An Immersive Approach Based on Two Levels of Interaction for Exploring Multiple Coordinated 3D Views

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Abstract. Multiple coordinated views have often been used for visual analytics purposes over the last years. In this context, if the exploration of 2D visualizations is not an obstacle, adding an extra dimension can be an issue. The interaction with multiple 3D visualizations in 2D conventional displays lacks usability and does not guarantee the usefulness the extra dimension would provide. Immersive visualization techniques can potentially fulfill these gaps by providing 3D visualizations and novel 3D interactions simultaneously. In this paper, we propose a new approach for interacting with composite and multiple coordinated visualizations in immersive virtual environments. We use a 3D-WIMP-like concept, i.e., virtual cubes (*Spaces*), for encapsulating views, which the user can freely control in the virtual environment. Moreover, operations like "cloning" and "coordinated interactions" features provide a way for performing composed tasks. We compared our approach with a desktop version to evaluate its performance when dealing with composed tasks. A user study with 19 participants was conducted, and the results show that the immersive approach has advantages over the corresponding desktop version regarding interaction with multiple coordinated 3D views.

Keywords: Multiple coordinated views · Virtual reality · Immersive analytics.

1 Introduction

Multiple Coordinated Views (MCV) are among the most commonly used ways of composing visualization techniques to show different perspectives of the same or potentially correlated data to facilitate insight into a complex dataset [16]. Such an approach is especially suited for visual analytics applications [40]. Depending on the data, using multiple 2D views in conventional 2D displays demands large displays, while for 3D visualizations, such setup may not guarantee a useful tool. Earlier studies showed that the interaction with multiple 3D visualizations in 2D displays does not meet usability criteria [33]. This lack of usability could be overcome if the exploration happens in immersive environments, where the user has an extra degree of freedom for interacting with 3D visualizations [14]. Additionally, human spatial awareness and organizational capabilities can help the analytical process performed interactively with the visualizations [19]. Immersive analytics approaches have been developed to take advantage of these characteristics.

Immersive Analytics (IA) is defined as an interdisciplinary field where any technology that remove barriers between users and their data can be used for building tools to support data exploration, communication, reasoning and decision making [29]. Technologies like Augmented Reality (AR) let the user navigate the physical environment to interact with different devices such as multiple displays [31]. The use of multiple devices helps collaborative tasks involving multiple views [37], while Virtual Reality (VR) techniques allow the user to be completely unaware of the surroundings providing a feeling of reality to the end-user [6]. A recent survey on immersive analytics [12] found more than one hundred papers related to VR, and only 15 employing AR technologies from 1991 to 2019, which shows a general preference for VR technology. One of the authors' conclusions is that the IA community should focus on real-life scenarios that require novel strategies for interacting with multiple views.

Developing techniques for using multiple views in VR is a challenge because they require more complex control of interaction techniques [19]. Furthermore, there is a need for interaction methods capable of achieving the functionalities of the predominant WIMP (windows, icons, menus, pointer) used for visual analysis tasks [23]. Some experiments performed with FiberClay [15] for exploring trajectories allowed the authors to report suggestions for improving the user experience in VR environments with multiple views, such as: avoid 2D graphical user interface components, limit the number of interaction modes, facilitate the navigation and preferential use of one primary view.

Although multiple views have been used for years [32], it is worth mentioning that the potential cognitive overload introduced by interaction makes designers ask themselves when and to what extent it should be used. Baldonado et al. [41] identified a list of issues of a multiple views system, where the first four concern to cognitive aspects, and the last three, to system requirements: (1) the time and effort required to *learn* the system, (2) the *load* on the user's working memory, (3) the effort required for *comparison*, (4) the effort required for *context switching*, (5) the *computational requirements* for rendering the additional display elements, (6) the *display space* requirements for the additional views, and (7) the *design, implementation, and maintenance* resources required by the system. Moreover, multiple views share a relationship that is used for coordination. Scherr [36] analyzed coordination techniques, the most common one being *brushing* where, given a selection of elements in one view, the same or related elements are highlighted in the other linked views. There is also *navigational slaving* that describes the relation between views and data, based on a $2x3$ taxonomy: selecting items – selecting items, navigating views – navigating views, and selecting items – navigating views.

In this paper, we present an approach for interacting with multiple coordinated views that display 3D visualizations. Our technique uses a virtual cube as a 3D-WIMP version – we call it *Space*, inspired by Mahmood et al.'s work [28] –, for encapsulating each view, and two modes of interaction with the views: the *macro* mode for interacting with the Spaces, and the *micro* mode for interacting with the data displayed in the Space (see Figure 1). In addition to standard interaction techniques, we provide "cloning" and "coordinated interactions" features.

Overview. Given that similar 3D-WIMPs could be displayed on 2D displays, we designed a similar desktop version to compare it with our VR Spaces approach and decided to focus our study on the following research question: *Do our Spaces approach improve the manipulation of multiple coordinated 3D views when they are explored in an immersive virtual environment? How does the approach differ from a 3D conventional desktop version?* We formulated hypotheses inspired by the problems described in the MCV studies reported in the literature. Then, we conducted a user study with 19 participants. The results contribute to future studies to develop new ways to interact with multiple views. Additionally, the 3D-WIMPs approach opens possibilities for investigating whether free control views are better than common metaphors (e.g., small multiples) in virtual reality.

Contributions. We propose a new approach for interacting with MCVs using a head-mounted display (HMD) to give users full control of the three-dimensional visualizations. Then, we report the lessons learned from the comparative study with 19 participants to create a basis for future works using multiple coordinated views in immersive 3D environments.

The remainder of the paper is structured as follows. In Section 2, we briefly review previous works on multiple coordinated views. The concept of *Spaces*, the interaction techniques proposed and additional technical details are introduced in Section 3. Sections 4 and 5 present the users' experiment design and the results, respectively, while Section 6 discusses our findings. Finally, Section 7 presents our conclusions and future work.

2 Related Work

Multiple coordinated views approaches implement the concept of "composite visualization views (CVVs)", which was recently formalized by Javed and Elmqvist [16]. Their proposal followed the concepts inherited from Card et al.'s pipeline [5]: *visual composition*, i.e., the placement or arrangement of multiple visual objects; *visual structure*, i.e., the graphical result of a visualization technique; and *view*, the physical display where a visual structure is rendered. A "composite visualization" is the visual composition of two or more visual structures in the same view. They identified different forms of composing visualizations and came up with *CVVs design patterns* as follows: *juxtaposition*, that corresponds to placing visualizations side-by-side; *superimposition*, which corresponds to overlaying two visualizations in a single view; *overloading*, which uses the space of one visualization for another; *nesting*, which is having the contents of one visualization inside another visualization, and *integrating*, which places visualizations in the same view with visual links.

Several immersive analytics studies have used diverse strategies to provide multiple views [19] regarding different CVVs design patterns, coordination techniques and settings. In this section, we briefly review the studies mostly related to ours, highlighting the limitations and challenges addressed by them.

2.1 Multiple Views on Large Displays

Several authors have explored multiple views in wall-sized displays, usually adopting a *juxtaposition* pattern. Febretti et al. [11] presented OmegaLib, a software framework for supporting the development of immersive applications using Hybrid Reality Environments (HREs), which integrates high-resolution wall-sized displays with immersive technologies. This framework allows the linking of 2D and 3D views, and is designed for a group to discuss the visualizations showed in the wall displays, while another group using laptops is in charge of the control management of the multiple views. With OmegaLib, they try to overcome known problems of these alternative approaches: the static spatial allocation of 3D and 2D used in most systems and the lack of unified interaction between the 2D and 3D visualizations.

Similarly, Langner et al. [21] presented a study based on an MCV system using interaction on a wall-sized display for analyzing the behavior of multiple users exploring more than 45 coordinated views. Their study implemented a general layout with multiple numbers and different sizes of views, and users could swap the views' positions (*juxtaposition*). The authors highlight that view management was not the focus of their study. To support interaction from varying positions, they combined direct touch and distant interaction using mobile devices. To interact with views, the users had to select the region's border showing the desired visualization. It is worth noting the importance of interactions for free navigation and the use of the border to change the mode for manipulating the data shown in the view.

A hybrid application developed by Su et al. [39] allowed the user to visualize 2D and 3D information using a Large High-Resolution Display (LHRD) and VR technology, respectively. The study qualitatively compared 2D/3D coordination data displayed in 2D displays, 2D/3D data without coordination, and 2D/3D coordinated data displayed in the 2D display and in the VR environment. The visualizations used in the study were: a geolocation map, chord and horizon time plots in 2D views, and a 3D scene of a city. The 2D visualization shows the location and link data over time for the highlighted assets and links in the 3D visualization. The location trail is *superimposed* to the 2D and 3D maps, while the chord and time plots show coordinated actions. The results favored to 2D/3D coordinated environment in understanding and interactivity, but 2D/2D was the global favorite due to the facility of staying in one context only. The participants showed signals of discomfort because removing the headset was too disruptive for the data analysis workflow. Nonetheless, the users agreed there are benefits in using hybrid environments.

2.2 Multiple Views in AR and VR Environments

An alternative way to avoid the problem of changing the environment is to adopt augmented reality (AR) solutions. Mahmood et al. [28] proposed a 3D version of a conventional MCV designing a Multiple Coordinated Spaces workspace. AR techniques were used to integrate a physical environment and to combine 2D views and virtual 3D spaces, such as 2D displays with virtual 3D visualizations. This workspace is built by obtaining positions of 2D surfaces, and then plotting 3D spaces. The workspace area is adjusted and subdivided into multiple spaces with similar sizes. The visualization methods used were based on 2D WIMP, displaying 3D parallel coordinates that linked real or virtual views (*overloading*) and topographic maps with *superimposed* scatterplots. Three-dimensional visualizations contained maps and 3D scatterplots included in 3D spaces. The interaction techniques implemented were data/view selection, scaling, and translating (allowing *juxtaposing* views), show/hide visualizations, and creation of history, which saves a configuration of the workspace, all with the help of hand gestures and voice commands provided by the Microsoft HoloLens. This work focused mainly on Coordinated Spaces for supporting immersive analytics in a physical environment and motivated our approach.

The number of works using MCVs in VR environments has been increasing over time. ImAxes [8] is an interactive tool that allows users to manipulate multiple charts' axes like physical objects in a VR environment to design visualizations. The user can manipulate one axis for observing a 1D histogram. Two or three axes placed perpendicularly create 2D and 3D scatterplots, while parallel coordinates are created distributing the axes in parallel in the VR environment. ImAxes was used by experts for economic analysis in a subsequent study by Batch et al. [2]. Since ImAxes is based on placing axes in the VR environment, users can *juxtapose* them. In addition, the proximity between visualizations can create linked 2D and 3D scatterplots (*integration* pattern).

Other studies using the *juxtaposition* pattern are presented by Johnson et al. [18]. In Bento Box, a VR technique for exploring multiple 3D visualizations juxtaposed in a grid, like small multiples. Their tool was evaluated within a CAVE, and results showed that the users found it good for data analysis because it facilitates collaborative discussion. More recently, Jiazhou Liu et al. [26] also used 3D visualizations in small multiples in an immersive environment.

Coordination techniques were studied by Prouzeau et al. [30]. The authors proposed a design space for routing visual links between multiple 2D views in immersive environments, which we classify as the *integration* pattern. Their real-time algorithm allows them to draw links to connect multiple visualizations considering their coordination and the users' views. These visualizations were evaluated without interactive techniques showing the challenges of strategies for MCVs applied in VR.

Two recent works describe approaches that allow users to interact with multiple views in a way close to ours. Satriadi et al. [34] describe the exploration of multiple 2D maps in a VR environment. Each map view could be created, scaled, and arranged by the users. Their study focused on the exploration of user-generated patterns with the maps views. Based on a *juxtaposition and overload* patterns, their work shows an interesting way to arrange 2D maps to better understand how users arrange the views. More recently, Lee et al. [22] developed FIESTA, a system for collaborative data analysis in immersive environments using VR. FIESTA uses static visualizations floating in a virtual room (*juxtaposition*). Its interactions are based on direct contact with UI elements and distant contact using a laser pointer.

Finally, we should mention the toolkits and frameworks that have been developed for supporting data visualization in VR and AR environments. DXR [38], IATK [7], VRIA [4] are examples of such tools. DXR and IATK are based on the *juxtaposition* pattern [16], while VRIA supports also the *overlaying* pattern.

In summary, an increasing number of works report experiments with multiple views and highlight the limitations of the methods provided to control composite visualizations with coordinated interactions using 2D/3D views. For example, the studies surveyed herein commonly used the juxtaposition pattern followed by superimposition, which is typical of geographical maps. The absence of methods and practical guidelines to use composite views in IA induced the development of different strategies, which showed disadvantages, especially in VR environments [13]. Our work presents an approach to allow users to compose visualizations moving MCVs for improving the scene layout, facilitating data exploration.

3 The *Spaces* Approach

The change from standard 2D to 3D WIMP induces differences in perception and interactivity [29]. Following the design space of composite visualization [16], where multiple "visual structures" are combined in the same "view", we designed our approach based on similar concepts. The "visual structure" is mapped to a virtual cube where it is rendered. The virtual cube is called *Space* inspired by Mahmood et al. [28]. An overview of the approach is shown in Figure 1 and its details are presented below.

3.1 *Spaces*

A *Space* is a container for one visualization only and can be manipulated similarly to an object but without physics, weight, or texture associated. The objective of a *Space* is to facilitate the interaction across multiple visualizations. We chose a cuboid shape to represent a *Space* to have a reference point for the coordinate system, and added a title identifying the dataset being visualized in the *Space*. It can be cloned, and then the title is customized with the version number

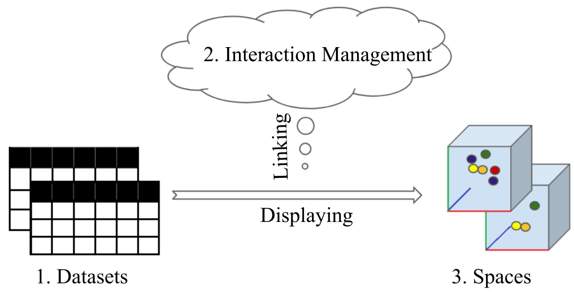


Fig. 1. Overview of the *Spaces* approach: reading from the datasets (1); a visualization instance is added to the interaction manager (2) for coordination techniques (Brushing and Navigational Slaving); data is rendered in the virtual environment, in the *Spaces* graphical representation (3).

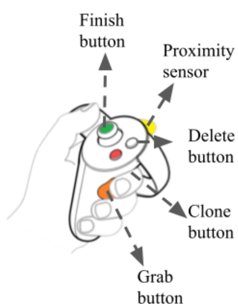
Fig. 2. The proposed macro/micro modes of interaction allow the user to interact with the Spaces and the data. The Spaces can be grabbed and overlaid to facilitate comparison of the data represented inside each one (left). The two virtual hands are independent from each other: the user can grab a Space with one hand and explore its information with the other one (center). Our approach allows the exploration of Multiple Coordinated Spaces (right).

to distinguish it from the original *Space* (see Figure 2-left). To interact with a *Space*, the interacting agent must be in *macro* mode, while to interact with the data displayed inside a Space, it must be in *micro* mode (see Subsection 3.2).

In a VR environment, the interacting agent used is the virtual hand, which is considered the most natural interaction paradigm [3] for 3D interaction with near objects. The user can change between macro and micro modes of interaction through the proximity sensor of the index finger. For evaluation purposes, we developed a similar 3D desktop version. In that version, the mouse cursor is the interacting agent, and the mode change is based on events. We present the distribution of the events for both the VR and desktop versions in Figure 3.

3.2 Interaction Techniques

The standard WIMP functions are moving, close, and minimizing or maximizing. We developed similar functions for both the VR and desktop versions of our



Target	Action	Virtual Reality	Desktop
Container (macro)	Select	Hand collision	Pointer collision
	Grab/Translate/Rotate	Select + Grab button	Select + Right click
	Clone	Select + Clone button	Select + Space bar
	Scale	Grab container with both controllers	Select + Mouse wheel
	Delete	Select + Delete button	Select + Delete button
Data (micro)	View detail	Index finger collision	Cursor pointer
	Highlight	View detail + Grab button	View detail + left click
Navigation	Virtual movement	Head movement	FPS control (A/W/S/D buttons)
System	Finish task	Finish button	Enter button

Fig. 3. Distribution of actions for each interactive command used in the Virtual Reality and Desktop versions. We propose two easily interchangeable modes of interaction, the *micro* mode to manipulate data displayed in the *Space*, and the *macro* mode to interact with the *Spaces*. A **controller module** manages how the user interacts with the *Spaces* and data, while an **interaction module** connects data to *Spaces*. All features needed for coordinating interactions are provided by this module.

approach for manipulating the *Spaces*, except for minimizing and maximizing. These functions are presented in Figure 3.

As mentioned before, the interaction techniques are divided into *macro* and *micro* modes.

Macro mode interaction. For ***selecting*** a *Space*, the *virtual hand* must be inside it. The *Space* chosen will slightly change color, avoiding perception changes in the visualization technique. In order to ***grab*** a *Space*, the user must keep the Grab button pressed, allowing to grab one Space per hand. We selected the Grab button because it resembles the behavior of holding an object. Once grabbed, the user can ***move*** and ***rotate*** the *Space* freely according to their movement. To ***scale*** a *Space*, the user must grab it with both hands, and by separating or joining them, the scale will increase or decrease the size of the *Space*, accordingly. To ***clone*** a *Space*, it is necessary to select it and press the Clone button: a copy of the *Space* will be created, including the same visual features. To ***remove*** a *Space*, one must select the *Space* and then press the Delete button: a confirmation window will open on the user's hand to verify whether or not the *Space* should be deleted.

Micro mode interaction. Two commands are available in the *micro* mode. The ***view*** interaction is based on touching a data item with the virtual hand:

it shows details about the data on the *Space* at hand. The second command is ***highlight***, which allows changing the color of a data item for contrasting with others. The way to highlight or remove the highlight is to point at the data item and press the Grab button.

Multiple coordinated *Spaces* are based on the **coordinate interactions**. Each time a *Space* is rotated, the linked spaces will rotate too (***navigation slaving***). When the data is highlighted or not, the linked data will undergo the same change, thus providing the ***linking-and-brushing*** functionality.

3.3 Implementation Details

We developed our proof-of-concept prototype using the Unity game engine, C#, and the SteamVR plug-in to build a tool compatible with the HTC Vive and Oculus Rift head-mounted displays. As we can see in Figure 1, datasets are read, and the visualizations are created in *Spaces*. A reference to the dataset and *Space* is instantiated in the **interaction module**, which is responsible for the interaction management thus linking both data and *Space* to support coordination. Also, each *Space* can be linked to other *Spaces* for *navigational slaving* and *brushing-and-linking* interactions. Each *Space* keeps track of the virtual hands that are inside it managed by the **controller module**, allowing the communication between them for *scaling* interaction. Axes of the coordinate system of each *Space* are drawn, which is useful when the user superimposes *Spaces* for comparison purposes, for instance.

The **controller module** manages the *macro/micro* modes of interaction (Figure 4). We use three states for managing the modes. The *idle* state is the default state, which indicates that the virtual hands are not inside any *Space*. The **primary use** state indicates that a virtual hand is ready to interact or is interacting with a *Space*, and the **secondary use** state is used for controlling interactions that need two virtual hands. Also, to differentiate the *macro/micro* modes for the virtual hands, the controller device is showed in the VR environ-

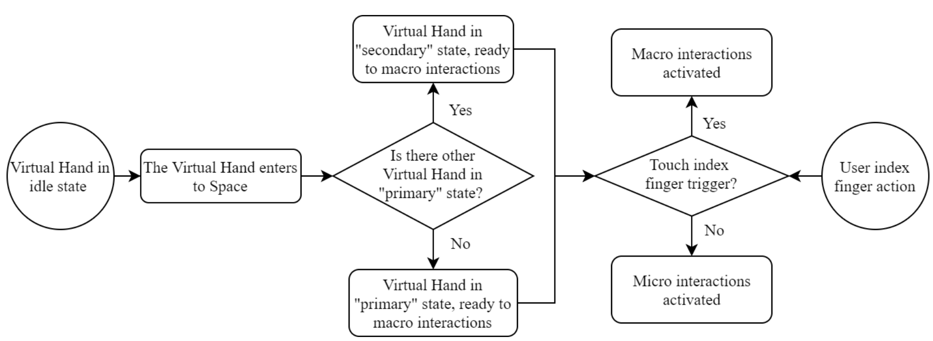


Fig. 4. Overview of the interaction flow and change of interaction modes.

ment every time the *macro* mode is active. The method chosen for the mode change is the index finger's proximity sensor.

4 Evaluation

The evaluation of our approach of multiple coordinate three-dimensional views in VR using the *Spaces* approach was performed through an experiment with users. We implemented a VR-based and a similar 3D desktop version with the same interactions to standardize the experiment variables. The *First Person* navigation technique was implemented for the desktop because it is more immersive than a third-person point of view (POV) [9] approach. Our user study compares the users' behavior while handling 3D visualizations in Desktop and Virtual Reality.

4.1 Hypotheses

To evaluate if our approach improves the MCV issues (mentioned in Section 1) [41], we focused on the comparative performance between the desktop (3D) and the virtual reality (VR) versions. We excluded the learning issue because it is challenging to have non-expert users available. Furthermore, issues related to infrastructure and implementation capacity were also not addressed because we assume that new technologies such as HMDs give support for those. The hypotheses that guided our user study are:

- **H1:** It will be faster to complete tasks using multiple coordinated views in VR than in 3D. Although there are several interaction techniques mapped to the desktop version, which can lead to interaction difficulties, the familiarity with mouse + keyboard can overcome those and allow a fair comparison.
- **H2:** The user will keep more information in VR than in 3D. We aim to analyze the first impression of the environment's data. The VR environment can be more fun for the user, and they would pay less attention to the data than in the desktop with physical space limitation. However, proprioception can help users in the VR version.
- **H3:** It will be easier to compare views in VR than in 3D. We aim to analyze the use of multiple visualizations, including cloning them.
- **H4:** The context switching will be hardest in VR than in 3D. The composed tasks let the user change visualization with different data interpretation. We displayed bar chart filters in one scene and increased the scatterplot chart filters in another.
- **H5:** Interacting with multiple coordinate views will be more comfortable in VR than in 3D.
- **H6:** Interacting with multiple coordinated views using the Spaces approach will be more efficient in VR than in 3D.
- **H7:** Multiple coordinated views using the Spaces approach will be easier to use in VR than in 3D.

4.2 Use Case

The use case we designed for testing our hypotheses is the exploration of a music dataset because music is a well-known topic that does not demand introduction effort.

The dataset used is the same previously used by Liang et al. [25], and it contains the following data for each music album: year, artist, genre, and also feature data from sound signals. For the experiment, the dataset was processed to avoid missing data. Finally, a total of 338 tracks were chosen.

The visualizations implemented are 3D scatterplots of music tracks, artists, and genres, obtained from a multidimensional projection technique, and bar charts showing the number of tracks per year, artist, and genre. The primary view is a scatterplot showing music tracks, and the other visualizations operate as music filters by brushing. Each visualization result is displayed in a *Space*.

The coordination between *Spaces* allows obtaining data corresponding to the intersection of filters applied to different visualizations and data corresponding to the union when more than one filter is applied to a single visualization. The *Spaces* of the genre and artist scatterplots are linked to the *Space* of the music scatterplot letting the *navigational slaving* interaction.

The 3D scatterplots are the result of the dimensionality reduction technique t-SNE [27] configured as follows: 100,000 iterations and perplexity equal to 40. We selected these parameters because they provided the best possible clusterization of genres. Then, to obtain the artist and genre scatterplots, we calculate the centroid using an average of their tracks' positions. Additionally, the centroids were multiplied by a weight (20) because more than one centroid was overlapping.

The implemented *brushing* interaction is based on highlighting data. Initially, the data is displayed with a shade that is sufficient for viewing details about the data item. A limitation of our brushing technique is that the information on the number of tracks is not refreshed (nor the height of the bar plots). The year, genre, and artist visualizations filter directly to the music scatterplot. Additionally, the user can clone any visualization for saving filtered data.

4.3 Tasks

For our user study, we designed composed tasks involving the manipulation of multiple views. The contexts used are artist, genre, and music tracks. Our test tries to emulate real system solutions. To finish each task, the user had to state the answer. A confirmation dialog similar to deleting cloned *Spaces* was used to confirm the end of each task.

T1. Select the artist with more music tracks of genre Punk between 2005 and 2010. A comparison of dense selected data from different filters is required. Cloning and comparing *Spaces* is the expected goal. Given multiple comparisons, this task exclusively tests H3 and helps to measure time for H1.

T2. Select the closest artist to the music most different from the majority of genre Folk between 2005 and 2010. This task aims at two objectives, the selection of the most atypical filtered data and the selection of the nearest data to a different context. We look for the overlapping *Spaces* – this task measures time to evaluate H1 and the accuracy to evaluate H4.

T3. Given to the user 2 min of free exploration, answer ten questions about genres, years, and artists with more and fewer music tracks (we asked 6 medium level questions), the more similar artists (2 difficult level questions) and music genres from the year 1991 and 1995 (2 very difficult level questions). With this task, we want to measure the memorization rate related to H2.

The hypotheses H5, H7 are evaluated through questionnaires, while H6 is assessed through the correct responses in tasks T1 and T2.

4.4 Training and Pilot Test

A brief description of the environment (VR and desktop), data, and visualizations were presented at the beginning of the experiment. The instructions of use for each environment were explained before it started. The first training took approximately 15 minutes (10 min to VR and 5 min to 3D Desktop) and included *macro* and *micro* interactions.

In a pilot test, we noted that the users could not perform the tasks taking advantage of the functionalities of cloning, overlaying, and walking navigation, and consequently, the tasks would demand too much time. In order to reduce the testing time, we extended the training, inviting them to walk over the virtual area to improve confidence. Also, short recommendations were given to deal with tasks that involved overlapping and cloning.

4.5 Experiment

The experiment was carried out in a 4 x 4 meters room; the users were aware of the space where they could walk. A similar virtual room was set up to improve immersion. Additionally, an existing TV in the room was also modeled in the VR environment for displaying the tasks (see Figure 5).

The user study followed a within-subjects design, combining VR and 3D desktop environments, 6/4 *Spaces*, where genre and artist scatterplots were added in the second case, and three tasks (independent variables). A Latin-square design counterbalanced the order of the environments and the number of *Spaces*. Each participant performed four sessions, where they started using 4 and 6 *Spaces* (or vice-versa) in the VR environment and later continued in a similar order on the desktop version (or vice-versa). Each of these scenarios started with a short training (learned from pre-testing) followed by the experimental session. We collected the time to complete each trial and correct answers as dependent variables.

Fig. 5. The virtual room had a TV that showed the tasks. The participants started the exploration in the middle of the room, and the visualizations were displayed around them. Users interacted with the visualizations using keyboard + mouse (left), while in the VR environment they used controllers as virtual hands (right).

The average training time was 30 minutes (20 min for VR and 10 min for 3D Desktop). After completing a task, the users were consulted through a Web version of the Subjective Mental Effort Questionnaire (SMEQ) [35], and one-select Emocards [10] used to validate H7 and H5, respectively. Finally, completing the number of *Spaces* series (6 or 4), a UMUX-lite form was asked to analyze H7.

The target population consisted of 19 participants (16 males and 3 females), where 18 were computer science students and 1 was a student on ecology. Their average age was 23 years. The majority of the participants had none or minimal experience with VR headsets; only three reported high experience.

5 Results

To validate the usability of the environments, we compared the perceived difficulty of the tasks T1 and T2 with the SMEQ "How difficult or easy was to conclude the Task overall?". Results (Figure 6) showed a normal distribution by Shapiro-Wilk, and the statistical analysis by ANOVA indicates that VR was easier than 3D Desktop ($p = .0163$).

Additionally, the System Usability Score (SUS) was calculated from UMUX-lite [24]. ANOVA analysis was used for finding the effects of the number of *Spaces* using the SUS score (normal distribution validated by Shapiro-Wilk), resulting in significant differences. Post-hoc analysis by Tukey's HSD suggests that using 4 Spaces in VR is significantly more usable than in a 3D Desktop with 4 Spaces ($p = .0121$) and 6 Spaces in VR shows a higher usability score than in 3D Desktop with 4 Spaces ($p = .0184$). H7 is validated in both analyzes (results can be visualized in Figure 7-left).

Analyzing the duration of tasks for validating H1, the time showed a normal distribution validated by Shapiro-Wilk. We found through ANOVA that there was no significant difference for T1 ($p = .7380$) and T2 ($p = .2830$) in the duration of tasks.

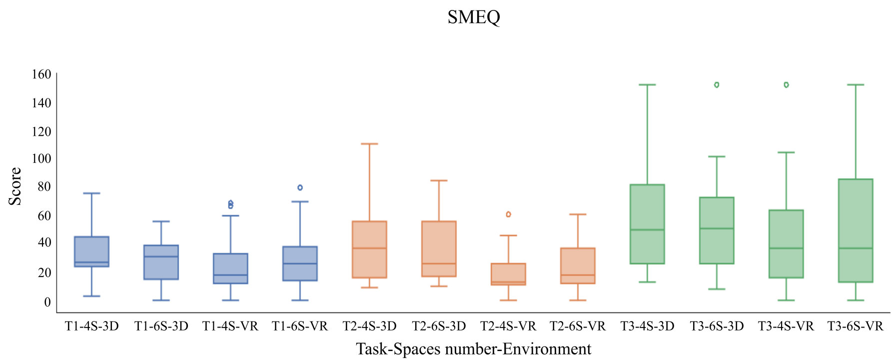


Fig. 6. Box-and-whiskers plot of SMEQ scores for each trial. For T1, the VR version with 4-Spaces was the easiest (Mean = 26.57, SD = 21.16), the 3D Desktop version with 4-Spaces was the most difficult (Mean = 34.21, SD = 20.24). Also, T2 in the VR version with 4S was the less difficult (Mean = 18.26, SD = 16.40) and the 3D Desktop version with 4-Spaces, the most difficult (Mean = 39.94, SD = 29.89). T3 had similar result, the VR version was hardly less difficult (Mean = 47.50, SD = 41.24) than 3D Desktop (Mean = 55.28, SD = 36.55).

We selected the correct answers to calculate the efficiency for validating H3, H4 and verify H6. From 152 answers, we obtained only 8 wrong answers in T1, and 17 errors in T2. The time of correct answers did not show significant differences for T1 (p = .9170) and T2 (p = .9070). The efficiency distribution can be observed in Figure 8.

Friedman test was performed to compare the number of correct answers for T3 (Shapiro-Wilk showed no normal distribution). Results demonstrate that there are no significant differences (p = .7960), not validating H2 (see Figure 8-right).

The comfortability of each environment was evaluated based on emotional categories using emocards (Figure 7-right). We calculated Cohen's kappa of 114 responses (6 answers by user), evaluating the two environments per categorical answers ("pleasant", "unpleasant" and "neutral"). The results are summarized in Table 1. Cohen's kappa was 0.26 and conducted a reliability "fair" [20]. We concluded that the VR version was "average pleasant" (Mdn = 3) over the "calm pleasant" for 3D Desktop (Mdn = 4) with fair reliability validating H5.

The SUS ranged from 28.32 to 87.90 for 3D Desktop (M = 66.80, SD = 13.07) and from 44.57 to 87.90 for the VR version (Mean = 77.64, SD = 10.44). According to surveys that compare SUS scores for different systems, our VR version is ranked as "Good" [1].

In summary, only H5 had significant differences and was validated, showing that our approach is more comfortable than the 3D version. The other hypotheses could not be proved nor rejected due to lack of statistical significance.

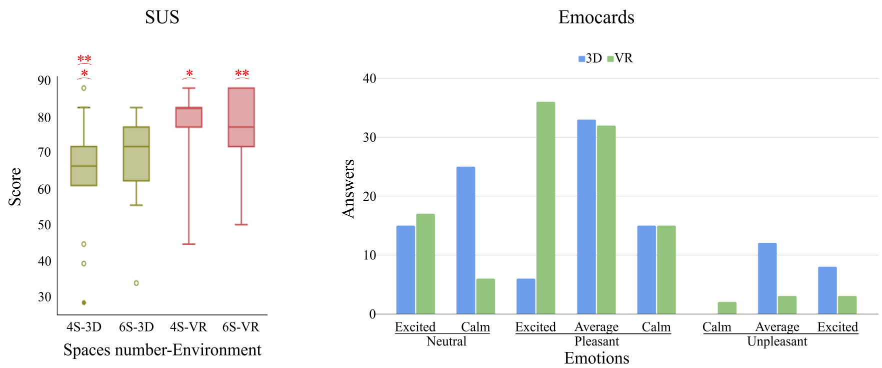


Fig. 7. Box-and-whiskers plot (left) of SUS score for each condition. * and ** indicate significant differences. Histogram of emocards (right) selected by users per environment (VR and 3D).

Table 1. Results of 114 emotional answers per environment.

		3D Desktop			
		Pleasant	Neutral	Unpleasant	Total
VR	Pleasant	46	24	13	83
	Neutral	6	15	2	23
	Unpleasant	2	1	5	8
	Total	54	40	20	114

6 Discussion and Limitations

While visual analytics systems often use multiple coordinated views to explore and analyze complex datasets in 2D desktop environments, literature shows that fully-immersive analytics applications lack well-established techniques to use similar approaches.

We analyzed the difficulties of multiple coordinated views and proposed and evaluated an approach to provide multiple three-dimensional views in immersive Virtual Reality. Our method allows the user to use virtual hands to grab the visualizations displayed in three-dimensional versions of WIMPs (the *Spaces*) for free interaction in *macro* mode and interacting with the data items in *micro* mode. This way, the approach divides the interaction between *Spaces* and data, respectively. Moreover, the use of two modes for each *virtual hand* increases the number of grouped interactions that can be implemented (*macro, micro, macro - macro, micro - micro, macro - micro*). Another significant aspect is that our approach does not depend on the user's dominant hand.

6.1 Findings

The evaluation of our approach was based on comparing it with a 3D desktop version for testing 7 hypotheses. We designed and conducted an experiment

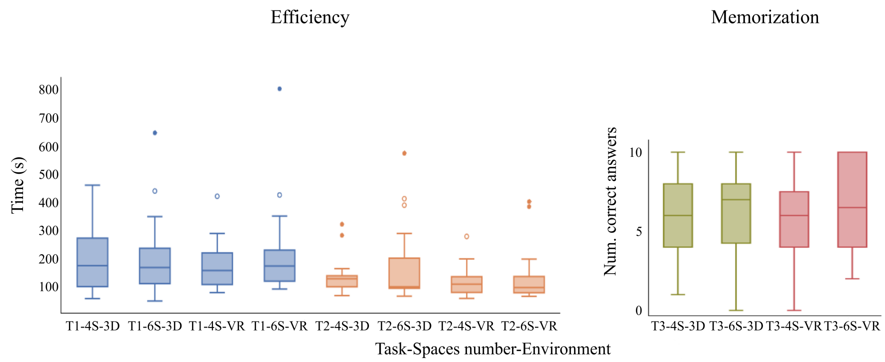


Fig. 8. Box-and-whiskers plot of time (seconds) for correct answers for T1 and T2 (left). Similar distributions were obtained for T1 in the 3D Desktop version (Mean = 187.54, SD = 104.33) and VR (Mean = 202.68, SD = 136.39), and T2 in the 3D Desktop version (Mean = 135.57, SD = 74.58) and VR (Mean = 123.44, SD = 86.31). Box-and-whiskers plot of trials per number of correct answers (right). No significant differences were found.

where 19 subjects explored a music dataset, employing 4 and 6 coordinated views in both environments.

Before the actual experiment, a pilot test with five users made us recognize that although the case study was easy, the manipulation of multiple views required users with experience in data exploration. Interactions, as navigation and visualization grabbing, cloning, and overlaying, were not known, so they did not learn the most optimal manner to perform the tasks, and the tests demanded excessive time. The training was then improved, reducing the experiment time and the difficulties of the tasks.

However, the pilot test also showed that the usability of grabbing and manipulating visualizations had good results in comfort, in favor of our VR version. The three-dimensional visualization could be placed in different locations for better exploration. In addition, the training in physical walking for navigation caused the users to trust our system. This is reflected in the comfort results and comments. Furthermore, the navigation for the 3D desktop version was intuitive because most users knew the FPS format, but the translation and rotation interactions were hated due to the depth.

Concerning the hypotheses, although the quantitative results indicated no significant differences between the VR and 3D desktop, some interesting findings came from the questionnaires.

As for hypothesis **H1**, "It will be faster to complete tasks using multiple coordinated views in VR than in 3D." (tasks T1 and T2), one might assume that the familiarity with mouse + keyboard could lead the desktop version to be faster than VR but that was not confirmed. This might suggest that our approach did not introduce difficulties even for users with no experience in VR, presenting competitive execution times.

Regarding hypothesis **H2**, "The user will keep more information in VR than in 3D", it was evaluated based on the correct answers for task T3. Results were also non-significant, most likely due to a learning effect. We noticed that the participants acquired memorization strategies after completing task T3 and applied them to the other tasks. The shuffled questions ordering did not avoid the learning effect as we assumed it would.

The time spent and correct answers for tasks T1 and T2 allowed us to evaluate hypothesis **H3**, "It will be easier to compare views in VR than in 3D" and **H6**, "Interacting with multiple coordinated views using the *Spaces* approach will be more efficient in VR than in 3D". Both hypotheses were not statistically confirmed. However, participants commented that they had better confidence using the VR version, probably by novel technology. Also, most of them liked being able to organize the visualizations in the 3D virtual environment.

Regarding **H4**, "The context switching will be hardest in VR than in 3D", was also assessed by task T2, which was far more complex than the others. Since there were no significant differences in time or number of correct answers between the VR and 3D versions, this hypothesis was also not confirmed. Such a result might suggest that our approach did not increase the cognitive effort demanded to complete the task compared to a well-known setting such as the desktop.

Finally, the hypotheses **H5**, "Interacting with multiple coordinate views will be more comfortable in VR than in 3D", and **H7**, "Multiple coordinated views using the *Spaces* approach will be easier to use in VR than in 3D", were evaluated through questionnaires. The results showed that the comfort of handling multiple *Spaces* is higher in our fully-immersive environment than in the 3D desktop version, which probably might have influenced the same good result regarding usability.

Summary. Motivated by the challenges related to multiple views [41, 17, 19] and the increasing use of immersive analytics applications [29], we proposed an approach that allows composite visualization patterns in VR and comfortable and easy ways of interacting with multiple 3D visualizations in such environments. Our results show that the Desktop version is not significantly better than the VR version in terms of time and accuracy despite using the standard FPS approach with keyboard and mouse. Multiple 3D views are not typically used in desktop versions, and this could be the reason for the non-significant results. Subjective results show that our VR approach is significantly better than the Desktop version. We infer that the participants are not able to explore multiple 3D visualizations with common desktop interaction devices.

6.2 Limitations

When designing our approach regarding the composite visualization patterns, we chose to support the juxtaposition and superimposition patterns. However, our application's architecture separates interaction with the *Spaces* (macro mode) from interaction with the data (micro mode), allowing a *Space* to be used with any data visualization. Therefore, overloading (by proximity) and integration (showing linking) are feasible patterns to evaluate in future works.

Another limitations are related to our experimental application. Multiple views are used to solve complex tasks, which is not feasible with non-expert participants. Having only non-expert users as subjects may be the most probable cause of not finding significant differences.

The brushing technique also introduced a limitation because the information on the number of music tracks is never updated. If we had that feature, we could have proposed other comparison tasks. Finally, the interaction techniques are based on direct contact between the users' hands and the virtual cube representing the *Spaces*. So, far interaction strategies using ray casting are missing.

7 Conclusions and Future Work

In this work, we have presented an Immersive Analytics approach to interact with multiple coordinated three-dimensional views in Virtual Reality. The main idea is that the user can grab the visualizations inside a virtual cube container (a *Space*), allowing composite patterns. The proposed technique combines different components to provide users with a comfortable interaction. We have demonstrated the usability of our approach in a user study with non-expert participants comparing with a similar 3D desktop version. It suggests that our approach can be used in real-life scenarios.

From the lessons learned with this experiment, in an on-going work we are considering to offer to the users the possibility of interacting with near objects using the virtual hand and also with far objects, through ray casting.

As future work, we would like to conduct an extensive experimental study involving a more complex use case involving different visualization techniques and employing the overloading and integration CVVs patterns, with the support of expert participants. Considering that expert users in visualization are not necessarily familiar with immersive VR and the use of the proprioception in virtual environments, we will also extend the training to motivate them to better explore the real environment and their body movements. In this way, we believe we will be able to better investigate the hypotheses that could not be demonstrated statistically here, and reason on the results achieved.

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References

1. Bangor, A., Kortum, P., Miller, J.: Determining what individual sus scores mean: Adding an adjective rating scale. J. Usability Studies **4**(3), 114–123 (May 2009), https://dl.acm.org/doi/10.5555/2835587.2835589
2. Batch, A., Cunningham, A., Cordeil, M., Elmqvist, N., Dwyer, T., Thomas, B.H., Marriott, K.: There is no spoon: Evaluating performance, space use, and presence with expert domain users in immersive analytics. IEEE transactions on visualization and computer graphics **26**(1), 536–546 (2019). https://doi.org/10.1109/TVCG.2019.2934803
3. Bowman, D., Kruijff, E., LaViola, J., Poupyrev, I.: 3D User Interfaces: Theory and Practice, CourseSmart eTextbook. Pearson Education (2004), https://books.google.com.br/books?id=JYzmCkf7yNcC
4. Butcher, P.W.S., John, N.W., Ritsos, P.D.: Vria - a framework for immersive analytics on the web. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems. p. 1–6. CHI EA '19, Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3290607.3312798
5. Card, S.K., Mackinlay, J.D., Shneiderman, B. (eds.): Readings in Information Visualization: Using Vision to Think. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA (1999), https://dl.acm.org/doi/10.5555/300679
6. Chandler, T., Cordeil, M., Czauderna, T., Dwyer, T., Glowacki, J., Goncu, C., Klapperstueck, M., Klein, K., Marriott, K., Schreiber, F., Wilson, E.: Immersive analytics. In: 2015 Big Data Visual Analytics (BDVA). pp. 1–8 (Sep 2015). https://doi.org/10.1109/BDVA.2015.7314296
7. Cordeil, M., Cunningham, A., Bach, B., Hurter, C., Thomas, B.H., Marriott, K., Dwyer, T.: Iatk: An immersive analytics toolkit. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). pp. 200–209 (March 2019). https://doi.org/10.1109/VR.2019.8797978
8. Cordeil, M., Cunningham, A., Dwyer, T., Thomas, B.H., Marriott, K.: Imaxes: Immersive axes as embodied affordances for interactive multivariate data visualisation. In: Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology. p. 71–83. UIST '17, Association for Computing Machinery, New York, NY, USA (2017). https://doi.org/10.1145/3126594.3126613
9. Denisova, A., Cairns, P.: First person vs. third person perspective in digital games: Do player preferences affect immersion? In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. p. 145–148. CHI '15, Association for Computing Machinery, New York, NY, USA (2015). https://doi.org/10.1145/2702123.2702256
10. Desmet, P., Overbeeke, K., Tax, S.: Designing products with added emotional value: Development and appllcation of an approach for research through design. The Design Journal **4**(1), 32–47 (2001). https://doi.org/10.2752/146069201789378496
11. Febretti, A., Nishimoto, A., Mateevitsi, V., Renambot, L., Johnson, A., Leigh, J.: Omegalib: A multi-view application framework for hybrid reality display environments. In: 2014 IEEE Virtual Reality (VR). pp. 9–14 (March 2014). https://doi.org/10.1109/VR.2014.6802043
12. Fonnet, A., Prié, Y.: Survey of immersive analytics. IEEE Transactions on Visualization and Computer Graphics **27**(3), 2101–2122 (March 2021). https://doi.org/10.1109/TVCG.2019.2929033

13. Gračanin, D.: Immersion versus embodiment: Embodied cognition for immersive analytics in mixed reality environments. In: Schmorrow, D.D., Fidopiastis, C.M. (eds.) Augmented Cognition: Intelligent Technologies. pp. 355–368. Springer International Publishing, Springer, Cham (2018), https://doi.org/10.1007/978-3-319-91470-1_29
14. Greffard, N., Picarougne, F., Kuntz, P.: Beyond the classical monoscopic 3d in graph analytics: An experimental study of the impact of stereoscopy. In: 2014 IEEE VIS International Workshop on 3DVis (3DVis). pp. 19–24 (Nov 2014). https://doi.org/10.1109/3DVis.2014.7160095
15. Hurter, C., Riche, N.H., Drucker, S.M., Cordeil, M., Alligier, R., Vuillemot, R.: Fiberclay: Sculpting three dimensional trajectories to reveal structural insights. IEEE Transactions on Visualization and Computer Graphics **25**(1), 704–714 (Jan 2019). https://doi.org/10.1109/TVCG.2018.2865191
16. Javed, W., Elmqvist, N.: Exploring the design space of composite visualization. In: 2012 IEEE Pacific Visualization Symposium. pp. 1–8 (Feb 2012). https://doi.org/10.1109/PacificVis.2012.6183556
17. Javed, W., Elmqvist, N.: Exploring the design space of composite visualization. In: 2012 IEEE Pacific Visualization Symposium. pp. 1–8. IEEE (2012)
18. Johnson, S., Orban, D., Runesha, H.B., Meng, L., Juhnke, B., Erdman, A., Samsel, F., Keefe, D.F.: Bento box: An interactive and zoomable small multiples technique for visualizing 4d simulation ensembles in virtual reality. Frontiers in Robotics and AI **6**, 61 (2019). https://doi.org/10.3389/frobt.2019.00061
19. Knudsen, S., Carpendale, S.: Multiple views in immersive analytics. In: IEEE VIS 2017 Workshop on Immersive Analytics (2017), https://tinyurl.com/immersiveviews
20. Landis, J.R., Koch, G.G.: The measurement of observer agreement for categorical data. Biometrics **33**(1), 159–174 (1977), http://www.jstor.org/stable/2529310
21. Langner, R., Kister, U., Dachselt, R.: Multiple coordinated views at large displays for multiple users: Empirical findings on user behavior, movements, and distances. IEEE Transactions on Visualization and Computer Graphics **25**(1), 608–618 (Jan 2019). https://doi.org/10.1109/TVCG.2018.2865235
22. Lee, B., Hu, X., Cordeil, M., Prouzeau, A., Jenny, B., Dwyer, T.: Shared surfaces and spaces: Collaborative data visualisation in a co-located immersive environment. IEEE Transactions on Visualization and Computer Graphics **27**(2), 1171–1181 (Feb 2021). https://doi.org/10.1109/tvcg.2020.3030450
23. Lee, B., Isenberg, P., Riche, N.H., Carpendale, S.: Beyond mouse and keyboard: Expanding design considerations for information visualization interactions. IEEE Transactions on Visualization and Computer Graphics **18**(12), 2689–2698 (Dec 2012). https://doi.org/10.1109/TVCG.2012.204
24. Lewis, J.R., Utesch, B.S., Maher, D.E.: Umux-lite: When there's no time for the sus. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. p. 2099–2102. CHI '13, Association for Computing Machinery, New York, NY, USA (2013). https://doi.org/10.1145/2470654.2481287
25. Liang, D., Gu, H., O'Connor, B.: Music genre classification with the million song dataset. Machine Learning Department, CMU (2011), https://www.ee.columbia.edu/~dliang/files/FINAL.pdf
26. Liu, J., Prouzeau, A., Ens, B., Dwyer, T.: Design and evaluation of interactive small multiples data visualisation in immersive spaces. In: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). pp. 588–597 (2020). https://doi.org/10.1109/VR46266.2020.00081

27. van der Maaten, L., Hinton, G.: Visualizing data using t-sne. Journal of Machine Learning Research **9**(86), 2579–2605 (2008), https://jmlr.org/papers/v9/vandermaaten08a.html
28. Mahmood, T., Butler, E., Davis, N., Huang, J., Lu, A.: Building multiple coordinated spaces for effective immersive analytics through distributed cognition. In: 2018 International Symposium on Big Data Visual and Immersive Analytics (BDVA). pp. 1–11 (Oct 2018). https://doi.org/10.1109/BDVA.2018.8533893
29. Marriott, K., Chen, J., Hlawatsch, M., Itoh, T., Nacenta, M.A., Reina, G., Stuerzlinger, W.: Immersive analytics: Time to reconsider the value of 3d for information visualisation. In: Immersive analytics, pp. 25–55. Springer International Publishing, Cham (2018). https://doi.org/10.1007/978-3-030-01388-2_2
30. Prouzeau, A., Lhuillier, A., Ens, B., Weiskopf, D., Dwyer, T.: Visual link routing in immersive visualisations. In: Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces. p. 241–253. ISS '19, Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3343055.3359709
31. Ran, X., Slocum, C., Gorlatova, M., Chen, J.: Sharear: Communication-efficient multi-user mobile augmented reality. In: Proceedings of the 18th ACM Workshop on Hot Topics in Networks. p. 109–116. HotNets '19, Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3365609.3365867
32. Roberts, J.C.: State of the art: Coordinated multiple views in exploratory visualization. In: Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV 2007). pp. 61–71 (July 2007). https://doi.org/10.1109/CMV.2007.20
33. Russo Dos Santos, C., Gros, P.: Multiple views in 3d metaphoric information visualization. In: Proceedings Sixth International Conference on Information Visualisation. pp. 468–473 (July 2002). https://doi.org/10.1109/IV.2002.1028815
34. Satriadi, K.A., Ens, B., Cordeil, M., Czauderna, T., Jenny, B.: Maps around me: 3d multiview layouts in immersive spaces. Proc. ACM Hum.-Comput. Interact. **4**(ISS) (Nov 2020). https://doi.org/10.1145/3427329
35. Sauro, J., Dumas, J.S.: Comparison of three one-question, post-task usability questionnaires. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. p. 1599–1608. CHI '09, Association for Computing Machinery, New York, NY, USA (2009). https://doi.org/10.1145/1518701.1518946
36. Scherr, M.: Multiple and coordinated views in information visualization. Trends in Information Visualization **38**, 33 (2008), https://www.mmi.ifi.lmu.de/lehre/ws0809/hs/docs/scherr.pdf
37. Sereno, M., Wang, X., Besancon, L., Mcguffin, M.J., Isenberg, T.: Collaborative work in augmented reality: A survey. IEEE Transactions on Visualization and Computer Graphics pp. 1–1 (2020). https://doi.org/10.1109/TVCG.2020.3032761
38. Sicat, R., Li, J., Choi, J., Cordeil, M., Jeong, W.K., Bach, B., Pfister, H.: Dxr: A toolkit for building immersive data visualizations. IEEE Transactions on Visualization and Computer Graphics **25**(1), 715–725 (Jan 2019). https://doi.org/10.1109/TVCG.2018.2865152
39. Su, S., Perry, V., Dasari, V.: Comparative study for multiple coordinated views across immersive and non-immersive visualization systems. In: Chen, J.Y., Fragomeni, G. (eds.) Virtual, Augmented and Mixed Reality. Multimodal Interaction. pp. 321–332. Springer International Publishing, Cham (2019), https://doi.org/10.1007/978-3-030-21607-8_25
40. Thomas, J.J., Cook, K.A.: Illuminating the path: The research and development agenda for visual analytics (2005), https://www.hsdl.org/?abstract&did=485291

41. Wang Baldonado, M.Q., Woodruff, A., Kuchinsky, A.: Guidelines for using multiple views in information visualization. In: Proceedings of the Working Conference on Advanced Visual Interfaces. p. 110–119. AVI '00, Association for Computing Machinery, New York, NY, USA (2000). https://doi.org/10.1145/345513.345271