requires virtual representations of individuals. Another work that accentuates the potential of visualizations of avatars is Multi-User Cell Arena (MUCA), where (Bailey et al. 2019) offer customizable avatars. Embodiment is the foundation of many social VR experiences and positively affects presence. Customizable VR avatars have the potential to increase the sense of belonging.

4.6 Training and simulation

VR provides the capability of training people from different professions to deal with complex situations and prepare them for their roles in real environments. It has become an essential training tool for soldiers, doctors, drivers, and pilots. Also, it is used for patient rehabilitation and disaster management. Recently, virtual reality has started to substitute traditional rehabilitation methods. Proposed methods for this transition blend the various hypotheses coming from different areas. For example, based on hypotheses stemming from neuromotor rehabilitation, game development and design took shape together in Rehabilitation Gaming System

(RGS) and Personalized Training Module (PTM), which was developed to adjust task difficulty. According to the intended results, rehabilitation requires specialized visualization techniques. For example, in developing motor function awareness, vision is competent to give feedback, and neuromotor rehabilitation may depend upon movement and environment visualization (Tsuji and Ogata 2015). To meet these requirements, TRAVEE (Voinea et al. 2015) offers 3D scenes for neuromotor rehabilitation and a user-friendly interface that positively affects user processes.

According to Freina and Ott (2015), the main motivation to use VR is its ability to provide experiences for context or environment that are inaccessible, problematic, or dangerous. A collection of reviews in the study of Mikropoulos and Natsis (Mikropoulos and Natsis 2011) reported that in comparison with other systems, VR is more advantageous by only a sense of presence and dynamic 3D content, which have a positive impact on learning. Majority of the studies on training collected around the areas of medicine (Chang and Weiner 2016), safety (Xu et al. 2017; Jeelani et al. 2020a), industry (Grabowski and Jankowski 2015), and crisis and emergency management (Ronchi et al. 2016; Kwok et al. 2019; Molka-Danielsen et al. 2015; Surer et al. 2021), and rehabilitation (Joo et al. 2020; Yates et al., 2016).

As VR training scenarios mainly involve computer-generated 3D graphics, 3D modeling is important in creating virtual training environments. There are several options for developers to create related content. Advanced 3D modeling software, such as 3ds Max, Rhinoceros, Maya, and Blender, provides developers to create realistic environments. In addition to those tools, asset stores of the game engines and 3D model libraries present a variety of options. The reusability and customizability of 3D models decrease the cost of systems. To achieve high levels of immersion and presence essential for a training environment, the artificial generation of actual information needs to stimulate the major senses. Therefore, to sustain a fully immersive experience, stereoscopic displays, motion-tracking hardware, and input devices are employed. The release of motion-sensing controllers primarily developed for games such as Nintendo Wii Balance Board, Sony Playstation Move, and Microsoft Kinect has promoted the evolution of training. With the contribution of additional devices, VR training has expanded to a larger sphere, including dance training, aircraft controls, and rehabilitation.

Investigation of virtual reality for practical use gave birth to new terms such as virtual factories, which are simulated models that consist of many sub-models to represent the cells of a factory. This integration offers planning, improvement of product, efficient planning phase, decision support, testing, and controlling the systems. In the context of Industry 4.0, different visualization techniques, dynamic virtual models, and types of simulation, such as discrete event or 3D motion simulation, are employed by automotive engineering, aerospace engineering, mechanical engineering, and medicine. VR training is often preferable for medicine since it offers emergency management, cost-effectiveness, recursiveness for tasks, and remote surgical training, which requires haptic devices due to physical procedures. To manipulate virtual objects via haptic devices, in addition to geometry-based modeling, medical procedures require physics-based modeling to simulate deformable objects (Escobar-Castillejos et al. 2016). However, the animation of deformable objects in virtual reality environments is still a challenging problem, and an efficient physics-based method for virtual object interaction requires computational complexity.

Deformable body simulation with a physical foundation has been a prominent study area, particularly in the areas of game technologies and scientific visualization. In general, the proposed approach must be capable of accurately modeling objects with various material qualities, handling collision detection and collision response, and accurately updating the geometry and topology. To this end, researchers are still working to improve accuracy, robustness, and processing efficiency while keeping high-fidelity renderings (Yin et al. 2021). The physical interaction with the virtual objects needs to be realistically simulated to be convincing. This is especially important for the training scenarios that require detailed hand interaction, such as surgical training. Actual hand motion leads to unstable results in physics engines which cause interpenetration. Most proposed interaction approaches are simplified to avoid realistic simulations' complexity and error margin.

Initially, the majority of the approaches were based on meshes. To address the problems of mesh-based methods, meshless methods and hybrid techniques have been proposed to offer more alternatives to avoid drawbacks. Mesh-based approaches concentrate on increasing computational effectiveness, reducing the time needed for calculations, and effectively controlling topology changes while optimizing the quantity and quality of meshes (Wang and Ma 2018). Mesh-based methods may cause distortions in some circumstances involving significant deformations, necessitating mesh reconstruction, and substantially compromising the solution's accuracy. Techniques for meshless modeling, such as point-based approximations, successfully manage deformations and interrupted topologies. They can deal with the discontinuity issue without the instability problems of re-meshing. However, the complexity of the computations needed to solve the equations using meshless methods is higher. The Finite Element Method (FEM) was introduced to computer graphics by Terzopoulos et al. (1987). Although FEM is capable of handling complicated geometry and is physically correct, its high computational cost makes it unsuitable for real-time simulation. Another method, metaballs, was initially introduced and used to represent more complex shapes by Blinn (1982). Later, this method is extended to human body modeling and deformations. In essence, metaballs, often referred to as blobby or soft objects, can be thought of as particles, and in close proximity, they have the capacity to form a contiguous entity. Being surrounded by density fields, they can efficiently handle blending operations. This method improves computational performance since it can describe complex geometries with a minimal number of elements.

Hirota and Tagawa (2016) developed a real-time simulation of a deformable hand model based on FEM to enhance object manipulation in contact simulation. To solve the issue caused by polygon modeling, they combined particle-based physics simulation using the metaballs method to depict the smooth surfaces of the objects. Bender et al. (2015) introduced a constraint-based method for deformation simulations where the potential energy is constructed as position-based dynamics (PBD) by utilizing a continuum-based formulation. Solving the geometric constraints iteratively, PBD directly alters the position of deformable objects rather than requiring indirect information, such as velocity and acceleration. It is applicable to both mesh and meshless forms. PBD offers robustness and controllability, allowing it to be employed in interactive deformation simulations such as liquid simulations and cloth simulations. Although PBD's precision is relatively limited when compared to other approaches, such as FEM, it can offer a better visual experience. Yu et al. (2020) present a real-time suturing simulation framework that can manage the complex interactions between surgical equipment, such as a needle and soft tissue, that are both deformed by position-based dynamics with different restrictions. According to their experimental findings, the technique can provide real-time performance with a high level of visual realism and tactile accuracy, although occasionally, PBD suffers from physics and produces inaccurate results.

Pan et al. (2015) suggested a hybrid physical modeling methodology for digital organs via metaballs and meshlesh methods to enable adaptive topology modification and cutting surface reconstruction. They used a fine surface mesh with highly accurate geometric structure and texture to depict the outside structure of the organs and a set of overlapping spheres to represent the internal structure. They employed PBD to enable physical modeling capabilities so that the metaballs-based digital organs could actively engage in dynamic simulation. Although the simplified geometry of metaballs affords fewer details for interior structures, according to results, the approach can effectively reduce the computational cost during dynamic simulation. However, this method is ineffective for objects with sharp edges, and the physical accuracy of our deformation method is lower than FEM.

Despite a large body of the literature on various techniques for producing accurate models to simulate fluids, a comprehensive and realistic 3D fluid dynamics solution remains elusive due to a lack of resources to facilitate complex simulations. The equations' complexity necessitates extreme simplifications for interactive simulations. Rigid-body coupling is also required for most simulations, which includes forces such as buoyancy, drag, and contact reactions such as splashes and dynamic and static entities. For discretization, grid-based and particle-based methods are widely used. In grid-based methods, either complex adaptive grids are needed, or the whole environment needs to be simulated. Particle-based methods like Smoothed Particle Hydrodynamics (SPH) are increasingly adopted for large-scale fluid simulation in interactive computer graphics (Liu and Liu 2010). However, high-quality real-time surface rendering for such dynamic particle sets is challenging in interactive applications. Generally, particle-based liquid surfaces can be represented by a level set based on an implicit function to render liquids realistically and then extracted as polygonal meshes. To create simulations based on physically correct computation, various approaches have been proposed, such as multi-resolution mesh modeling (Yang et al. 2005) Perfectly Matched Layers (Liu et al. 2013), hybrid water simulation method that combined grid and particles-based approaches (Chentanez et al., 2010), Lattice Boltzmann Method (LBM) (Schreiber et al. 2011), Secondary Distorted Textures (SDT) (Li et al. 2018a, b).

To improve human behavior under artificial and natural disasters, simulations such as hurricane flood for analysis and control, fire safety, and earthquake simulations to assess human perception and behavior (Gamberini et al. 2015) have been designed and used. Emergencies are unexpected events that require a rapid and effective response. Evaluation of the situation and the reaction time are key factors for a successful pre-evacuation or action. Simulations of different emergency cases provide anticipation to assess the situation, awareness, and improvements in action time and behavior. For example, according to (Rosero 2017), most participants present unsuccessful fire growth estimation results. Simulations that are physically based improve visual behavior, but the absence of synchronous sound degrades the user experience. In the past, the recorded sound was frequently used to address the issue of auditory presentation; however, it is not feasible for dynamic circumstances as it requires manual intervention, and it is challenging to anticipate most interactive activities under dynamic conditions in advance. Due to the nonlinearities of fluid motion, the sounds produced by fluid-rigid engagement are more difficult to simulate and synchronize than those produced by rigid-rigid interaction. To improve sound authenticity and real-time performance, real-time sound synthesis methods for rigid-fluid interactions were studied by Cheng and Liu (2019). They proposed a modified granular synthesis technique that generates complex sounds using small sound snippets. In order to eliminate the repetition in the analysis of the complex motion of fluid particles, this multi-force variant of the granulation algorithm incorporates haptic forces to steer the sound synthesis. In order to effectively handle low-frequency data, Liu and Yu (2015) proposed using the Fourier Transform. The low-frequency content was then enhanced with middle- and high-frequency wavelet features to create the fire sound. They created a method for real-time acoustic rendering that improved computational efficiency and quality of the audio interpolation, leading to more immersive virtual reality scenarios. However, their method does not include different solid combustibles; therefore, the study does not address the discrimination of such materials.

The learning approach and nature of virtual environments made interaction an essential characteristic, including multifaceted features such as manipulation navigation. Additional to those features, personalization approaches and adaptive technologies should be preferred to increase the effectiveness of VR-based training (Jeelani et al. 2020b). Utilizing the advantages of game engines, Shamsuzzoha et al. (2019) propose a framework consisting of five stages, from database to evaluation for industrial training and maintenance. Their prototype includes minimaps, blinking exclamation marks for attention, realistic visual effects, and an IoT screen to interact with the system, which are visualization preferences that make the interaction and information flow possible.

Despite the advantages of contributing to cognitive and psychomotor skills and helping users gain control over emotional response, virtual reality-based simulators that train individuals for high-risk industries remain questionable due to cybersickness and technological challenges. Areas such as aviation, firefighting, military, medicine, and manufacturing require a high level of realism to reach a certain level of success. Simulators may not efficiently represent uncertainties that result in oversimplified training environments. Another problem is that simulators are developed by software developers who are not experts on the selected subject most of the time. Therefore, the majority of studies in this branch focus on these problems. Vahdatikhaki et al. (2019) criticize most construction training simulators as unrealistic due to static site representations. Their framework offers four stages; context capture, context generation, context-user interaction, and context-based assessment. Although this process was proposed for construction site simulations, it applies to a wide range of cases requiring context-realistic environments. Besides, the ease of use and reason behind the extensive use of game engines is achievements in approximation to reality, especially with the particle system tools offered. To examine fire simulations, it is certain that smoke's realistic spread and diffusion process is crucial. Smoke visualization requires high computer performance and a high level of realism, which can be provided through game engines.

4.7 Web VR

Web services have become the primary data source, providing access to information anywhere and anytime. However, web browsers are limited in many cases, and most of the studies focus on solving those limitations. Due to the rendering capability of web browsers, presenting large-scale and real-time visualization demands a great deal of work. Yan et al. (2020) employed different online real-time fire training techniques to solve this problem. They prefer downloading the data gradually while the viewpoint changes and converting virtual people to lightweight versions. They employed a technique called "clone" rendering. In situ visualization or processing, the techniques where the data are visualized in real time as simulation generates it, are used. Therefore, it does not involve storage resources; it is a natural solution for data transfer. Since it is a real-time generation, users can interfere with analyzing immediate effects.

VRSRAPID (Mascolino et al. 2019) web application uses extensible 3D virtual reality models (X3D) for interactive scientific computing. It is a collaborative and interactive environment designed for nuclear systems supported with real-time simulations. Traditional nuclear modeling and simulation tools are mostly built upon deterministic or statistical methods. Deterministic solutions are memory intensive and require significant computation resources. On the other hand, statistical approaches, such as the Monte Carlo method, may lead to statistical uncertainties. To build an accurate and real-time model, they use RAPID Code System and generate the X3D models at the end of the calculation.

With the increased importance of network environments based on VRGIS, the WebVRGIS engine (Lv et al. 2016) offers support for data publishing, transmission, and multiple users using and solving the problems of peer-to-peer (P2P) technology. Spatial analysis requires three-dimensional visualization of a largescale and multi-source urban landscape. Due to the computation workload and required memory, rendering massive data in real time are troublesome. They used an interactive rendering system and visualization optimization technologies such as texture mapping, automatic level of detail, occlusion culling, and frustum culling to solve this problem. On top of this work, Li et al. (2016) offer to use the WebVRGIS engine to analyze and visualize real-time dynamic traffic data. As it is understood in the previous sections, most scientific visualizations rely on volumetric visualizations, especially in medical studies. To visualize mesh and volumetric data captured using 3D medical scanning in VR, Kokelj et al. (2018) developed a web-based application. Using the rendering pipeline of the Med3D framework, they used the volumetric ray casting technique, which performs calculations using output images.

NeuroCave (Keiriz et al. 2018) is a visual analytics tool that offers interactive methods and visualization choices for exploration. It enables users to distinguish regions and their functions using a color scheme. Instead of using realistic rendering methods, they construct a connectome using different platonic solids. To simplify the rendering process, ProteinVR (Cassidy et al. 2020) utilizes game-like camera movements where the objects are stable, and only the camera can move. Thus, they were able to use pre-calculated shadows and textures to advance the performance of the browser.

For more abstract cases, libraries and frameworks allow users to construct 3D visualizations by mapping the datasets that are obtained from external sources. Following the Shneiderman mantra, the web-based ExplorViz (Fittkau et al. 2015) tool presents a software city metaphor with gesture recognition for translation, rotation, zoom, selection, and reset tasks. Vria (Butcher et al. 2019) prefers 3D bar charts for data exploration and analysis due to their simplicity. Aiming to explore visualization methods for health data, Hadjar et al. (2018) propose a prototype application that utilizes several libraries and an A-Frame framework. Web analytics include charts, graphs, diagrams, animations integrated into visualization systems, and a combination of other visualization techniques. Using A-Frame allows developers to create interactivity based on ray casting and animating objects to efficiently interpret a multidimensional dataset.

4.8 Games, visualization and VR

Video games are a collection of information and extensively rely on the presentation of information which holds various attributes that change according to state. Possessing a large amount of data, games played in the digital world are more complex and have different needs than games played in the physical world that are easily comprehensible. According to (Polys and Bowman 2004), visualizations in games should be functional and pleasing instead of focusing on utility. Their developed framework proposes five elements to identify visualization techniques: primary purpose, target audience, temporal usage, visual complexity, and immersion.

Data visualization has been used in games for generations to create continuous communication. While visualization components in older games are more straightforward and generally transmit gameplay data, they are used for multiplexed situations in modern games. Representations like bar graphs and tree diagrams related to information visualization widely occur in games; however, the entertainment aspect makes a difference in implementation. Beyond the implementation details, the utilization of virtual reality in the video game industry has created the need for more radical differences. Although pioneering commercialized virtual reality video games presented with the release of Sega VR and Nintendo's Virtual Boy, they were considered unsuccessful in the nineties. The process began in 2016 and was followed by the introduction of various products such as Gear VR (Oculus), HTC Vive (HTC and Valve), PlayStation VR (Sony Interactive Media), and Samsung Gear VR had achieved massive success by offering major novelties for video games.

Virtual reality games differ from traditional video games in terms of the level of immersion and type of interaction with virtual content. The decrease in connection-level between the outer world and the inclusion of body and hand movements provide innovative gaming experiences, which require new techniques for visualization of the virtual world. The interaction does not only occur between HMD users, but co-located participants can also interact. VR game ShareVR (Gugenheimer et al. 2017b) offers asymmetric interaction between HMD and Non-HMD users. Recent visualization research and studies involve additional interface features, adaptive hints, context-sensitive tutorials, and new approaches for player navigation. To make 3D manipulation easier in VR games, Rachevsky et al. (2018) offer to graphically represent the player's gestures as a part of the interface.

4.8.1 Visual realism and presence

Slater et al. (2009) proposed a division between components of realism as geometric and illumination. While geometric realism considers the properties of virtual objects, illumination realism deals with the convenience of lighting. Most of the existing studies and discussions recently conducted ground on Slater's theoretical framework of the place illusion (PI) and the plausibility illusion (PSI) in virtual reality and the sub-components of geometric and illuminations realism. Slater has argued on responses and defined two types of illusions based on the credibility of the events and the places. The PI mechanism in VR games endeavors to present game objects and places to increase presence. PSI mechanism offers persuasive game events and activities while the player actively engages with the simulated environment with a large field of vision. Beyond the visual, VR systems should offer auditory and haptic displays to sustain PI and PSI effectively. Impact levels of PI and PSI can vary according to the main objective of the environment. For example, Lynch and Martins' (2015) survey study examined the fright experience in immersive VR games. Later further categorized fear elements and identified the strategies and reactions toward fear elements. According to the results of their study, PSI elements trigger a higher level of fear response than PI elements. Another study conducted on the works of Slater complements (Hvass et al. 2018) the suggestions on the effects of visual realism. The results of the physiological measures and self-reports of the participants revealed that a higher degree of geometric realism induces a stronger sensation of presence and emotional responses.

4.8.2 Gameplay data

Gameplay-related data in the textual format are processed and presented through graphical representations that enable users to absorb the data. According to the literature surveys (Sevastjanova et al. 2019; Wallner and Kriglstein 2013) on gameplay data, charts and diagrams, heat maps, different types of movement visualizations, self-organizing maps (SOMs), and node-link representations are the most used types. Selection of the most efficient and convenient approach according to the information to be represented is a crucial step. Although they can be interpreted in different forms, charts and diagrams are more suitable for direct demands than exploratory tasks.

According to the taxonomical study of Kriglstein (2019), there are two ways to collect gameplay data. Observation-based data can be collected by either observing the player interactions or using questionnaires and interviews, and it helps developers understand the players' motivations, behaviors, and preferences. Data can be collected through developed mediums automatically. One of the main differences between these approaches is that while the first one presents qualitative outputs, the second one produces quantitative data, which is more available for visualization. The data can be spatial, non-spatial, or temporal. The taxonomy of Kriglstein (2019) presents six different categories: comparison, distribution, relationships, time, space, and flow, based on tasks and types of data.

To our knowledge, unfortunately, there is not enough research to build a concrete understanding of building visualization for gameplay data in virtual reality yet. Visualization studies related to the presentation of the gameplay data mostly focus on traditional video games. Taxonomies and techniques built for information visualization are not available to adapt because of the unique needs of game data.

4.8.3 Game analytics

The increasing complexity of games and audiences called for new fields instead of traditional methods like user testing, play testing, surveys, and videotaping to evaluate player behavior. Designers, programmers, marketers, executives, and players are all using gameplay data in various ways and for different purposes. Using visualization is an inevitable option to digest data collectively. Although information visualization techniques are used, video games give various audiences a new direction to analytics with unique visual experiences. InfoVis community already has defined systems used for data analysis where analytics is not only focused, as "Casual Information Visualization" (Pousman et al. 2007)—belonging to this category, ambient, social, and artistic information visualizations are criticized for being unproductive. Visualizations integrate the play with data analysis considered as Playful InfoVis. Medler and Magerko (2011) have offered to broaden the scope and capabilities of Playful InfoVis.

Due to the nature of VR, analytics has become a vital component of VR games. Analytics helps developers increase performance by providing real-time information, fine-tuning via data presented, realizing problems in the design phase, and understanding player segments, players' engagement levels, and playing styles. Like gameplay data, game analytics are also not studied in the immersive visualization domain. Distinctively, game analytic visualizations produced for traditional environments can be used in immersive environments within the information visualization domain.

4.8.4 Gamification and gameful concepts

Even though it is not a new concept, "gamification" has always been considered a contentious term, and parallel terms are continued to be introduced in the game community. Deterding et al. (2011) proposed the definition of "gamification" as the use of game design elements in non-game contexts. Later in their survey, Seaborn and Fels (2015) define gamification as "the intentional use of game elements or a gameful experience of non-game tasks and contexts." Gamification uses game elements such as points, unlocking, achievements, leaderboards, levels, virtual items, quests, avatars, collections, competition, or cooperation in non-game applications to strengthen user motivation. For example, GamefulVA (Sevastjanova et al. 2019) is proposed for fostering motivation by combining gameful design concepts with visual analytics. On the other hand, serious games are designed for additional non-entertainment purposes. Previous studies verify that visual properties affect the user's motivation in citizen science games (Curtis 2015; Miller et al. 2019). EyeWire (Tinati et al. 2017) is a web-based gamified citizen science platform that encourages users to perform complex tasks by transforming them into more manageable tasks in a gamified environment. Foldit (Curtis 2015) is another citizen science game that is a puzzle game that contains molecular visualizations of protein folding. Analysis of gameplay data on view option settings displays significant differences in the visualization choices of experts and novices according to tasks (Miller et al. 2019).

With VR, AR, and MR technologies, data visualization transforms from passive to more interactive exploration. According to a study (Tinati et al. 2016), gamification elements such as leaderboards, individual points, customizable roles, and visual appliances increase users' engagement. Combining the interactive nature of gameful design concepts with data visualization can reduce cognitive overload while immersing the players in the content. For this purpose, Wanick et al. (2019) provide two case studies on orbital visualization and earth data visualization for scientific data, where they combine game design concepts and data worlds with VR technologies. To test the usability of VR game interactions in scientific domains, Bergmann et al. (2017) developed visualizations belonging to fields of particle physics, biology, and medical imaging appropriate for game interaction techniques in VR. They reported that although VR game strategies include some difficulties, such as simulation sickness, they offer a myriad of opportunities and a high level of immersion in scientific domains.

Another genre that combines video games with other domains is exergames. Exergames aim to blend physical exercise and video games, requiring players to move physically due to gameplay mechanics. Beyond the non-immersive exergames played with controllers such as Wii Remote and Microsoft Kinect sensor, there are also pervasive games such as Ingress and Pokemon Go that also encourage physical activities. Recent developments have made VR more efficient in engagement and performance. Therefore, video games are converted into VR format, and new games that require body movement are released, such as Fruit Ninja VR, Hot Squat, Holopoint, and Portal Stories: VR. According to an evaluation study (Gugenheimer et al. 2017b), VR games reduce perceived exertion, motivating people to exercise more. Additional to opportunities presented directly with VR, some studies focus on personalization and difficulty adjusting adaptable interfaces to keep the player engaged. Different strategies have been proposed for the visualization of physical activity. In an abstract information display named HappyFit (Yoo et al. 2017), they prefer to keep visualizations abstract, nonintrusive, and positive via colors, shapes, and metaphors to give consistent information and keep the players engaged. The primary aim behind this strategy is to encourage physical activity in the short and long term by increasing awareness, which creates a personal response.

4.9 Design considerations and user interactions

This section of the article aims to explain the importance of the evaluation methods and results with advice for design considerations in previous studies. The visualization field tends to rely on assumptions that are not proven but are firmly rooted. Kosara (2016) defines this situation as an "empire built on sand" and explains with his studies that even assumptions on most commonly used visualizations can be wrong. Questioning and testing assumptions repetitively to reach evidence is crucial to create a solid foundation for development and evolution (Kosara, 2016). As collective responsibility of the community, in the literature, hundreds of authors can be found who used and developed various metrics, taxonomies, and typologies, proposed guidelines, and created models for the multi-level understanding process behind and making assessments for different aspects of visualizations.

4.9.1 Visual perception

Although perception is extensively studied in VR, new perceptual challenges continue to proliferate. Those challenges not only include the 3D visualization features such as depth and distances, shapes, sizes, colors, and contrasts but also involve hardware-related problems. 3D human visual perception is closely related to depth perception, which also can define the effectiveness and comfort level of 3D visualizations (Dede 2009). Visual cues provide depth perception in 3D environments, such as occlusion, rotation, shadows, and shading. Viewing 3D visualization through multiple angles enhanced the understanding of the data. Unfortunately, rotational aspects are not suitable for data presented in textual format. According to Bertin (1983), three levels of human visual perception can be described. Individual elements, groups of elements, or whole images can be the subject of focus. The ability to focus sustains users to complete specific tasks. According to the density of the data, raw data should be converted in a way that helps users' focusing abilities. To achieve this, methods can include visual attributes like color, position, size, shape, and techniques, such as different perspectives or clustering.

Visual perception in virtual environments generally has been studied through the lens of Gibson's theory. Gibson (1977) stated that the environment offers different action possibilities to actors, called affordance. According to this idea, actor and environment coexist, and perception is directly related to action. From this perspective, researchers have studied perceptions of affordance for different situations, heights, and depth perception. Cliquet et al. (2017) analyzed the perception of affordances while standing on a slanted surface in VR, and also they considered the effects of different materials. According to the results of their experiments in VR, although participants could discriminate the angles appropriate for upright positions, the approximate critical angle for an upright posture determined by participants is lower than the results of the studies conducted in real environments. Nagao et al. (2018) designed an interface for infinite stair demonstration with passive haptic slats and markers to increase a sense of presence and riser height. Later, to examine height perception while moving, Asjad et al. (2018) designed an infinite ascending staircase for the virtual environment, which shares exact dimensions with a staircase in the physical world. According to their study, virtual shoes positively affect presence and error estimation.

By expanding this reality from three dimensions to any number of dimensions, the concept of virtual reality might significantly alter what it means. Jamroz (2009) provided a virtual multidimensional labyrinth program that allows users to navigate in four- and five-dimensional environments constructed with n-dimensional cubes. The ability of a person to escape an n-dimensional labyrinth that represented a rare attempt to create a multidimensional computer game was tested in one intriguing experiment. Later, the author expanded the method of "multidimensional virtual reality" (MVR) (Jamroz 2020), solving the problems of previous research. Additional calculations on the use of lighting and reflection produced a deeper understanding of depth and perception, increasing the number of information channels. With the introduction of the concept of perspective to higher dimensions, spatial understanding of created interiors has been improved, which helps to solve problems related to the perception of movement.

4.9.2 Movement

Sustaining efficient navigation for users in the virtual environment has been a challenge. Although the most natural virtual locomotion technique is mapping users' physical movements directly, different locomotion techniques have been offered due to the limited physical space.

Teleportation is a locomotion technique that generally requires the user to aim for the target location in a virtual environment. Although it overcomes spatial constraints and provides users to travel in multi-user experiences, it may cause confusion and lack of constant feedback due to spatial discontinuity of users due to teleportation. To solve this problem and maintain communication between users, Thanyadit et al. (2020), considering time efficiency, traceability, intuitiveness, and recognizability, propose four different visualizations: hover, jump, fade, and portal. Those representations of movements aim to create traceable visualization to give feedback to other users to avoid confusion. Cues such as traces are helpful for users to understand their location and decrease the spatial cognitive cost. Cherep et al. (2022) conducted a study to understand the effects of teleportation interfaces on different individuals. Their results suggest that the design of the interface and individual differences create diverse spatial cognition cases, and concerning those parameters, users' awareness of location changes. This study points out the importance of defining the target audience and knowing the effects of design choices in immersive environments.

4.9.3 Interaction

Immersive technologies have introduced many new challenges to researchers. Interaction techniques can make the experience more effortless or cumbersome. Meaningful interaction between the audience and the visualized data enhances the immersion in a virtual world where the audience can see the data and explore different aspects. Research has produced a myriad of interaction techniques for VR, such as selection, manipulation, and locomotion. Researchers are searching for creative ways for visualization tasks to interact with data. Onorati et al. (2018) developed an immersive bubble chart to get information from unstructured data. Their work includes category bubbles that semantically group individual bubbles and allow users to explore data through words. An experience designed in Unity allows the user to grab, zoom, remove and merge bubbles and keep track of previous views. A First-Person Shooter (FPS) game for both HMD with specialized controls and non-immersive games that utilize monitors and have traditional controls was developed and evaluated by Rachevsky et al. (2018); the different versions of the game were tested. While the free aim version provides better results in the immersive version, since the users moved the camera with the keyboard in the free aim version, the fixed aim version has better results for the non-immersive versions. In terms of usability, the results are different for immersive and non-immersive cases, and they agree that more natural and intuitive interactions are necessary for immersive games.

The five design guiding principles for interactions that effectively convey users' intent, according to Goncalvez et al. (2021), are affordances, signifiers, constraints, feedback, and mappings. Drawing from identified principles various tools and approaches can be employed to carry out a range of activities. For instance, hand-free interfaces use voice, typically through speech commands, and eye-gazing techniques, using eye trackers embedded into HMD. This results in multimodal interaction. Those multimodal approaches can also be used to guide users in virtual environments. Guidance can occur via sounds, visual cues, or animations. For example, annotations in virtual environments are generally represented in abstract gestures, texts, or simple objects for indication. Alternative guidance can be based on imitation using a virtual tutor, which demonstrates the task that needs to be done. Lee et al. (2019) compared the effectiveness of Annotation and Tutor based on three different tasks. According to overall results, Annotation was found more helpful for accuracy and time performance. On the other hand, using a tutor improves recalling the pattern. Researchers still have a lot of room to grow in terms of investigating novel interaction strategies and enhancing the usability of existing user interfaces to make them feel more natural to users. While previously, the majority of VR research focused on primarily audio-visual channels, recently, researchers have started to design and test experiences utilizing multiple sensory modalities such as auditory, visual, haptic, and olfactory, which augments the multisensory stimulation. Visual, acoustic, and haptic rendering algorithms are used to compute the virtual environment's graphic, sound, and force responses.

Transducers subsequently transform these computer signals into forms that the user can understand.

A collection of formulas used to compute and produce kinesthetic or tactile experiences. The process of transforming force-incorporating computer algorithms into a mechanical interface that can convey haptic information to a user is known as haptic rendering. Haptic rendering combines software and hardware elements. To generate the haptic forces between the fluid and deformable objects more accurately, Liu et al. (2019) propose a computational framework incorporating the forces of buoyancy, pressure, elastic force, and viscosity. They applied the PBD approach to stabilize the computing process. Their approach enhances the authenticity of the haptic force of the coupling and provides a computational solution. To provide a multiphase fluid haptic feedback force, Zhang and Liu (2017) employed SPH and a unified particle model for the rigid body–liquid coupling to enhance realistic sensing in virtual reality.

4.10 Comparative studies

Design and implementation decisions have significant importance for data presentation. The process starts with the raw data, and until it takes its final form, many choices must be made. The emergence of new technologies, techniques, and ideas requires continuous analyses to create a concrete background. Unfortunately, immersive visualizations suffer from the lack of standard guidelines to build upon. To prove the rationale behind the preferences, comparative studies were examined. Immersive technologies imply specific outcomes when they are tested for user experience. There is a threshold requirement to pass to choose immersive visualizations over traditional ones. This threshold is closely related to widely studied questions in HCI, which are user experience and technology acceptance. For example, Shrestha et al. (2016) recreated historical sites in Nepal for the CAVE environment to compare with the Paper-Based Artifacts. The results indicated that participants had difficulties solving complex problems in VR. This struggle can be the reason and result from the resistance originating from not being accustomed to new technologies.

Ren and Hornecker (2021) conducted a user study to compare virtual and physical data representations by creating two equivalent representations of the same data set for physical and virtual environments. This study showed that while physicalization helps decrease response time, participants tend to move slowly in the VR environment due to VR lag, affecting the experience quality. According to a study conducted by Millais et al. (2018) on scatterplots, the workloads of traditional visualizations and visualizations in VR are almost equal. They reported that users feel more satisfied and successful when using VR for data exploration. Task-based comparisons of the 2D and 3D versions of visualizations give more diverse results. According to the results of a comparative study (Kraus et al. 2020), which utilizes visualization tasks taxonomy by Brehmer and Munzner for the overview tasks, 2D heat maps gave better results while reading and comparing single data items, and 3D heat maps tested in virtual reality environment showed lower error rates. This situation leads researchers to use hybrid techniques.

In their study, Roberts et al. (2022) discuss different visualization techniques using case studies to identify the key features to create diverse 3D visualizations. Their results show that using multiple views and different viewpoints enhanced the understanding. However, each visualization technique requires solving a variety of problems. Those problems are not always related to the structure of the visualization. Immersive visualizations require optimizing several parameters at the same time. Beyond those comparisons, finding the effective use of space to represent data in immersive environments is another research subject. A Meta-analysis study (Akpan and Shanker 2019) consists of 162 synthesized studies. VR offers more effective model development, verification, and validation performance on DES task performance when compared with 2D visualizations. There are several approaches to guide users in virtual environments.

5 Discussion

Due to vast options and a lack of common ground, selecting or creating methods and techniques to visualize a particular type of information is challenging. Although the main aim of all visualization techniques is communication via visual medium according to data, user, defined tasks, and presentation techniques starting from the data gathering, the whole process requires different techniques. Most scientific visualization data are obtained through devices such as sensors, microscopes, and cameras or via simulations, volume rendering, and slicing to extract sections. Therefore, data is already suitable to be transferred to virtual 3D environments.

Data visualization studies are more related to abstract data and focus on presentation and analysis aspects. Considering studies according to the subject, information visualization can include aspects of both. For example, techniques used in art and architecture domains have more similarities with scientific visualization techniques, while computer sciences deal with similar problems with data visualization. Specific requirements of the domains create different discussions on various subjects. For example, nanosciences and architectural heritage domains already have 3D physical forms to transform. For this transformation, discussion topics can be clustered around the level of abstraction, interaction techniques for the model, or presentation of textual data. On the other hand, if statistical data on cultural heritage is subjected to visualization, this time, data do not have a physical equivalent to display it visually. Physical attributes will be attended to features of data and design principles; color and perception theories may have a more dominant role.

Physical attributes and perception theories are widely used for abstraction. Considering the interaction possibilities presented by data, there is generally a correlation between abstraction level and presented interaction capabilities. Abstract visualizations are more open to manipulation and interaction and more suitable for analysis. On the other hand, more literal and realistic visualizations are more representative. Scientific visualizations mostly rely on 3D volumetric data combined with abstract elements. Although domain and subject are different according to data type, common visualization structures can be used. The combination of dynamic visualizations with time-series data is widely used in both information and scientific visualizations. 3D versions of bar graphs, line, and scatter plots are still the most commonly used visualizations in various domains. The common objective is finding the best user-friendly navigation and interaction techniques in an immersive environment. Therefore, studies belonging to different research areas have common problems and challenges considering visualization. In general, most of the research questions gathered around concepts of representation, perception, interaction, locomotion, and decision-making.

In the information visualization community, cultural heritage and construction popularity is increasing due to CAD-based and BIM-based models. Therefore, interaction with the integrated models gains importance. In addition to interaction with 3D models and multidimensional visualization, collaborative studies present various opportunities to users. Most real-world cases require possessing sophisticated and expensive equipment or being in a dangerous environment. Scientific visualizations, simulations, and visualizations built for training serve as a replacement for real-world equipment and situations. Educational visualizations are also expanding their scope, creating more active and dynamic relations by including game elements. Gamification motivates learners, and a combination of visual senses together with physical interaction improves users' recall mechanism. Movements, embodiment, and gestures also increase the level of understanding and provide more active roles. The learners have the opportunity to interact with objects of different scales. VR breaks space limitations: therefore, the chosen subject can include objects of any size. The scale of the data representations can be arbitrary and controlled by the user to interact with the representation at different levels. While users can prefer large-scale visualizations that surround them or manipulate them more quickly for a specific task, data can be room-scale or smaller. By changing the scale, users move between egocentric and exocentric approaches suitable for different tasks. Egocentric visualizations provide more immersive experiences since data surround the user, fly through it, and demand less cognitive load. On the other, exocentric visualization gives better results in analytical tasks.

As the interaction methods are developed, chronological observation of visualization taxonomies shows that the scope, the number of tasks, and primary objectives also continuously expand. A correlation between this expansion and new data extraction techniques and technology development can be constructed. For example, while advanced techniques provide new data types, technologies like haptic devices, sensors, AR, VR, and MR define new interaction techniques. There is no comprehensive visualization taxonomy study specialized in VR to our knowledge. At the same time, even though previous taxonomies have certain limitations due to similarities, they can be used as a base to construct taxonomies for VR.

Virtual reality technologies (Fig. 6) increase the number of interaction techniques and transform the existing ones. For example, hands-free pointing either by eye gaze or with a head pose is an interaction method that comes into literature with VR—presenting the third axis rotary motion together with physical immersion. Users can perform locomotion by walking in the physical environment, using controllers or teleportation methods. VR comes with additional aspects that need analysis and classification to broaden the existing taxonomies. The visualization community needs more comparative studies showing the clear distinctions between traditional visualization techniques and VR visualizations to create objective rules and a baseline for design decisions.

Classifying and defining the target users are crucial for producing taxonomies, guidelines, and classifications. According to cognitive capabilities, technology use, and special situations of the users, decisions should be taken considering interaction and visualization preferences. There is a need for comparative studies to identify common patterns and specific groups to construct such knowledge. As can be seen in the related section, collaborative studies can produce controversial results. Especially, different results in the studies that compare VR visualizations with desktop environments stand out. Even the effect of different visualization mediums on spatial understanding is still debatable. This situation may stem from the differences in participants' or design-specific problems. Therefore, they should be repeated until the results converge at the same point. The user-centered design process is essential for visualization tasks.

After determining guidelines, tools can be produced to create more accurate visualizations. This way, visualization studies can gain speed and find a common language and visual consistency. Having previously tested and proved de facto standards is also helpful to accustom users to new technologies and switch between them. Unfortunately, developed

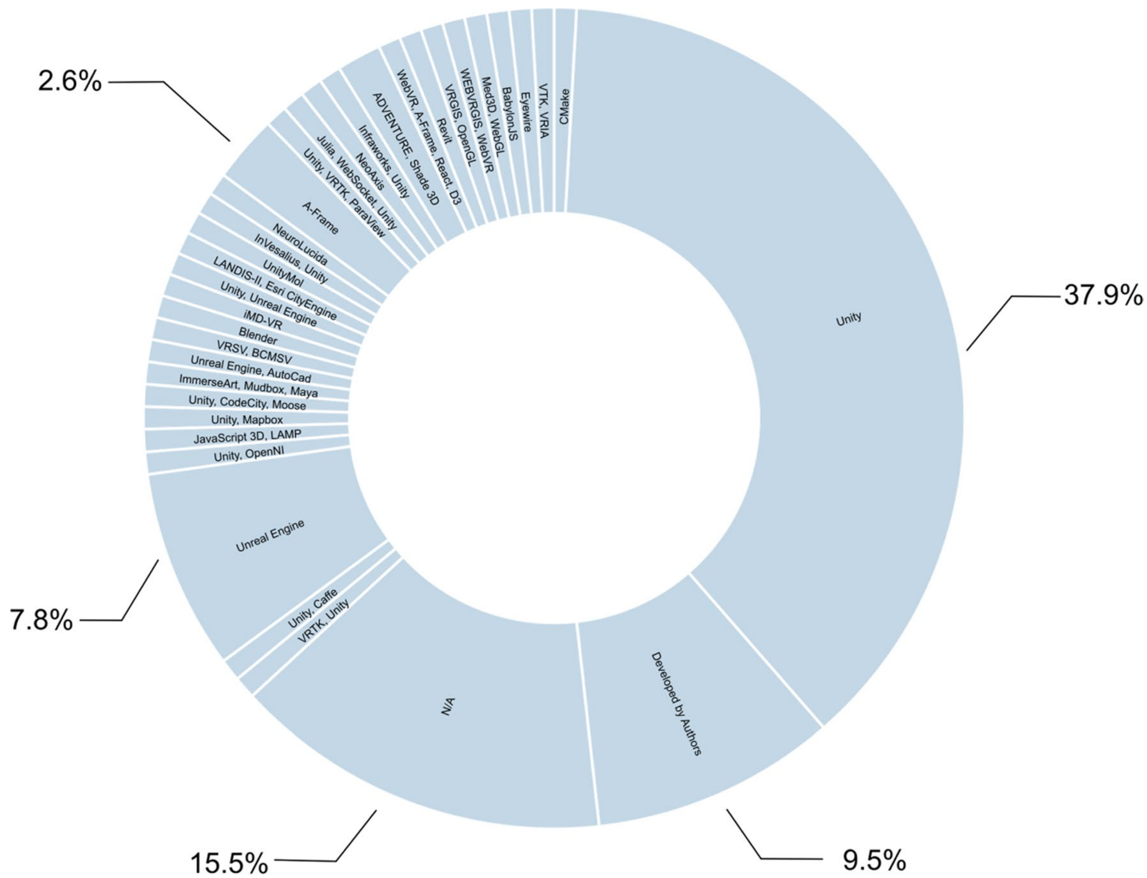

Fig. 6 Usage rates of visualization tools across 110 research studies that were chosen. Sunburst diagram was created using RAWGraphs

tools are limited to specific data and visualization types. For example, most toolkits are produced to represent quantitative data, and their scope is limited to quantitative analysis. Also, creating toolkits for qualitative analysis is a more complicated task. Tools need to be flexible to create possible solutions and different interaction methods since design preferences also direct user behavior.

Virtual reality still suffers from technology acceptance, and, due to hardware requirements, it is still not common. WebVR, VR games, and collaborative studies are essential in breaking the acceptance barrier. Recent trends are promising for the increase in virtual reality systems. Especially recent orientation toward remote collaboration paved the way for VR versions. Other examples can create a high degree of immersion, such as free-viewpoint video technologies that can be adapted for both WebVR and smartphone visualizations. Smartphones are being widely used in almost all aspects of our daily activities. Also, creating mobile versions of visualizations resolves the need for hardware. Simpler hardware, such as Google Daydream and Samsung Gear VR, offer controllers for mobile VR. However, mobile VR is not suitable for complex visualizations due to technological requirements since the performance is entirely based on smartphones. Unfortunately, applications using the web browser also have rendering and speed limitations. Even so, for specific areas, they can be beneficial.

Exergames take the lead in visualization studies in the game domain. Most studies encourage users to exercise regularly and engage with the activity. Since they target users with specific needs, visualization and interface requirements are variable and require elaboration. To reach further potentials of VR integration in daily life activities, as in the exergames, can overcome the usage barriers.

Another subfield open to further developments to overcome acceptance problems is collaboration studies. They can include a combination of synchronous or asynchronous, on-site or remote, and symmetric or asymmetric approaches. Asynchronous and remote collaboration is crucial for scientists working together on the same project. Synchronous and on-site ones are primarily used in training and architectural studies. Asynchronous and on-site version is the less common version, but their scope can include architectural projects. For example, to create more efficient smart cities, users can engage through visualizations in specific hubs in the city. The combination of synchronous and remote allows collaborators to work together in real-time while they are in different locations. The synchronous aspect of the collaboration helps users not to feel isolated. Therefore, the acceptance problem is one of the essential features to overcome. Multi-user experiences have more positive effects on users compared to single-user versions. It increases the users' engagement and success rate. The combination of Web, collaboration, and mobile technologies can provide quick and easy dissemination of information.

Although most of the studies provide solutions for particular problems of VR, problems relating to virtual reality hardware have not been solved completely. Most of the time, problems of cybersickness, latency in tracking, and low refresh rates disturb the users and break presence. Studies try to fixate the experience on a fast frame rate to avoid VR sickness. While this approach works for simple visualizations, they follow different complex visualizations and simulations techniques. Allowing users to transport physically in a consistent environment allows VR to create complete immersion that makes it distinctive. However, the design of the visualization can also create fluctuations in the user's sense of presence and break the immersion. Inside VR, the user is only able to see computer-generated imagery. Therefore, the objects the user stares at should be more apparent than objects farther away or nearer.

Visualizations can also use focusing techniques to create hierarchy levels to differentiate essential aspects of data. Geometric realism affects the presence in VR and can create a strong presence and emotional response. Polygon count and texture resolution are generally increased to create more realistic environments. However, intended realism levels require powerful hardware. Therefore, different techniques are used, such as foveate rendering and occlusion culling. In immersive environments, the user can see all directions; therefore, different from the 2D representations, 3D mapping techniques can be applied to data. Visibility of the presentation is also vital for the user. Developers can use different rendering or layering techniques when the data includes complex relations. For example, edges and nodes can be dense if a network visualization represents the data. To lower the occlusion level, developers can prefer to play with scale and line width or divide the data into more layers. The crucial point is conveying the data without deterioration. To ensure correct and practical interpretation of data, proper and explicit visual encoding of the information is crucial.

Scale is another aspect that should be taken into consideration for precision. For example, large-scale maps are designed for estimation or extraction value tasks; some parts can be diminished according to visual encoding. Perceived object sizes are also changed according to avatar realism and scale. The effectiveness of a graph representation of a dataset can be objectively evaluated according to visual features. The features of association and selection enable people to perceive and discriminate against particular objects or features. Visual features should be consistent throughout the whole visualization experience. Graphical perception studies that measure users' performances across visualization designs and different displays offer other studies new insight into the utility of depth, color, geometries, and scale.

To encode spatial data according to positional aspects, data elements can be placed in the virtual coordinate system or placed on constructed maps or globe view, according to data. In parallel to this selection, developers select different interaction methods. Globe visualizations include rotational movement. However, users can only see a particular part of the globe. Therefore, while information visualization prefers to use placement on maps, scientific visualizations employ exact shapes or coordinate systems due to the accuracy aspect. Different 3D shapes, colors, opacity levels, and textures are used to represent located elements. There are also data-specific preferences, such as a combination of rotational models with a network diagram. Spatiotemporal visualizations are mainly used for simulations. One of the most used visualization techniques for multidimensional data is 3D scatterplots. Most of the immersive tools and toolkits provide immersive scatterplot construction. Since they are already available for various visual channels, the encoding process does not require additional techniques. However, it is not suitable for complex datasets for specific tasks due to visual clutter. To solve this problem, filtering methods are used. For selection tasks, ray casting is still the most used method. These methods allow a user to select a single object, draw a bounding box, or brush multiple objects that can be selectable. Interactive visualizations always need to give necessary feedback and visual cues to point out possible interactions. For example, selected objects should be visually identifiable.

Data quality, data stream handling, and semantic relation extraction from raw data remain challenging. Although machine learning algorithms are promising, automatization of the process may yield inaccurate visualizations. Providing compact representations for large volumes of multivariate data is still waiting for more advanced techniques. Although studies generally employ supervised and unsupervised machine learning algorithms and dimensionality reduction techniques, they also report that the results can be misinterpreted or poorly handled. Thus, efficient and effective methods for compression and feature extraction are needed. For scientific visualizations, accuracy gains more importance in filtering data or calculating probability. Generally, fine-tuning the hyper-parameters is used to arrange the sensitivity of the algorithm.

6 Conclusion

Following the protocols for a systematic review, sources related to immersive visualizations were identified and filtered out. We investigated the various techniques used in various domains, as well as their collaboration. The resulting articles were further analyzed, and relevant studies were grouped according to the most common problem domains and represented in different sections. We presented the overview of existing literature, discussed the strengths and weaknesses of the described methods, identified gaps in existing research, condensed these findings, and pointed out unsolved problems and challenges. The results of our study show that there is a growing body of research examining immersive visualizations in a wide variety of problem domains. While research consistently points to advantages in immersive environments, the evaluation of different immersive technologies revealed that constant technological progress leads to the continuous development of new interaction modalities for immersive environments, and there is a need to overwrite the results of previous studies with outdated technologies and techniques. While most of the studies have been gathering around the development of immersive visualizations, only a minority have focused on building theoretical backgrounds. While most of the studies have been gathering around the development of immersive visualizations, only a minority have focused on building theoretical backgrounds. Most studies developed visualizations based on data type and domain and later tested them for visualization tasks. However, those tasks also have certain specifications. Using tasks only to evaluate the visualizations eliminates possible integration options and task-specific design decisions.

Within visualization, the most mature research areas have come from training, architecture, and game technologies. One of the most striking results is that although game engines are widely used in various domains, only a few studies target gameplay data visualizations for VR games. Many studies focused on how VR could be used for training and the requirements for increasing effectiveness. Already having a 3D presentation, most of the architectural studies have accomplished the transition process. Especially, the use of immersive systems to maintain cultural heritage in digital mediums is increasing. Most visualization studies utilize game technologies and novel techniques derived from computer graphics and human–computer interaction. With these technologies, the visualization domain has given rise to new research questions, followed by usability, interactivity, and reliability issues.

2D visualizations still protect their ground in displaying statistical and abstract data in information visualizations, while 3D visualizations are commonly used in physical sciences, engineering, and design. 3D versions of traditional statistical visualization techniques, such as bar plots and scatter plots, are still commonly used in data visualization contexts. However, only a few studies focus on creating standard guidelines for virtual reality, and each study individually provides a framework or employs previous studies on traditional 2D visualizations.

With the myriad of advantages provided by visualization and virtual reality, most studies prefer to use game engines. However, accuracy requirements are not convenient for critical scientific studies. Due to occlusion problems, perceptual distortion, absence of a common baseline, and noneffective 3D representations of abstract data on standard 2D monitors, validation of 3D are still waiting for further research and alternative approaches for solving design challenges.

7 Future directions

Virtual Reality visualizations have made some compelling advancements in recent years, but there is still plenty of room for improvement and further exploration. Many research questions are waiting for comprehensive studies: Which data types and visual structures are more suitable for VR, and are they increasing the performance of qualitative and quantitative data analysis? Is there a need for analytical methods specific to VR, and how can they be produced? Although different frameworks allow quick prototyping of specific visualizations for abstract data, uniform frameworks or libraries that can be used to generate visualizations for specific domains, such as medicine, WebVR, and heritage, should be provided.

Future research in immersive visualization should collaborate with research in other domains, use cross-domain knowledge transfer, and use findings and insights from other domains as the foundation for new hypotheses. The third dimension includes issues with depth perception, occlusion, conveying meaningful relations between spatial 3D views and 2D views, and displaying quantitative values and texts. Converting 2D visualization techniques, such as bar plots and node-link diagrams, to 3D presentations and using axes and coordinate systems is common. However, perception is affected by user movements, which cause occlusions. Even though 3D can use multiple view systems, it is unclear how to add detailed quantitative information to 3D worlds. As in the life sciences, a more holistic approach can be their hybrid use to compensate for each other. More refinement is still required in the design space and the practical design, implementation, and testing of less-used techniques in immersive settings, such as Sankey diagrams or cartograms.

More research is recommended on the study of cross-modal impacts of different senses in VR, which requires more attention to synthesize and deliver these stimuli to the participants and evaluation of perception levels of participants. Increased levels of immersion achieved by allowing the user to touch, hear, smell even taste enhances the notion of reality and can influence visual analysis tasks. Haptics is, by far, the most used stimuli in multisensory setups. However, studies use similar interaction methods provided by controllers. This situation is not sufficient to meet the requirements of specific areas. New interaction paradigms that exploit full-body interactions should be searched. Despite the importance of smell and taste, these senses are still very intrusive and costly and require more research and development. Under-explored, multisensory setups and methods can bring noteworthy value to VR visualizations. The assessment of more complex niche visualizations is possible by employing transitional interfaces in conjunction with collaborative methods and appropriate visualization and interaction metaphors (Ens et al. 2022).

The constant changes in the underlying technology require repeated studies and constant development in theories behind empirical studies. Together with the promising nature of VR, the quality and sophistication of visualizations are waiting for further improvements.

Availability of data and materials The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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