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Interactive Data Visualisation in Immersive Environments

Seminararbeit

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ABSTRACT

This paper analyses immersive data visualisations for high-dimensional data. It focuses on interaction methods, as this is the key part for better data exploration and thus pattern discovery. Interaction should be intuitive and effective, but this seems difficult to achieve and has not been explored much. Interaction techniques depend on the input device used, which could be mouse and keyboard on a desktop setup, touch and tangible input on a tablet, input from controllers using head-mounted display (HMD)s, gesture input or even some individually developed techniques such as tangible markers. Interaction with a mouse is very precise as humans nowadays are used to interacting with it, but limits the user to not move around freely. On the other side gesture-based interaction is limited by the correct tracking of the hands and thus its accuracy, but is more intuitive and benefits productivity. Using HMDs allows the user to move around freely and the interaction can be done with hand-held controllers or tangible markers. Tangible markers are effective, precise and lead to natural interaction in both physical and virtual space. In general, the interaction methods in immersive environments or 3D space can be categorised into three typical tasks: navigation, selection & manipulation and system control. Where teleportation, one-handed flying (OHF) or World in Miniature (WIM) are typical for changing the perspective, selection is solved by using improved ray-casting techniques, that try to include more context of the data. Still, it is difficult to be accurate as the data points need to be selected from multiple dimensions. Finally, some open-source tools are summarized, which facilitate creating data visualisations and thus make it more broadly available without specific domain knowledge needed.

1 INTRODUCTION

Interactive data analysis requires the user to interact with and explore the data to better understand it. The use cases for this are rapidly increasing, leading to a greater need for new design space interaction techniques that enable intuitive and effective interaction with abstract high-dimensional data. While 2D space visualisation can make use of a direct mapping from interaction space to display space, immersive environments also need to consider the context of the setup and the task to be solved. Either way visualization is the key part for humans to understand large and complex data sets (Donalek et al. 2015).

Recent approaches try to further explore tangible interfaces, which compared to traditional desktop setups allow a higher degree-of-freedom (DOF) (Bach et al. 2018) (Besançon et al. 2017) and HMDs, that lead to a better sense of stereoscopic depth and perception. The use of HMDs is connected to Virtual Reality (VR) or Augmented Reality (AR) environments, often also called mixed or extended realities, where compared to traditional 2D desktop settings a more natural interaction is possible. As Bach et al. 2018's research shows, combining immersive environments with tangible user interfaces appears to be a potentially effective approach for interacting with multidimensional data visualisations.

Immersive visualization can be described as the field of visualizing information in immersive environments such as VR or AR. This not only leads to improved effectiveness of the data visualisations, but also allows the user to explore it in a more intuitive way and speeds up pattern finding [(Butscher et al. 2018, 3), (Wagner Filho et al. 2018, 489)]. Use-cases vary a lot, where commonly used visualisation methods are 3D scatter plots or graph visualisation. However, also new approaches are explored e.g. flexible axes arrangement (Cordeil, Cunningham, Dwyer, et al. 2017) and proven to be useful for certain tasks due to a higher DOF.

Compared to 2D visualisation, high-dimensional immersive visualizations try to overcome typical problems of occlusion, perceptual distortion or misleading correlation of data. Immersive environments distinguish between the interaction-space, usually the user's real environment and the display-space, where the actual visualisation is presented in a virtual context. Designing interaction mapping from these two spaces is what remains a challenge.

This paper analyses and evaluates already existing possibilities for immersive visualisations starting by discussing different setup scenarios and data visualisations methods. It continues to analyse interaction techniques, that can potentially be as effective, as mouse and keyboard interaction techniques in 2D space. Typically there are three types of interaction issues in 3D space: Navigation & Movement, Selection & Manipulation and System Control, to which it will be referring. Interaction implementations in immersive environments are then discussed in terms of their input techniques used. To conclude, the paper presents some Open-Source tool-kits and examples for immersive data visualisations and how they solve interaction issues in AR or VR.

2 IMMERSIVE VISUALIZATION METHODS

There are many different data visualisation methods. The most common are 3D scatterplots or graph visualisations. 3D scatterplots in combination with VR setups overcome issues such as over-plotting or occlusion by providing new ways of interacting with it (Prouzeau et al. 2019). These scatterplots use three quantitative attributes of the data and map them to display space. But when it comes to high density regions they are inefficient and need further optimization (Prouzeau et al. 2019). For high-dimensional data, it is common to use dimensional reduction (DR) to create a reduced version of the data with the same characteristics, which can then be displayed in 3D scatterplots as shown in Fig. 1 (Wagner Filho et al. 2018, 484).

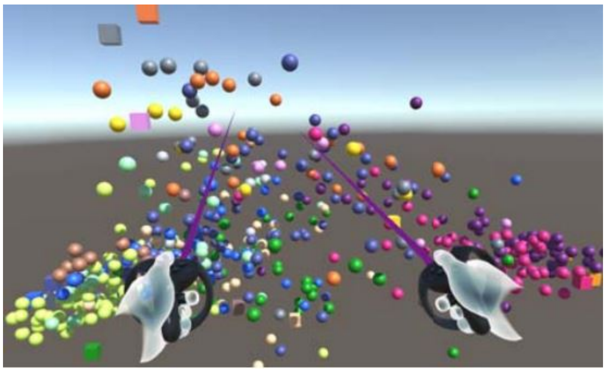


Figure 1: Exploration of DR data scatterplots in HMD-based immersive environments (Wagner Filho et al. 2018).

Kwon et al. 2016 investigated spherical graph layouts, in which the user's field of view (FOV) is placed at the center of the sphere (Fig.2) to reduce spatial navigation overhead. A challenge in graph visualisations is dealing with the large set of edges, which is addressed by routing the edges around the surface of the sphere (Kwon et al. 2016, 1803). ImAxes uses a

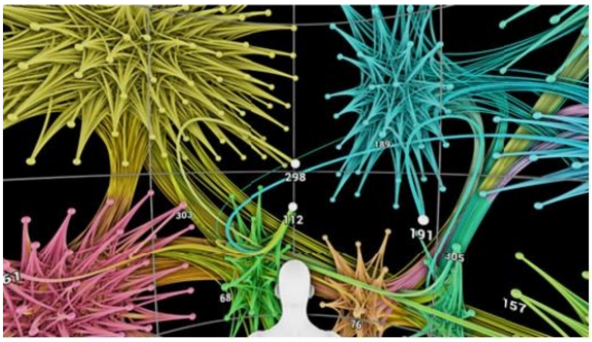


Figure 2: The user's view is centered in the spherical graph visualisation (Kwon et al. 2016).

grammar-based approach to construct the visualisations with spatial placement of data axes. The user is then allowed to build upon grammar rules and combine them in any way he likes. The only restrictions are, that the different axes must be touching and either parallel or orthogonal to the other axes (Cordeil, Cunningham, Dwyer, et al. 2017). This allows the user to decide whether they want to see a histogram, a scatterplot or more complex visualization views. ImAxes is limited by the number of axes used as well as by the size of the data set, as these affect the smooth interaction and performance of the visualization.

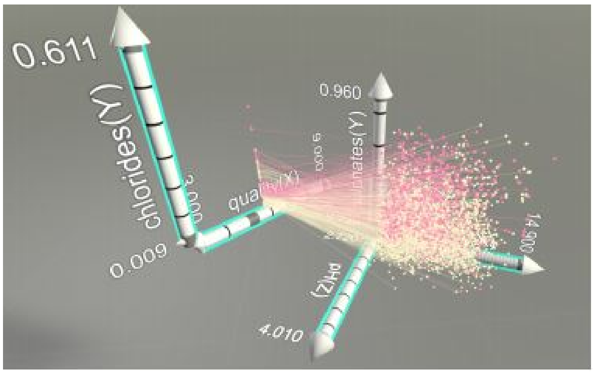


Figure 3: Possible axes arrangement with data visualisation using ImAxes (Cordeil, Cunningham, Dwyer, et al. 2017).

3 HARDWARE

This paper will focus on two platforms for immersive visualization as they are widely available: HMDs and tablets. Alternative setups are desktop setups or CAVE systems, but are not focus of this work.

3.1 Head-Mounted Displays

HMDs offer high-resolution displays and accurate, low-latency head-motion tracking, as well as stereo vision depth, greatly enhancing human perception in 3D space (Cordeil, Bach, et al. 2017, 46). Because those displays are placed directly in front of the user's eyes, only the user's view needs to be rendered and thus can be controlled easily (Kwon et al. 2016, 1802). Furthermore, the use of HMDs invites to embodied navigation, as the user can move around and change their viewpoint without losing sight of data. Handheld controllers such as the HTC Vive controller [1] or free hand gestures with a leap motion controller [2] or the Microsoft Kinect are most commonly used for interaction tasks.
A possible HMD is the Microsoft Hololens [3] - a lightweight see-through AR headset for usage on the PC and the AR view (Wang et al. 2020). Technical shortcomings include a limited FOV and low display resolution, but will be removed in future hardware (Wang et al. 2020). Compared to other hardware, HMDs not only enhance the sense of presence in the immersive environment with proper tracking, but also enable interaction with both the virtual and real word.

3.2 Tablets

Tablets are a broadly used alternative to HMDs, as they offer both tangible and tactile input and are capable of tracking their own position in 3D space. On tangible user interfaces (TUI) the interaction space and the display space can be integrated on the same device. However, they can also be used for processing only interaction input and the display is done on a

1. https://www.vive.com/us/accessory/controller/
2. https://www.ultraleap.com/product/leap-motion-controller/
3. https://www.microsoft.com/en-gb/hololens

separate device.
Tactile input benefits from its directness, precision and rich feedback, whereas accuracy of interaction can be an issue with finger fatigue. With a minimum of 6 DOF, tangible interaction uses advantages of users natural skills for manipulating physical object (Besançon et al. 2017, 881-882).
TUIs use a direct mapping from interaction to the visualizations and are designed to support navigation, selection, and menu interaction [(Cordeil, Bach, et al. 2017, 47),(Butscher et al. 2018, 4)]. Users report them to be more engaging then other interactions devices, because they aim to use their natural abilities to manipulate objects. Although, they have problems with accuracy and interaction tasks such as zooming to navigate (Besançon et al. 2017, 882).
In general, a limitation of tablets compared to HMDs is, that they do not allow the user move freely and thus interact in a room-sized design space. In addition, one must consider that the need to hold the tablet while interacting prevents the user from interacting with both hands (Besançon et al. 2017, 883).

4 Interaction Techniques Overview

Interaction with visualizations in immersive environments is still an issue and needs further research. 2D interaction devices such as the mouse or touchscreens allow very precise control by directly mapping from physical space to the virtual data space (Cordeil, Bach, et al. 2017, 1). Interaction in 3D space is important for exploring dense data sets, but requires a higher degree-of-freedom (Bach et al. 2018). It should also be remembered, that these are dependent on the setup used. The challenge is to design enjoyable interaction techniques with precise mapping (Jankowski et al. 2014). Typical interaction tasks in immersive environments can be categorised into three areas: Navigation & Movement, Selection & Manipulation and System Control. In the next chapters, this paper summarizes existing interaction techniques, that can be assigned to one of the previously mentioned fields.

4.1 Navigation and Movement

Navigation means changing the user's perspective on the display space relative to the interaction space by rotating, translating and scaling (Cordeil, Bach, et al. 2017, 48). In desktop visualisations the two most established techniques are zooming in or out to gain more or less details of a region, and providing a minimap window that shows all the data at all times (Yang et al. 2021, 1214). In immersive environments, the most obvious approach to navigating is physical movement. This reaches its limits in setups that do not allow movement or are limited to the size of the room.
Teleportation is another common technique to navigate through space in VR settings by ray casting to a desired location in visualisation space using a tracked controller. Whereas drag-and-drop teleportation gives the user more control over their position and orientation, point-and-click teleportation requires fewer steps but may not achieve as accurate results. In general, teleportation seems to be a preferred technique by users, as it requires less effort, reduces the amount of collisions and increases speed (Drogemuller et al. 2020, 2).
WIM is the equivalent to the minimap used in desktop visualisations, for always keeping an overview of the data and the possibility to move quickly to a specific location (Yang et al. 2021, 1214). One of the main issues to be solved with that technique is the placement of the minimap, because it should be constantly present on the one hand, but on the other hand it should not distract the user or lead to unwanted occlusions.
OHF or two-handed flying (THF) are other navigation techniques that measure the user‘s pointing in a direction and also take into account the time duration of pointing, i.e. the longer the user extends his arm in a certain direction, the faster he travels. During the duration of travel, it is common to fix the user's FOV to a specific point to reduce discomfort and motion sickness (Drogemuller et al. 2020, 2).

4.2 Selection and Manipulation

Since users want to interact in with the data, object selection and manipulation is an important component. Existing selection techniques for 3D object in virtual environments use ray-casting to pick or point at them, which is highly prone to error in the absence of an explicit 3D shape(Yu et al. 2016, 1). One problem that arises with structure-aware-selection techniques that use a 2D lasso drawn on the 3D projection is, that the user must first select a good view for the selection interaction, which can be problematic in complex data sets (Yu et al. 2016, 1). Therefor, Yu et al. 2016 developed context-aware selection techniques (CAST), which attempt to infer the user's subtle selection intent from gestural input, and was found to be faster and more flexible than other interaction techniques. Moreover, it is not limited to mouse or pen-based input (Yu et al. 2016).

4.3 System Control

Compared to selection and navigation interactions, which take place in the interaction space, system control needs further commands that can be more related to the display space (Cordeil, Bach, et al. 2017, 48). It can be referred to as the user-system communication, as those commands change the state of the application (Jankowski et al. 2014). Menus for common tasks such as switching modes, setting parameters, or selecting a data set should be easily accessible to the user. That is why they are often placed in a corner or the top, so that they are constantly on the interface (Besançon et al. 2017, 885). Other system control tasks may consist of allowing the user to enable or disable various input modalities or settings. Shortcuts are commonly used to efficiently access system control functions via menu items or icons (Jankowski et al. 2014).

5 Interaction In Immersive Visualisations

Interaction methods to interact with immersive visualisations are hardly explored, but a key part for data exploration. This paper analyses some of them based on their input system.

5.1 Mouse-based Interaction

Since people today are used to working on desktop-setups with mouse and keyboard, this is still often used to interact with visualisations. Wang et al. 2020 designed a system that uses mouse and keyboard input, as previous work pointed

out that scientists prefer to use well-know interaction techniques over novel and even more effective ones. Reasonable as mouse and keyboard offer high precision, which is important for data analysis.
Kwon et al. 2016 found that for selection tasks in his graph-based study controlling the cursor via mouse input relative to the fixed spherical space is the most effective. The issue of the cursor leaving the user's FOV was solved by displaying an arrow pointing at the cursor's position and a shortcut for resetting its position (Kwon et al. 2016). In the comparison study of Bach et al. 2018, the desktop environment with mouse interaction also recorded high precision.

5.2 Tablet-based Interaction

The rich feedback and accuracy of touch and tangible input on tablets can be used for user data interaction. Besançon et al. 2019 developed a Tangible Brush technique for selecting regions of interests in the data. Therefor the user must first draw a closed shape on the tablet display (2D lasso), which then is extended into 3D space. After that, the user can move the tablet in physical space to brush through the data and finalise the selection. Compared to CAST techniques (Yu et al. 2016) it resulted in being very accurate but slower.
Spatial interaction is another approach, that takes the advantage of the tablet's position and orientation tracking capability to navigate data sets. Compared to touch input, participants in this study preferred spatial interaction because it was more supportive and comfortable to use (Büschel et al. 2017). For filtering and selection tasks, however, the touch input is still used and needed.

5.3 Controller-based Interaction

The use of HMDs is usually accompanied by the use of handheld controllers for interacting in immersive environments. As discussed in section 4.1, teleportation is commonly used to move around and change the perspective on the data, which is triggered by interacting with the controllers.
Hand-held controllers are used by Cordeil, Cunningham, Dwyer, et al. 2017 to scale and filter the data axes. Therefore widgets are animated out of the according axes and respond to the interaction, which gives continuously feedback.
Scaptics and Highlight-Plane (Fig.4) are alternative interaction techniques for exploring hidden features in 3D scatterplots. Scaptics (Scatterplot Haptics) integrates haptic feedback to HTC Vive handheld controllers by mapping density information in the data to vibration on the controller. Highlight-Plane uses a cutting-plane to enable the user to explore density and spatial arrangement of data as shown in Fig. 4 (Prouzeau et al. 2019).

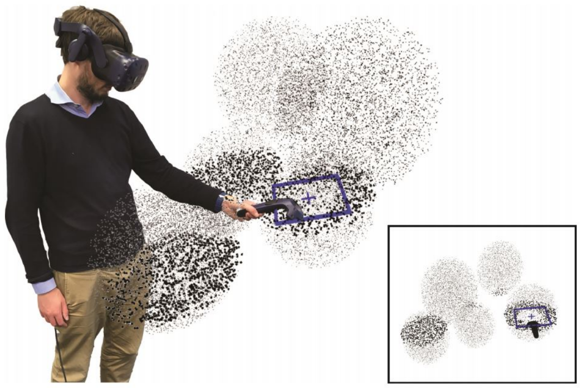


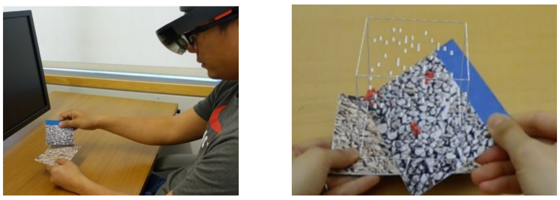
Figure 4: Highlight Plane technique (Prouzeau et al. 2019)

5.4 Gesture-based Interaction

The most natural input for interacting with data visualizations in immersive environments seems to be gestures, but interaction detection and interpretation is a difficult problem to solve, so it is not as effective as expected.
Cordeil, Dwyer, et al. 2017 used a Leap Motion controller tracked on the top of a HMD to allow natural gestures as input. Participants in his collaborative study complained about issues when the controller could not track the position of the fingers because they were out of sight.
Also Clarke et al. 2016 used the Leap Motion controller to track the user's hand position and orientation for interacting with a time-dependent graph visualised in a cube. Rotation is achieved by rotating a smaller instance of the cube, where feedback is given through the real time rendering of the cube and the mapping of the user's hand from real into virtual world.
Another possible input device for gestures is the Microsoft Kinect, which was used in the study of Nagao et al. 2017. Interaction contained pressing virtual buttons, changing values in sliders on the HMD interface or physically moving the open hand to rotate the data images.
Using a hand-tracked interface for exploring microscopy data ledgt to higher productivity (Theart, Loos, and Niesler 2017) and lower cognitive load (Filho, Stuerzlinger, and Nedel 2020), despite side effects of inaccuracy and frustration. A recent study for object selection in dense immersive visualisations showed, that a point and tap gesture works best for participants (Bhowmick 2021).

5.5 Tangible Interaction

A more novel approach is interaction via tangible objects e.g. markers. Besançon et al. 2017 designed a flexible seed point placement method, where ray-casting as tactile and cutting plane manipulation as tangible input can be used in combination by the user (Besançon et al. 2017, 885).
Immersive tangible AR - the combination of the HoloLens and tangible fiducial markers - allows the user to place the visualisation wherever he wants. The interaction with tangible markers e.g. a cutting plane technique can improve time and accuracy (Bach et al. 2018). It was at least as precise as interacting with a mouse and can be improved with training. Furthermore, tangible markers provide seamless two-handed interaction in both input and display space (Billinghurst, Kato, and Poupyrev 2008).



(a) (b)

Figure 5: Immersive Tangible AR with the HoloLens and tangible markers (Bach et al. 2018).

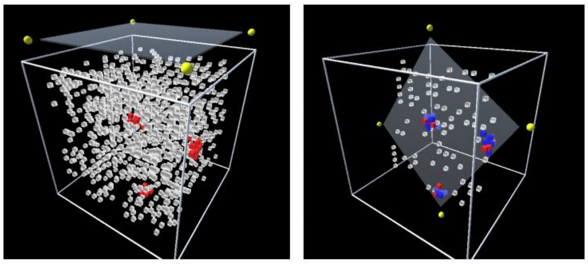


Figure 6: Cutting plane technique for selecting three data points at the same time (Bach et al. 2018).

6 Tools and Examples

Building applications and tools for immersive visualisations comes with many challenges and often requires domain specific knowledge in the fields of data visualisations, analytics, computer graphics, human-computer-interaction and AR/VR (Sicat et al. 2019, 1). Below this paper presents open-source tools, that facilitate the creation process of immersive visualisations.
ART - Augmented Reality above the tabletop uses AR HMDs to visualize a 3D parallel coordinates plot in a physical space by linking together individual 2D scatter plots and combines it with a touch-sensitive tabletop for interaction. Furthermore, it supports collaborative analysis (Butscher et al. 2018).
DXR - an Unity[4] based open-source toolkit, that helps to speed up building and prototyping data visualisation applications for eXtended Reality by providing a higher level interface for constructing and adapting visualisations. Regarding interaction DXR provides scaling up and down, rotating along x, y, z-axis, view configuration controls and can be extended to further device-dependent affordances (Sicat et al. 2019, 2).
IATK, the Immersive Analytics Toolkit is an open source software package for Unity to facilitate the creation of data visualisations and immersive analytic systems by providing standard routines, predefined visualisations and support for creating novel visualisations and interactions. It uses a grammar of graphics, that is configurable by the user with a GUI (Cordeil et al. 2019).
iViz - a multi platform data visualizer prototype based on Unity includes a broadcasting function, allowing collaborative, multi-user data exploration. It supports the Leap Motion sensor, a 3D mouse and Kinect for interaction and the Oculus Rift VR googles as display device. (Donalek et al. 2015)
ImAxes - Immersive Axes - is an Unity based immersive visualisation toolkit for exploring multidimensional data visualisations. It relies on the spatial arrangement of data axes, that can be combined and manipulated easily via controller-based interaction (Cordeil, Cunningham, Dwyer, et al. 2017).
VRIA - a web based framework for creating VR immersive analytics experiences based on WebVR, A-Frame, React and D3.js. Because of being implemented on web-based technologies, it is accessible everywhere and easy to extend and manipulate via the Document Object Model (Butcher, John, and Ritsos 2020). It supports gaze, controller and touch based interaction methods, but is limited by performance.
MIRIA - a mixed reality toolkit for collaborative in-situ analysis of multidimensional spatial data visualisations using Microsoft HoloLens HMDs (Büschel, Lehmann, and Dachselt 2021). It supports multiple visualisation views and multiple ways to filter the data.
MARVIS - a framework that combines mobile devices and AR using the Microsoft HoloLens HMD (Langner et al. 2021). The main interaction is handled via touch input on the mobile device(s) and then visualised in virtual space above the displays.

4. https://unity.com/

7 Discussion

As discussed and demonstrated in this paper, a tool or application for interactive data visualisations should provide different interaction techniques depending on the setup used, to allow the user to choose, which one is most beneficial to him and the data selected. Immersive tangible AR (Bach et al. 2018), for example, has shown, that personalized use is possibl and leads to more flexibility. Typical data visualization issues can be overcome with DR or highlighting techniques (Prouzeau et al. 2019). Mouse-based interaction is often preferred in setups where users are seated because they are accustomed to interacting with the mouse and it is precise and fast. But HMDs offer new possibilities, including embodied interaction, which makes the experience more pleasant and facilitates pattern recognition. Gestures are the most intuitive interaction approach, but they are limited by technology and the ability of precise mapping. Without those limitations, interaction with hand gestures is intuitive, fun, and increases productivity. Instead of a physical feedback, visual feedback is needed (Theart, Loos, and Niesler 2017). Tangible interaction also seems promising for selection tasks, but is subject to perceptual and interaction errors (Bach et al. 2018). Controller interaction is well suited for controlling the system by using shortcuts or navigating through virtual space.
An open question is, whether a single interaction technique, for example gestures, can cover all tasks needed for effective data exploration. The results of this work tend to answer this question in the negative. It most cases a combination of multiple input techniques and also visualisation techniques seems to be the way for future work. Users of a immersive data visualisation and exploration system should be able to customize it to their needs and personal preferences.

8 Conclusion

As immersive data analysis is a huge field, there are many more topics regarding it that are not covered in this paper. For example, collaborative analysis is another important component of data exploration in immersive visualisations. Cordeil, Dwyer, et al. 2017 developed a study regarding collaborative visualisations comparing an expensive CAVE system to more affordable HMDs. Collaboration is also mentioned by Cordeil, Dwyer, et al. 2017.

Visualizing the data is one part, but designing visualisations that also provide more in-depth information about the data is another. Donalek et al. 2015 mentioned how even more information could be added to the data by implementing a link and opening a website by clicking on a data point.

When using immersive devices such as the HoloLens or tangible marker tracking, there are still technical limitations that affect performance (Bach et al. 2018). This is also relevant for considering what size of data a system allows to visualise. Tangible interfaces as shown by Bach et al. 2018 are promising for improving immersive data visualisation exploration. Also an effective approach is to use HMDs on a seated environment and mouse interaction for selection and manipulating data. Besides the interaction tasks mentioned in this paper, other techniques such as slicing (Issartel, Gueniat, and Ammi 2014) or filtering, need a more detailed look in future work.

The visualisation approach of Cordeil, Cunningham, Dwyer, et al. 2017 shows, that there is room for novel visualisation techniques, that go beyond the typical visualisation views used in traditional data analysis. This should continue to be considered when developing new immersive data visualization systems in the future. In general, immersive visualisations speed up decision making (Kwon et al. 2016), offer natural interaction and help to better engage with the data, a great improvement for data analysts or researchers of multiple domains.

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Diese Arbeit hat folgende Länge (gezählt mit texcount):

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Sum count: 3605
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Words in headers: 38
Words outside text (captions, etc.): 72
Number of headers: 18
Number of floats/tables/figures: 6
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Number of math displayed: 0
Subcounts:
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  437+1+0 (1/0/0/0) Section: Introduction
  258+3+30 (1/3/0/0) Section: Immersive Visualization Methods
  33+1+0 (1/0/0/0) Section: Hardware
  172+2+13 (1/0/0/0) Subsection: Head-Mounted Displays
  212+1+0 (1/0/0/0) Subsection: Tablets
  121+3+0 (1/0/0/0) Section: Interaction Techniques Overview
  304+3+0 (1/0/0/0) Subsection: Navigation and Movement
  131+3+0 (1/0/0/0) Subsection: Selection and Manipulation
  126+2+0 (1/0/0/0) Subsection: System Control
  28+4+0 (1/0/0/0) Section: Interaction In Immersive Visualisations
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  107+2+23 (1/2/0/0) Subsection: Tangible Interaction
  397+3+2 (1/0/0/0) Section: Tools and Examples
  269+1+0 (1/0/0/0) Section: Discussion
  266+1+0 (1/0/0/0) Section: Conclusion
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