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Narrative scientific data visualization in an immersive environment

Richen Liu *, Hailong Wang*, Chuyu Zhang, Xiaojian Chen, Lijun Wang, Genlin Ji, Bin Zhao, Zhiwei Mao and Dan Yang

School of Computer and Electronic Information/School of Artificial Intelligence, Nanjing Normal University, Nanjing, 210023, China

*To whom correspondence should be addressed
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Abstract

Motivation: Narrative visualization for scientific data explorations can help users better understands the domain knowledge, because narrative visualizations often present a sequence of facts and observations linked together by a unifying theme or argument. Narrative visualization in immersive environments can provide users with an intuitive experience to interactively explore the scientific data, because immersive environments provide a brand new strategy for interactive scientific data visualization and exploration. However, it is challenging to develop narrative scientific visualization in immersive environments. In this article, we propose an immersive narrative visualization tool to create and customize scientific data explorations for ordinary users with little knowledge about programming on scientific visualization. They are allowed to define point of interests (POIs) conveniently by the handler of an immersive device.

Results: Automatic exploration animations with narrative annotations can be generated by the gradual transitions between consecutive POI pairs. Besides, interactive slicing can be also controlled by device handler. Evaluations including user study and case study are designed and conducted to show the usability and effectiveness of the proposed tool.

Availability and implementation: Related information can be accessed at: https://dabigtou.github.io/richenliu/

Contact: richen@pku.edu.cn or 19180104@njnu.edu.cn

Supplementary information: Supplementary data (video) are available at *Bioinformatics* online.

1 Introduction

Narrative approaches toward data visualizations and data explorations for scientific data can help users especially for the non-experts get a better understanding of the domain knowledge. They often rely on a combination of annotations, highlighting, animated transitions, and single-frame interactivity (Segel and Heer, 2010). Typically, the data are not presented all at once. Rather, each view is presented in an animated fashion, with annotations explaining the steps. Narrative animations are often used to disseminate domain knowledge and illustrate the principal ideas of scientific processes and natural phenomena.

The traditional scientific data visualizations and explorations are limited by the 2-D interactions manipulated by keyboard, mouse and multi-touch devices, which restrict the operation space within a 2-D space. Due to the limitations of the traditional devices, the mouse and multi-touch devices show poor performance in terms of depth-direction moving and hybrid 3-D interactions (Fang et al., 2020).

The immersive experience allows users to better observe and explore scientific data in a 3-D space. It enables users to intuitively discover significant features and has an intuitive spatial perception of the data. The immersive technologies such as virtual reality (VR), augmented reality (AR) and mixed reality (MR) usually employ an extra device called head-mounted display (HMD) to make the real world and the virtual world mixed, making people perceive the data. They refer to interactive experiences of a real-world environment in which the objects in the real world are enhanced by digit devices generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.

Narrative visualization in immersive environments can provide users an intuitive experience to interactively explore the scientific data, because immersive environments provide a brand new strategy for interactive scientific data visualization and exploration. However, it is challenging to develop narrative scientific visualization in immersive environments due to two reasons: First, it is challenging for users to understand the codes or even customize the story-telling animations through programming because there is a steep learning curve for them to understand or even edit the complex codes of scientific visualization. Scientific data visualization often relies on complex implementations such as computation-intensive programming and hardware dependent rendering. Second, immersive visualization often requires extra devices like VR/AR/MR devices or somatosensory interaction devices. It is hard to couple the existing scientific visualization codes into the immersive devices, which are often some embedded system with a standalone development environment.

In this article, we propose an immersive narrative visualization tool to create and customize scientific data explorations for ordinary users with little programming knowledge on scientific visualization, who can define point of interests (POIs) conveniently by the handler of an immersive device. Users do not need to know the complex computation and rendering implementations, i.e. the codes of data modelling, model computation, visualization rendering, and so on. Automatic exploration animations with narrative annotations can be generated by the gradual transitions between consecutive POI pairs. Evaluations including user study and case study are designed and conducted to show the usability and effectiveness of the proposed tool. Besides, interactive slicing can be also controlled by device handler.

To make the ordinal users with little programming knowledge on scientific visualization and non-experts to customize the exploration process easily, we build an immersive framework for them to customize narrative animations to better illustrate and explore scientific data. Users just need to load the data and customize the steps by using familiar codes. Besides, users are also allowed to select a rendering mode, such as sphere, cuboid, and so on. Users can also select an immersive environment for the narrative visualization. Furthermore, users can add narrative annotations for each step of scientific data explorations. For example, users can annotate each step for the 2-D map-based visualization for different countries or regions like America, Africa, Australia, Asia, and so on. It brings many new opportunities to enhance interactive narrative visualization with customized animations freely in an immersive environment.

We test our system with four datasets: 2-D map-based global carbon emission data, three CT scanning biomedical volume data including lung, hand and head. The rendering tasks are assigned to a VR device and explored by users in an immersive way. It opens up many opportunities for enhancing human interaction with three-dimensional objects and visualizations freely. Evaluations including user study and case study are designed and conducted to show the usability and effectiveness of the proposed tool.

2 Related work

In this article, we review the related work on narrative visualization, rapid customization and scientific data visualization to show the background of this work. Some representative papers have been summarized in Table 1 follow the style of survey paper (Chen et al., 2019a; Shen et al.,2020).

2.1 Narrative visualization for scientific data

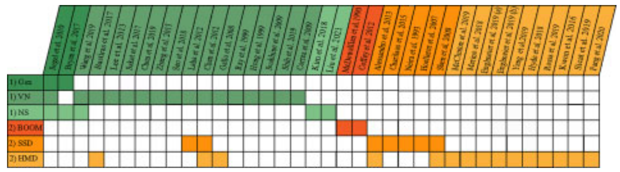
2.1.1 Genre

In the past few years, people tended to present data content in the form of stories so that users can better explore and conduct teaching-related activities. Consequently, narrative visualization for scientific data has received increasing attention. As a pioneering design study work in the narrative visualization domain, Segel and Heer (2010) observed the emerging trend of data visualization for journalists to tell stories. Bryan et al. (2017) proposed a time summary image (TSI) method to explore data and create corresponding stories based on the data to perform linear story expressions.

2.1.2 Visual narrative tactics

Inspired by some film narrative models, Kim et al. (2018) put forward story curves, the visualization technology to explore and communicate non-linear narratives. Liu *et al.* (2021a) proposed a novel narrative data presentation method named IGScript to help novice users or domain experts with limited programming knowledge to generate narrative animations for scientific data.

Table 1. Some representative papers selected from each of the two major categories It consists of literatures that focuses on Genre (Gen), Visual Narrative Tactics (VN) or Narrative Structure Tactics (NS), and the immersive visualization for scientific data categorized into four types according to their technics, like Surround-Screen Display (SSD), Binocular Omni Orientation Monitor (BOOM), and Head Mounted Display (HMD)



2.1.3 Narrative structure tactics

Another important role of narrative visualization is for data experts to show and exchange ideas to the audience and realize the interaction of data teaching. Sketchstory (Lee et al., 2013) was described as a digital white board capable of creating personalized and expressive data charts. Subsequently, Saket *et al.* (2017) proposed a visual representation paradigm. The illustrative visualization can also be used to present the scientific data, e.g. there are a series of work (Gao et al., 2019a; Liu et al., 2018, 2020) proposed to illustrate seismic volume data.

In the presentation of narrative visualization, Chen et al. (2019b) came up with a narrative visualization approach with an interactive slideshow. A slide authoring tool named Narvis (Wang et al., 2019) was also proposed. It aims to introduce data visualization to non-experts effectively and improve the experts' efficiency of data visualization in tutorials. Bastiras and Thomas (2017) also realized the process of integrating narrative visualization with modern 3-D VR technology.

2.2 Immersive visualization for scientific data

In this section, we summarize two aspects of immersive visualization for scientific data as follows: Immersive Platforms and Head Mounted Display Technologies. These methods use two types of data: medical data and non-medical data. Volume visualization is widely used in scientific data visualization (Liu et al., 2021b; Ray et al., 1999). However, these technologies only display data through the screen, which cannot make users understand and explore the data intuitively.

2.2.1 Binocular omni orientation monitor

In order to enhance the visual perception of the spatial structure of volume data and make the visualization effect more flexible and easy to use, scientists created some immersive platforms to let users have an immersive feeling in the process of exploration, so as to better explore data. The first immersive platform, called Binocular Omni Orientation Monitor (BOOM), was implemented (Ian et al., 1990). It was a balanced CRT-based stereoscopic display, which consists of a manipulator fixed on the ground, and each joint angle is controlled by a microprocessor and a motor to ensure that the movement of the structure requires low energy consumption by users.

2.2.2 Surround-screen display

Cave automatic virtual environment (CAVE; Cruz-Neira et al., 1993) is a highly immersive virtual demonstration environment composed of three or more hard back projection walls. For example, Allosphere (Hollerer et al., 2007) is a 10 m spherical CAVE. The CAVE2 (Febretti et al., 2013) and the Reality Deck (Papadopoulos

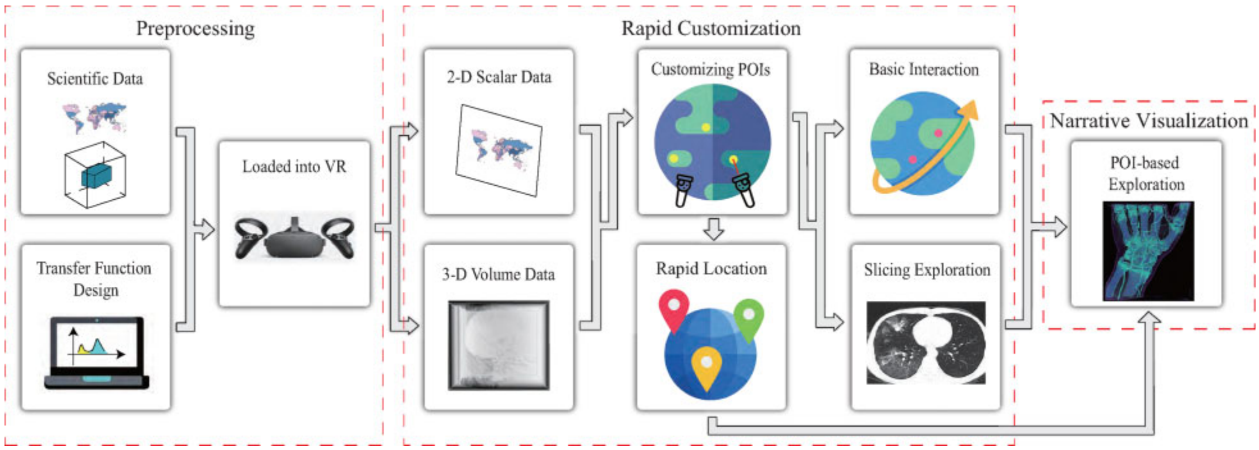


Fig. 1. Our proposed tool consists of three steps, namely pre-processing, rapid customization and generating narrative visualization animations. In the pre-processing stage, users obtain scientific data and adjust the transfer function on the PC side. Our tool allows users to define point of interests (POIs) by rapid location, basic interaction (i.e. rotation, translation and scaling) and slicing exploration functions. Finally, users can experience narrative visualization animations based on POIs

et al., 2015) were firstly built in 2013 and 2015, respectively. These systems used tiled-displays instead of projectors. Although they lost a certain immersion experience, these systems did improve the resolution of classic CAVE but are quite expensive to develop.

2.2.3 Head mounted display technologies

In the process of the research on the effect of display characteristics, Chen *et al.* (2012) found that the performance of task completion is not proportional to the size of the screen. Compared with the giant surround-screen display, HMD gives users a better experience, and promotes the exploration and comprehensive understanding of data. With the extensive popularization and application of HMD, scientists tended to use HMD as a more portable display technology to process the related work of VR/AR/MR.

David et al. (Englmeier et al., 2019b) put forward that spherical visualizations can facilitate the exploration of certain types of data and better support user interaction in data analysis and exploration. They then further studied the visual effects of holding a virtual global in their hands (Englmeier et al., 2019a) and compared the use of two acrylic glass balls of different sizes to draw corresponding conclusions. Yang *et al.* (2019) also mentioned in their article that 3-D sphere is the fastest and most accurate flow visualization. 3-D balls are more effective than 2-D or 3-D flows on planar maps because they make up for possible occlusion and distortion and solve visual confusion in complex flowcharts. Furthermore, VRGE (Hyde et al., 2018) and MOSIS (Rossa et al., 2019) presented in 2018 and 2019 also enable geologists to establish and understand the increasingly complex geological model in the virtual field environment.

3 Our method

To assist ordinary users with little programming knowledge on scientific visualization, we propose an immersive narrative visualization tool (Fig. 1). Users only need to load the scientific data and compiled transfer function into the proposed tool and customize the steps to get the narrative rendering animations and explore the results in an immersive environment.

3.1 Pre-processing

3.1.1 Transfer function design

We design a transfer function editor on the traditional PC side, which equipped keyboard–mouse interaction devices. The transfer function of a scientific volume data is edited online on PC side in a visual steering scheme because it is easy to manipulate the traditional 2-D transfer function editor in a 2-D visualization space. The transfer function editor consists of an adjustment view (Fig. 2 left) and a preview view (Fig. 2 right). The adjustment view is designed based on a grid coordinate system. The x-axis represents the intensity value of the volume data, and the y-axis represents the opacity of the intensity on the x-axis. At the same time, users can change the opacity ratio of the y-axis unit grid by sliding the wheel on the right side of the coordinate system. The lower part in the adjustment view is the colour spectrum. Users can select a colour (RGBA values) from the colour band chart, and then determine the corresponding saturation in the rectangle to get an optimal colour value. After that, users can adjust the control points in the grid coordinate system of the transfer function editor, forming various peaks, and achieve the change of colour and opacity for a certain intensity value of the volume data. After obtaining a suitable preview effect, users can save the transfer function data and share them into the immersive device for immersive rendering. Users can adjust the transfer function more effectively that reflects the structures with the help of the editor.

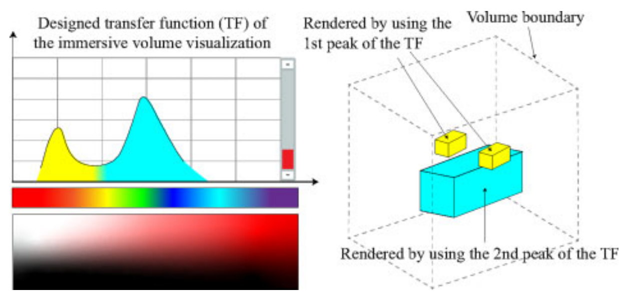


Fig. 2. The transfer function editor consists of an adjustment view (left) and a preview view (right). In the adjustment view, the user can modify the color and opacity corresponding to a certain range of intensity values for a tissue if it is a medical data, and preview the real-time rendering result in the preview view. (Color version of this figure is available at *Bioinformatics* online.)

3.2 Interactive customization of POIs

3.2.1 POI definitions

The proposed approach is allowed to define POIs to better generate the narrative animations and explore scientific data in immersive devices. Users can define their POIs through the interaction of the Touch Handle of the immersive device. Users can set the mark points by pressing the 'IndexTrigger' button on the handle for the POIs on 2-D scalar data (i.e. the global map-based data) and 3-D volume data, and then press the 'HandTrigger' button to hide the ray of handle (in Fig. 3b). According to the order of marked POIs, the narrative visualization animation is generated and users can explore it automatically.

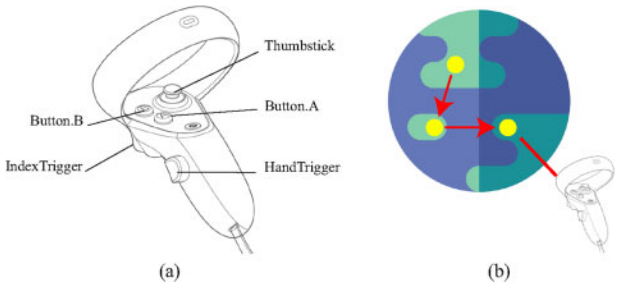


Fig. 3. Buttons and joystick on the Touch Handle can be defined to mapped to different functions. (**a**) The joystick 'Thumbstick' is connected to the rotation interaction in our experiment and user study. Buttons 'A' and 'B' can be used to perform the zoom in and zoom out of the rendering result. (**b**) Users customize the POIs through the handle and add narrative annotations for each step of the scientific data exploration animation, which are automatically generated by the POIs sequence selected by users

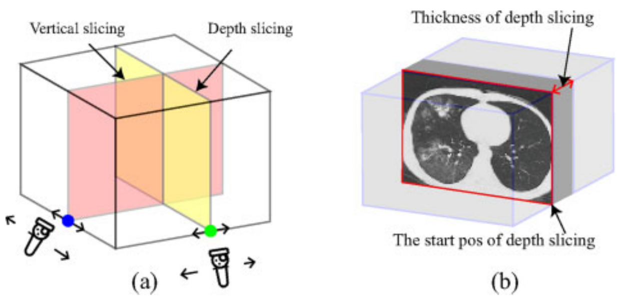


Fig. 4. Users can intuitively adjust the starting position and thickness of the slicing through the Touch Handle. (**a**) Users can adjust the position of the depth slicing by moving the handle in and out, and adjust the position of the vertical slicing by moving the handle left and right. (**b**) Users can change the starting position by moving the handle in and out, and adjust the thickness of the slicing by pressing the handle buttons

3.3 Interaction design of the immersive visualization tool

Actually, we use Oculus Quest as our immersive device in our experiment. The movement of the view is handled by the tracking system of Oculus Quest, and other interaction methods are handled by Touch Handle and our defined event respond script.

3.3.1 Basic interactions

We provide some basic interactions based on the Oculus Touch Handle. To interact with the rendering result, we bind basic interactions such as rotation, translation and scaling (zoom-in and zoom-out) to the buttons and joystick on the Touch Handle (in Fig. 3a).

3.3.2 Rapid location definitions

We define the rapid location functions in the immersive device for the further POI location altering. It is allowed to automatically adjust the position and rotation angle of the rendering result by the redefined POIs. At the same time, the narrative annotations of this POI will be drawn to the upper right corner of the field of view to enhance our narrative scientific data visualization.

3.3.3 Slicing explorations

We provide a Focus+Contexts (F + C) exploration scheme for the immersive visualization tool. It helps to strengthen users' exploration of detailed information or structures presenting in the data while keeping the overall overview information. There are two slicing methods, depth slicing and horizontal/vertical slicing (Fig. 4). The depth slicing can reflect the structure of each layer of the rendering result. Vertical slicing can highlight the distribution of a certain tissue in the vertical direction, if it is a medical volume data.

Algorithm 1 `Multi-camera_Fusion()` function.

```
function MULTI_CAMERA_FUSION(camera_list, target_texture)
    camera_list[0].Render_layer = Layer_Mask.Background
    camera_list[1].Render_layer = Layer_Mask.Raycasting_object
    camera_list[2].Render_layer = Layer_Mask.POI
    render_texture_list = GetRenderTextures(camera_list)
    while frag in target_texture do
        while i < 3 do
            color = texture(render_texture_list[i], frag.xy)
            frag = (1.0 - color.a)×color.rgb + color.a×frag
        end while
    end while
end function
```

Algorithm 2 `Raycasting_With_Slicing()` function.

```
function RAYCASTING_WITH_SLICING(rendering_frag, volume_texture, transfer_texture)
        position = entryPoint
        stepCount = MAX_STEP
        stepDistence = (outPoint—entryPoint)/stepCount
        fragColor = color.white
        while i ≤ stepCount do
            position = position + stepDistance
            if SlicingFlag then
                if rendering_frag in rendering_area then
                intensity = texture(volume_texture, position).a
                color = texture(transfer_texture, intensity)
                color.rgb = color.rgb×color.a
                fragColor = (1.0 - fragColor.a)×color +
                  fragColor
                lookup = texture(volume_texture, position)
                end if
            else
                intensity = tex3D(volume_texture, position).a
                color = tex1D(transfer_texture, intensity)
                color.rgb = color.rgb×color.a
                fragColor = (1.0 - fragColor.a)×color +
                  fragColor
            end if
        end while
end function
```

4 Algorithms and implementations

We design two algorithms deployed and run in immersive devices. Regarding the volume rendering in an immersive device, the rendering should be implemented by multiple layers (three layers in our implementation) to achieve a blending effect of background rendering, volume rendering (ray-casting) and POI rendering. Each layer corresponds to a virtual camera, for example, camera #01 is designed for background rendering, camera #02 for volume rendering and camera #03 for POI rendering. The detailed fusion algorithm for multiple cameras is shown in Algorithm 1.

The second algorithm (Algorithm 2) is designed to render volume data together with slices in immersive devices, which corresponds to the camera #02 in Algorithm 1. The major differences between Algorithm 2 and the traditional ray-casting algorithms (Gao et al., 2019b; Levoy, 1990) are that the slicing functions are integrated into Algorithm 2 in immersive devices.

5 Results

We use four datasets to evaluate in the proposed immersive visualization tool to demonstrate the effectiveness and flexibility, e.g. a map-based 2-D scalar data on global carbon emission, three CT scanning 3-D volume datasets including 'HAND', 'CHEST-LUNG' and 'HEAD'. Tests on different data have produced quite interesting similarities and differences.

5.1 User study

We conducted two user study evaluations (free exploration and task evaluation). The first one is free exploration. Users are allowed to explore the three datasets freely. All of the participants are independent of their performance and they are also not co-authors of the paper. Specifically, we evaluate the approach by asking participates in the study in two groups. The first group users have little experience in programming and immersive exploration. Two of them have basic knowledge of computer science while six of them are novice users with no programming knowledge. Then we find some cases to show the usability of the proposed approach. Initially, the data will be loaded and rendered by the immersive tool, and then users were asked to define POIs by the Touch Handle of the immersive device and explore the automatically generated animations freely. One of their tasks is to define the POIs to the place where they are desired to explore and then explore the tissue structures by the generated animations.

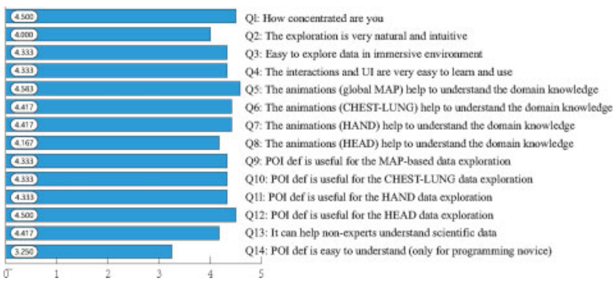


Fig. 5. Post-study: questionnaire results. The questionnaire included a series of 5-point scale questions

All of the second group users have experience in coding but all of them are programming beginners. We asked them to view the customization codes which are used to define the POIs after they finished the tasks of the user study. Most of them thought they were capable of understanding and editing the simple codes because they just edit some encapsulated C++ codes instead of complex scientific data rendering codes (GPU rendering codes). They can define the POIs and customize the animation steps which they are interested in before the narrative animations are generated. After that, we conducted a questionnaire for users and make an interview. Most of the feedbacks are positive which demonstrate the usability of the proposed approach as shown in Figure 5.

The questions in the questionnaire relate to involvement (Q1), usability (Q2–Q4), correctness (Q5–Q8), practicability of POIs (Q9–Q12) and practicability of our tool (Q13 and Q14). We also interview the participants and collect their suggestions, which are about the most impressive of the exploration of dataset and any other suggestions of the narrative visualization. In response to Q1 (4.5), almost all participants thought they felt quite concentrated on the study, and they all agreed with the design philosophy. The customization should be designed to be friendly to use because the immersive narrative visualization is mainly developed for ordinary users with little or even no implementation experience. Regarding the question Q2 (4.0 for the usage of the natural and intuitive volume data exploration), the immersive framework can help ordinary users to customize narrative animations and explore scientific data. In particular, for the questions of Q3 (4.3) and Q4 (4.3), the narrative immersive tool is evaluated to be good usability. In the correctness questions, there are a lot of positive feedbacks. For example, Q5 (4.6), for the map-based data exploration, Q6 (4.4), Q7 (4.4) and Q8 (4.2) for the medical volume data exploration users reacted positively to the comprehensible scripts. When it comes to practicability of POIs, most of the participants think POIs inspires them to concentrate and understand the domain knowledge data better. The questions Q9 (4.3), Q10 (4.3), Q11 (4.3) and Q12 (4.5) aimed at POIs definition of the four cases (datasets). They indicate the POI definitions can help users to enhance the customizabilities in interactive narrative visualization in immersive environment. However, users may have more difficulty in customizing the animation steps through the C++ codes and

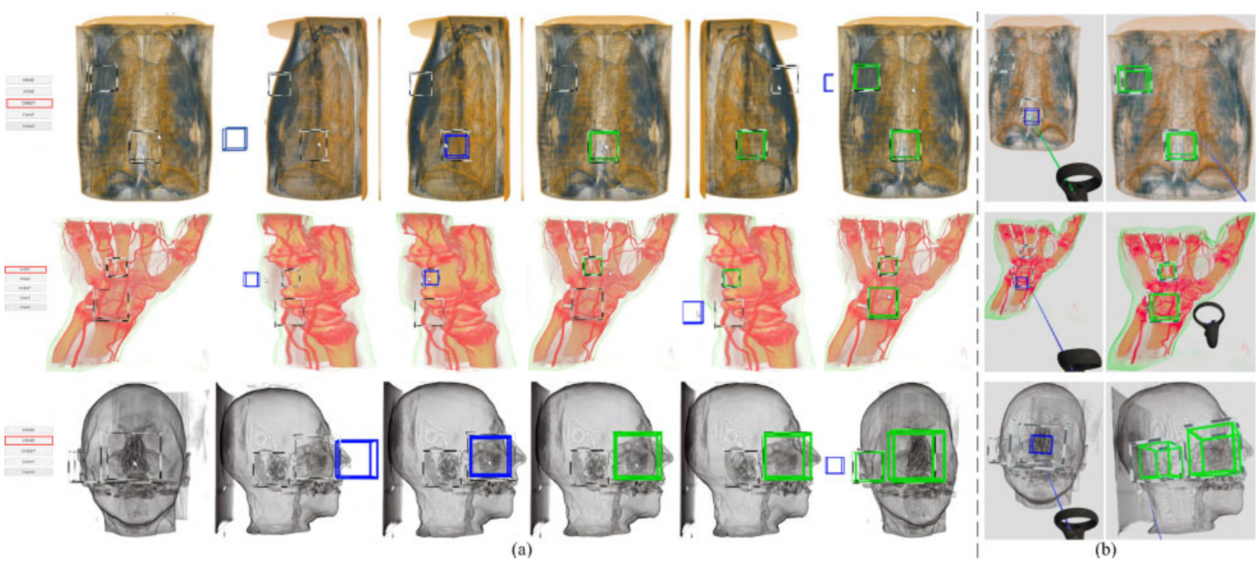


Fig. 6. The second evaluation: point of interest (POI) definition task evaluation by using three datasets. Participants need to move two POI boxes to their given positions and scale them to given sizes (green regions). (**a**) Tasks evaluated by using traditional volume rendering method (Gao et al., 2019b; Levoy, 1990) manipulated by keyboard and mouse. (**b**) Tasks evaluated by using the proposed immersive approach. It is more convenient to define POIs

changing the complex visualization codes to define the POIs. The evaluation tasks for the three datasets are shown in Figure 6.

Regarding the participates of programming beginners, Q14 (3.3) is to test the usability of the POI definitions. It is relatively harder for them to define POIs because they are not familiar with the Touch Handle, most of them are the first time to use the Touch Handle. In the future, we plan to use a natural language-like grammar to solve this problem.

The second user study in this article is task evaluation. We design three POI definition tasks for three datasets and evaluate their performance compared with the traditional method (Gao et al., 2019b; Levoy, 1990) using keyboard and mouse, because POI definition (moving a POI box to a given position and scaling it to a given size) is important to conduct narrative visualization, and the narrative animations are generated by visual traversals across the POIs. We find the average timing performances (Table 2) of the three tasks using the proposed immersive approach are 18.6%, 33.9%, 30.5% better than the traditional method, respectively. The reason why the proposed approach is better is that it is easier for users to specify a 3-D position in an immersive 3-D space than in a 2-D screen space. Besides, it is more convenient for them to move a POI box and scale its size simultaneously to a given 3-D position by the Touch Handle of the immersive device.

Table 2 Three POI definition tasks for the three datasets are designed in this user study The average timing results (seconds) of the three tasks are performed by 8 participants to evaluate the proposed immersive approach compared with the traditional volume rendering method (Gao et al., 2019b; Levoy, 1990) manipulated by keyboard and mouse.

Dataset	Method	Avg. task time
CHEST-LUNG	Traditional method (Gao et al., 2019b)	43.00
	Our approach	35.00
HAND	Traditional method (Gao et al., 2019b)	46.75
	Our approach	30.88
HEAD	Traditional method (Gao et al., 2019b)	49.25
	Our approach	34.25

5.2 Case 1: Immersive exploration of map-based 2-D scalar data

The first case is conducted for an immersive exploration of map-based 2-D scalar data, which is a global carbon emission data. In this case, users can transmit the 2-D carbon emissions data into a VR device, and select a sphere as the rendering mode.

After the rendering is finished in immersive devices, users can first view the built-in exploration steps across different continents. The results of the first case are shown in Figure 7, we use a yellow rectangle to show the current continent for each exploration step, and use a red circle to emphasize the regions with serious carbon emissions. Users can judge the carbon emissions in the area by the shade of the color. The color scheme is specified by transfer function editor of the color-mapping visualization of carbon emission. Red color means high emission and blue means low emission, while full transparency means zero emission. In addition, users can add narrative annotations about the current regional carbon emission to the upper right corner of the screen in the immersive device.

When users want to explore more regions, they can customize the exploration steps. By shaking the 'Thumbstick' described in Figure 3, then user can rotate the rendering result to view other locations of map-based carbon emissions data. A demo video about this data case can be found in the Supplementary Materials of the submission.

5.3 Case 2: Immersive exploration of dataset 'HAND'

The second case is conducted for an immersive exploration of 3-D volume data 'HAND', different from the first case. A 3-D volume data consists of a set of 2-D CT scanning data, which are packed together into the 3-D volume data.

Regarding the immersive exploration of the 3-D volume dataset 'HAND', users can use our PC-side transfer function edit tool first to adjust the transfer function and preview the volume data rendering result; then the volume data can be rendered by using the transfer function in the immersive device shared by the PC-side tool.

In Figure 8, there are three layers highlighted by the transfer function in the rendered 3-D hand. The layer of skin and muscles is marked with light green and the opacity of this layer is lowered to see the structure of other inner tissues in the hand. The bright red tubes are blood vessels in the hand. In Figure 8a, the blood vessels surrounding the five fingers are dense and slender. Besides, two

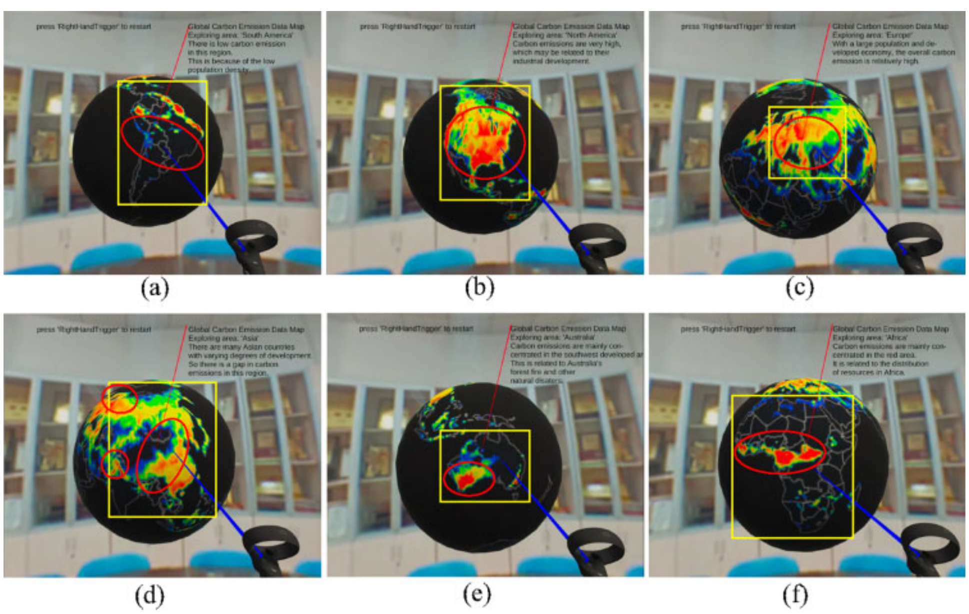


Fig. 7. The narrative visualization results generated by immersive explorations for the map-based global carbon emission data. (**a**) Carbon emission dense spots are in the northern part of 'South America'. (**b**) Carbon emissions in 'North America' are concentrated in the United States and Canada. (**c**) Carbon emissions in 'Europe' are generally high. (**d**) Carbon emissions in 'Asia' mainly come from southeast and the Northeast China and the Northern India. (**e**) Carbon emissions in 'Australia' are concentrated in the southwest of Australia. (**f**) A large amount of carbon emitted in central 'Africa'.

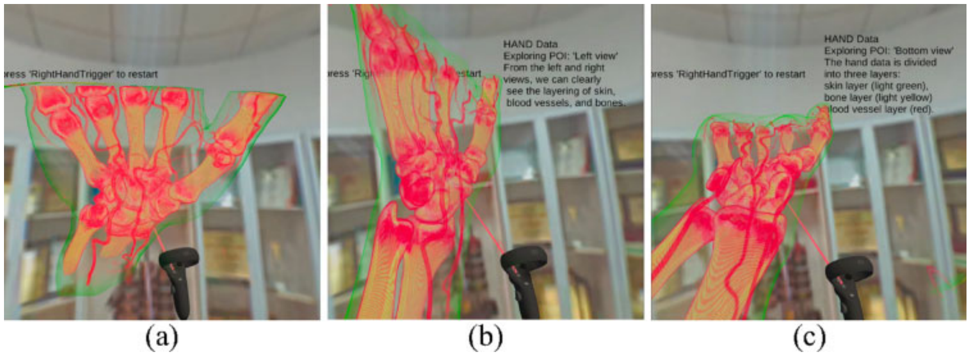


Fig. 8. The narrative visualization results generated by immersive explorations for the 'HAND' data. (**a**) The front view to narratively illustrate all fingers and blood vessels. (**b**) The left view of the illustration, the narrative annotations are updated accordingly. We can find the blood vessels are surrounded and protected by bones in the palm. (**c**) In the bottom view, the flow direction and distribution of blood vessels can be explored in a new perspective

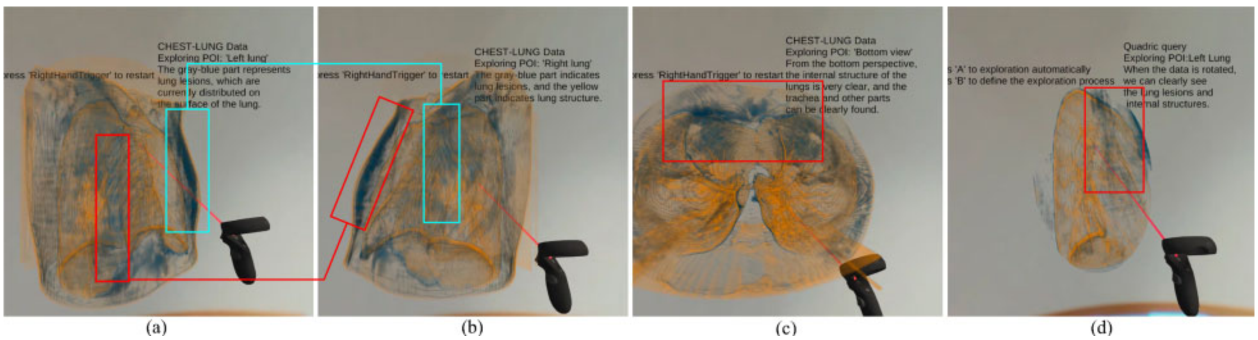


Fig. 9. The narrative visualization results generated by immersive explorations for the 'CHEST-LUNG' data. (**a**) A point of interest (POI) is placed in the left lung, and the red rectangle is placed to the region to emphasize the lesions distribution in the left lung. (**b**) A POI is placed in the right lung and the cyan rectangle is placed to the region to highlight the thickness of the lesions in the right lung. (**c**) A POI is placed at the bottom of the lung, and the lesions distributed on the surface of the lung are highlighted by the red rect. The lung structures are clearly to see in this view. (**d**) Quadric surface query is used to cut the left lung to get a quadric solid, showing more details about the lesions and the structure of the lung lobe. (Color version of this figure is available at *Bioinformatics* online.)

main blood vessels flow from the wrist and palm in Figure 8**b** and **c**. The light yellow layer of bones is the main body of the hand. The five metacarpal bones in the palm are evenly distributed and form a concave structure to protect the two main blood vessels.

Domain knowledge can be disseminated by both the immersive visualization result and the narrative annotations. When customizing the exploration steps, users can rotate the hand data to observe the back of the hand or a single finger. POIs can be customized in any place, the narrative annotations can be updated in real time to the domain knowledge.

5.4 Case 3: Immersive exploration of dataset 'CHEST-LUNG'

The third case is an immersive exploration on a 3-D volume data 'CHEST-LUNG'. Similarly, users can transmit the transfer function edited on the PC-side and dataset 'CHEST-LUNG' into the immersive device. POIs can be predefined and placed to the lesions and important sub-tissues of the lung by users.

In this case, the first POI is placed to the lesion centre on the surface of the left lung. In Figure 9**a**, gray blue lesions are mainly distributed in the middle area of the left lung, the corresponding illustration parts are shown in Figure 9b in another viewpoint. At the same time, users can also see the thickness and region of the lesions on the surface of the right lung. From the bottom perspective (Fig. 9**c**), we can see the branches of the main bronchus in the lung lobes. In addition, the translucent lung structures are visualized by transfer function to make the surface lesions clearer (Fig. 9**d**).

Users can use a Focus+Contexts (F + C) scheme to explore the volume data ('CHEST-LUNG') in the immersive environment. Users can explore the detailed sub-structures of the specific tissues by slicing the volume data. For example, if users are just interested in the left lung, they can slice it separately for observation, as shown in Figure 9**d**. In this case, visual clutter generated by other tissues can be removed. Therefore, it is convenient for users to explore the structure of a single tissue without too much clutter.

5.5 Case 4: Immersive exploration of dataset 'HEAD'

The fourth case is conducted by an immersive exploration of a 3-D volume data named 'HEAD'. The volume data contains tissues such as the cervical spine, skull, and throat. In this case, we choose the nasal cavity, upper jaw and throat as three POIs. At the same time, we chose a single color for the narrative exploration to prevent other colours from interfering with the rendering results.

Despite the influence of our rendering method which leads to the rendering results showing a layered situation, the structures of the upper jaw, nasal cavity and throat are still very clear. In Figure 10, the nasal cavity is marked with the red rect. The nasal passage is distributed in the centre of the nasal cavity and connect with upper jaw marked with the green rectangle and the throat highlighted by the blue rect. Similarly, users can also a F + C scheme to explore the 'HEAD' data in the immersive environment. Users can explore the detailed sub-structures of the specific tissues by slicing the volume data.

5.6 Case 5: Slice explorations

We also demonstrate the slice exploration results as shown in Figure 11. Users can perform slicing operations by Touch Handle of the immersive device and conduct slice explorations on different

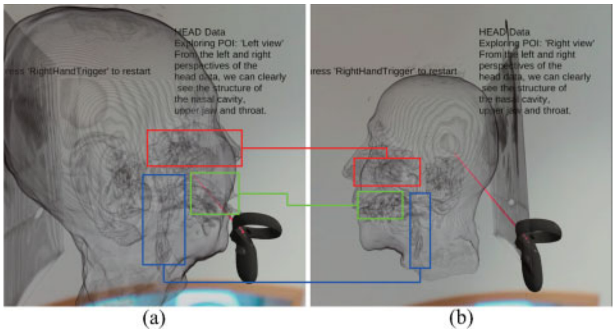


Fig. 10. The narrative visualization results generated by immersive explorations for the 'HEAD' data. The region in the red rectangle shows the nasal cavity, the blue one shows the throat, and the green one shows the upper jaw. The narrative annotations will be updated in different perspectives or animation steps. (Color version of this figure is available at *Bioinformatics* online.)

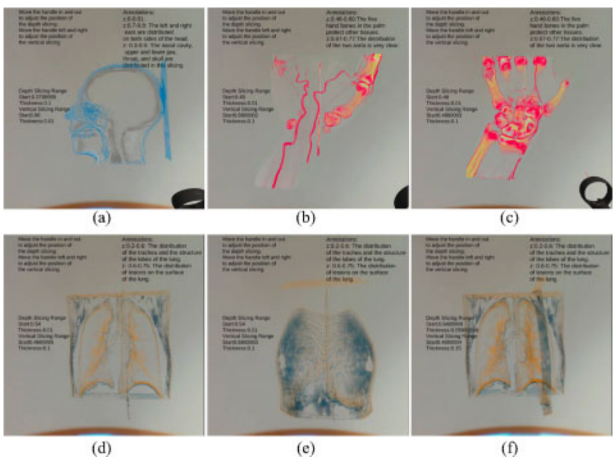


Fig. 11. The slice exploration results for all of the evaluated volume data. Slices selected from the 'HEAD' data (**a**), 'HAND' data (**b** and **c**) and 'CHEST-LUNG' data (**d–f**). (Color version of this figure is available at *Bioinformatics* online.)

datasets conveniently and intuitively. In the slice view, users can explore the detailed structures presented in the data. Besides, the annotations of each slice can be viewed by users when they select a slice to understand the background domain knowledge. Users can add and edit annotations for the slices.

6 Discussion

The immersive narrative tool is designed to create and customize scientific data exploration for ordinary users. However, the proposed tool still has some limitations:

First, users need to customize the animation steps through basic C++ codes instead of changing the complex scientific visualization codes. In the future, we will provide users with the natural language-like scripts in an immersive environment, which enables users without programming experience to customize the exploration steps. Second, users need to pre-define the background environment due to the limitation of current immersive devices. Because the APIs of immersive devices are limited, we do not have permission to edit the real background videos for the current latest version of the device. Third, the results of slice analysis are of great significance in scientific data analysis, while the interaction of slice analysis needs to be improved. For example, the foreground and background of the visualization results in medical data need to be further extracted more efficiently. Finally, we plan to upgrade or purchase latest immersive devices to improve the frame per second (FPS) of rendering, and allowing users' interactive operation smoother.

7 Conclusions

In this article, we design an immersive narrative visualization tool to create and customize scientific data explorations, which can help the ordinary users with little implementation experience on scientific visualization or non-experts get better understanding of the scientific data.

We propose an immersive framework, i.e. immersive environments based on narrative visualization, to organize all the interactions conducted on the medical volume data. The designed narrative visualization tool enables users to load the data and customize the exploration animations by using simple codes instead of complex scientific rendering codes, to customize narrative animations for better illustrate and explore scientific data. Users can define POI conveniently by the Touch Handle. Besides, it enables users to add narrative annotations for each step of scientific data explorations. Narrative visualization in immersive environments can enhance interactive narrative visualization with customized animations freely compared with the existing method. Furthermore, the narrative visualization system in immersive environment also supports the interactive slice analysis using the handle. Finally, it supports different rendering modes or immersive environments for the narrative visualization, and switch them efficiently. The immersive framework together with the parametric equations enables users to switch different rendering modes or get their arbitrary combination efficiently. In the future, we plan to fix the limitation problems mentioned in Section 6.

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References

Bastiras,J., and Thomas,B.H. (2017) Combining virtual reality and narrative visualisation to persuade. In *2017 International Symposium on Big Data Visual Analytics (BDVA)*, pp. 1–8.

Bryan,C. *et al.* (2017) Temporal summary images: an approach to narrative visualization via interactive annotation generation and placement. *IEEE Trans. Vis. Compu. Graph.*, **23**, 511–520.

Chen,J. *et al.* (2012) Effects of stereo and screen size on the legibility of three-dimensional streamtube visualization. *IEEE Trans. Vis. Comput. Graph.*, **18**, 2130–2139.

Chen,Q. *et al.* (2019b) Designing narrative slideshows for learning analytics. In *2019 IEEE Pacific Visualization Symposium (PacificVis)*, pp. 237–246.

Chen,X. *et al.* (2019a) A survey of multi-space techniques in spatio-temporal simulation data visualization. *Vis. Inf.*, **3**, 129–135.

Cruz-Neira,C. *et al.* (1993) Surround-screen projection-based virtual reality: The design and implementation of the CAVE. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH '93*, New York, NY, USA: Association for Computing Machinery, pp. 135–142.

Englmeier,D. *et al.* (2019a) Feel the globe: enhancing the perception of immersive spherical visualizations with tangible proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1693–1698.

Englmeier,D. *et al.* (2019b) Sphere in hand: exploring tangible interaction with immersive spherical visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 912–913.

Fang,S. *et al.* (2020) Interactive diffusion tensor imaging fiber data visualization via leap motion. *IEEE Access*, **8**, 54843–54855.

Febretti,A. *et al.* (2013) CAVE2: a hybrid reality environment for immersive simulation and information analysis. In: Dolinsky, M., and McDowall, I.E. (eds.), *The Engineering Reality of Virtual Reality 2013*, International Society for Optics and Photonics, SPIE, Bellingha, USA, 8649, pp. 9–20.

Gao,M. *et al.* (2019a) Interactive geological visualization based on quadratic-surface distance query. *J. Electron. Imag.*, **28**, 021009.

Gao,M. *et al.* (2019b) Histogram-based nonlinear transfer function edit and fusion. In *Lecture Notes in Computer Science (ICIG '19)*, Number Part II in Lecture Notes in Computer Science (ICIG '19).

Hollerer,T. *et al.* (2007) The Allosphere: a large-scale immersive surround-view instrument. In *Proceedings of the 2007 Workshop on Emerging Displays Technologies: Images and beyond: The Future of Displays and Interacton, EDT '07*, New York, NY: Association for Computing Machinery, p. 3–es.

Hyde,D.A.B. *et al.* (2018) VRGE: an immersive visualization application for the geosciences. In *2018 IEEE Scientific Visualization Conference (SciVis)*, pp. 1–5.

Ian,M. *et al.* (1990) Implementation and integration of a counterbalanced CRT-based stereoscopic display for interactive viewpoint control in virtual environment applications. In *Proceedings of SPIE - Stereoscopic Displays and Applications*, 1256, p. 02.

Kim,N.W. *et al.* (2018) Visualizing nonlinear narratives with story curves. *IEEE Trans. Vis. Comput. Graph.*, **24**, 595–604.

Lee,B. *et al.* (2013) SketchStory: telling more engaging stories with data through freeform sketching. *IEEE Tran. Visual. Comput. Graph.*, **19**, 2416–2425.

Levoy,M. (1990) Volume rendering by adaptive refinement. *Vis. Comput.*, **6**, 2–7.

Liu,R. *et al.* (2018) Interactive stratigraphic structure visualization for seismic data. *J. Vis. Lang. Comput.*, **48**, 81–90.

Liu,R. *et al.* (2020) Domain-specific visualization system based on automatic multiseed recommendations: extracting stratigraphic structures. *Softw. Pract. Exper.*, **50**, 98–115.

Liu,R. *et al.* (2021a) IGScript: an interaction grammar for scientific data presentation. In *CHI Conference on Human Factors in Computing Systems (ACM SIGCHI)*, Yokohama, Japan: ACM, pp. 1–14.

Liu,R. *et al.* (2021b) Multi-user collaborative illustration and visualization for volumetric scientific data. *Soft. Pract. Exper.*, **51**, 98–115.

Papadopoulos,C. *et al.* (2015) The reality deck–an immersive Gigapixel display. *IEEE Comput. Graph. Appl.*, **35**, 33–45.

Ray,H. *et al.* (1999) Ray casting architectures for volume visualization. *IEEE Trans. Vis. Comput. Graph.*, **5**, 210–223.

Rossa,P. *et al.* (2019) MOSIS: immersive virtual field environments for earth sciences. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, p. 1140–1141.

Saket,B. *et al.* (2017) Visualization by demonstration: an interaction paradigm for visual data exploration. *IEEE Tran. Visual. Comput. Graph.*, **23**, 331–340.

Segel,E., and Heer,J. (2010) Narrative visualization: telling stories with data. *IEEE Trans. Vis. Comp. Graph.*, **16**, 1139–1148.

Shen,L. *et al.* (2020) Domain-specific language techniques for visual computing: a comprehensive study. *Arch. Comput. Methods Eng.*, **28**, 1–22.

Wang,Q. *et al.* (2019) Narvis: authoring narrative slideshows for introducing data visualization designs. *IEEE Trans. Vis. Comp. Graph.*, **25**, 779–788.

Yang,Y. *et al.* (2019) Origin-destination flow maps in immersive environments. *IEEE Trans. Vis. Comput. Graph.*, **25**, 693–703.