Immersive View Management
for Interactive Data Visualisation

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Immersive View Management for Interactive Data Visualisation

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Abstract

A multi-view visualisation system uses two or more distinct visualisation views to support the investigation of a single conceptual data entity. Immersive technologies, such as VR and AR, offer users of data visualisations the capability to display and organise their visualisation views in the space around them. Currently, there are few clear design guidelines for managing visualisation views in such an environment. Therefore, we ask what factors could influence and inform view management interaction design for multi-view data visualisations in immersive spaces.

To investigate this research question, we start by exploring the design space for the display layouts for a typical type of multi-view visualisation, namely small multiples, in 3D immersive spaces. To further study the factors that could benefit from this immersive environment and influence the performance of data analysis tasks, we then evaluate the effect of layout curvature on users' ability to perform comparison and trend analysis tasks. In a follow-up investigation, we examine the effect of display layout on spatial memory. Finally, after a series of explorations, we introduce DataDancing: a comprehensive design space for visualisation view management for 3D surfaces and spaces. We characterise fundamental aspects, implement several prototypes to demonstrate interaction design possibilities, and evaluate them with a user study.

The work presented in this thesis explores immersive display and interaction technologies that are not yet widely used in visual data analytics. We hope such work can lay the foundation of immersive view management design and can be used by future researchers and data analysts.

Publications

Some of the contents and ideas presented in this thesis have appeared previously in the following publications:

Chapter 3: A Design Space for 3D Small Multiples Visualisations
and
Chapter 4: Effects of Display Layout for Data Comparison
[1] Jiazhou Liu, Arnaud Prouzeau, Barrett Ens, and Tim Dwyer, “Design and Evaluation of Interactive Small Multiples Data Visualisation in Immersive Spaces”, In Proceedings of the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR ’20), pp. 588-597, doi: 10.1109/VR46266.2020.00081.

Chapter 5: Effect of Display Layouts on Spatial Memory
[2] Jiazhou Liu, Arnaud Prouzeau, Barrett Ens, and Tim Dwyer, “Effects of Display Layout on Spatial Memory for Immersive Environments”, In Proceedings of the 2022 ACM Interactive Surfaces and Spaces Conference (ACM ISS ’22), Volume 6, Article 576, doi: 10.1145/3567729

Chapter 6: A Design Space for Visualisation View Management
and
Chapter 7: Exploration and Evaluation of Interactions for Visualisation View Management
[3] Jiazhou Liu, Barrett Ens, Arnaud Prouzeau, Jim Smiley, Isobel Nixon, Sarah Goodwin, and Tim Dwyer, “DataDancing: An Exploration of the Design Space For Visualisation View Management for 3D Surfaces and Spaces”, In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI ’23), doi: 10.1145/3544548.3580827.

Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes two original papers published in peer reviewed journals and one submitted publication. The core theme of the thesis is immersive view management for interactive data visualisation. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the student, working within the Faculty of IT under the supervision of Prof. Tim Dwyer, Dr Barrett Ens, and Dr Arnaud Prouzeau.

The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of Chapters 3-7, my contribution to the work involved the following:

Thesis Chapter	**Publication Title**	**Status**	**Nature and % of student contribution**	**Co-author name(s) Nature and % of Co-author's contribution**	**Co-authors, Monash student Y/N**
3 and 4	Design and Evaluation of Interactive Small Multiples Data Visualisation in Immersive Spaces	Published	60%. concept, literature review, prototype implementation, user study, manuscript	1) Arnaud Prouzeau, data analysis, manuscript 15% 2) Barrett Ens, manuscript 10% 3) Tim Dwyer, concept, manuscript 15%	No No No

5	Effects of Display Layout on Spatial Memory for Immersive Environments	Published	70%. concept, literature review, prototype implementation, user study, data analysis, manuscript	1) Arnaud Prouzeau, manuscript 10% 2) Barrett Ens, manuscript 10% 3) Tim Dwyer, concept, manuscript 10%	No No No
6 and 7	DataDancing: An Exploration of the Design Space For Visualisation View Management for 3D Surfaces and Spaces	Accepted	60%. concept, literature review, prototype implementation, user study, data analysis, manuscript	1) Barrett Ens, concept, manuscript 10% 2) Arnaud Prouzeau, concept, manuscript 10% 3) Jim Smiley, prototype 5% 4) Isobel Nixon, concept 2% 5) Sarah Goodwin, concept 3% 6)Tim Dwyer, concept, manuscript 10%	No No No Yes No No

I have not renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

Student name:

Student signature: **Date:**

I hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor name:

Main Supervisor signature: **Date:**

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Acronyms

1D One-Dimensional. 38

2D Two-Dimensional. xix, 2, 16, 21, 24, 30, 33, 38, 39, 46, 62, 64, 81, 82, 85, 119, 125

3D Three-Dimensional. vii, xix–xxi, xxiv, 1–4, 6, 9, 11, 13, 16, 17, 21, 24, 25, 30–33, 35–39, 41, 42, 46, 47, 54, 62, 64, 85, 97, 112, 115, 116, 119, 120, 125, 127

AR Augmented Reality. vii, xxiv, 3, 16, 21, 27, 29, 35, 82, 119, 121, 125

BIM Building Information Models. xx, xxi, 1, 11, 36, 41, 42, 45, 47, 51, 53, 153, 154, 156

GDP Gross Domestic Product. 37

GUI Graphic User Interface. 122

HCI Human-Computer Interaction. 6, 12, 29, 32, 50, 117, 122, 123

HMD Head-Mounted Displays. 3, 26, 45

IA Immersive Analytics. 1, 3, 4, 6, 16, 31, 127

RO Research Objective. 7, 8

VR Virtual Reality. vii, xx, xxiv, 3, 6, 15, 16, 20, 21, 26–31, 35, 39, 40, 45, 49, 56, 59–62, 64, 65, 68, 69, 77, 82, 99, 103–105, 113, 117, 120, 122–125

1 Introduction

> *There is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar.*
>
> — **Ivan Sutherland**
> (Virtual Reality Pioneer)

Visual analytics is the creation and use of interactive visual tools and processes to synthesise information and derive insight from massive data [Kei+08]. It can facilitate high-level, complex activities such as data-driven decision-making in various areas, such as marketing, sales, finance, medical science, and engineering. Generally, data visualisation plays a vital role in the visual analytics process, where we use charts, graphics, networks, and maps to gain insights and find patterns.

So far, visual analytics is overwhelmingly performed on conventional flat screens because of their low cost and ubiquity. Such screens come in various sizes (e.g., from hand-held device screens to wall-size displays), but generally, the sizes of screens are suitable to keep everything in the users' field of view without too much head rotation. However, some information must be lost when presenting large-scale or Three-Dimensional (3D) data visualisations on limited-sized screens (see Figure 1.1).

For example, airport managers and air traffic analysts routinely analyse aircraft trajectories to assess the maximal capacity of an airport before opening a new route. When many such trajectories are visualised together, patterns may emerge which inform the managers of airports about the efficiency of airspace utilisation, risks of collisions, and so forth [HTC09] (see Figure 1.2). However, projections of such spatio-temporal trajectory data onto flat screens make it difficult to understand the true 3D spatial nature of the data because of occlusion, perspective distortion, etc. [Mun14, Ch. 6] These issues persist in other situations when displaying visuals of 3D data, such as Building Information Models (BIM), 3D bar charts, and globes.

On the other hand, Immersive Analytics (IA) builds upon visual analytics using engaging, embodied analysis tools to support decision-making [Dwy+18]. These

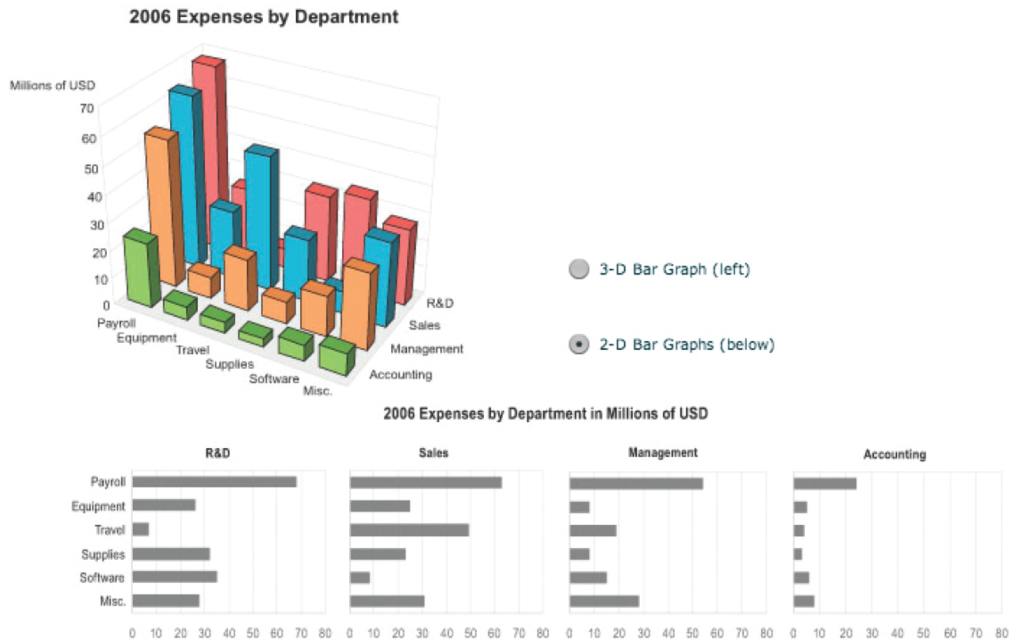

Fig. 1.1.: An example of displaying 3D bar charts (top) on flat screens. The perception of this visual representation is affected by both perspective distortion and occlusion, compared with Two-Dimensional (2D) bar charts (bottom) [Mun14, Ch. 6].

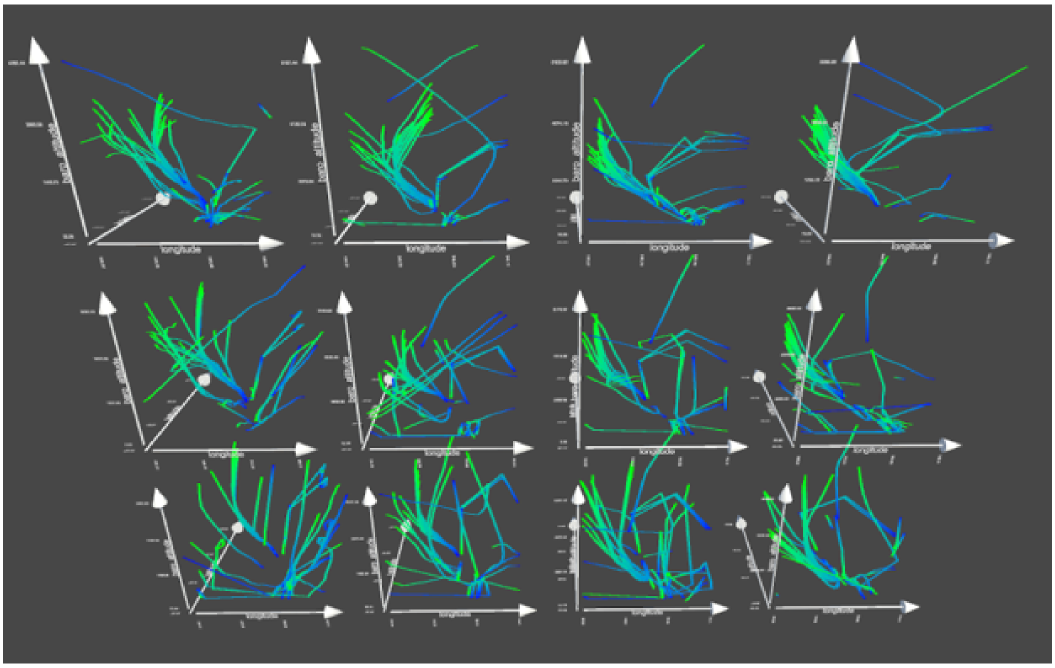

Fig. 1.2.: A small multiples display of aircraft trajectories aggregated from January to December (top-left to bottom-right).

tools are generally deployed in various immersive systems and displays, such as Virtual Reality (VR) and Augmented Reality (AR). In virtual reality, everything that the user sees or perceives is virtual or computer-generated. For example, with a VR headset, the user is immersed in a virtual world, and the real environment is entirely blocked. In contrast, AR adds virtual objects to the real environment to communicate additional information about real-world entities [Azu97]. This can be done with headsets or mobile displays, where virtual objects are perceived as part of the real environment. In recent times, IA has become a popular research topic due to increasingly affordable equipment, improved tracking ability, resolution, and boosted transmission speed of data.

IA may offer several advantages over conventional visual analytics on flat screens. Firstly, the display space in IA is not limited to the screen size but the whole working space around the user. For example, VR immerses users in virtual environments with theoretically unlimited space for displaying visualisations. Although the physical environment still constrains users, virtual navigation techniques, such as "teleportation", can help users interact naturally with visualisations. On the other hand, we can use AR displays to render data visualisations on physical surfaces or next to physical objects. This enables so-called "situated visualisation" for building maintenance [Pro+20], collaborative information visualisation on large displays [RFD21], and "tangible-virtual interplay" with physical globes [Sat+22]. These 3D spaces are ideal for 3D visualisation as users can directly interact with them from the best view angle without much distortion.

Secondly, IA enables diverse display options for multiple visualisations. Traditional flat screens naturally support the flat layout of data representations. However, we can render visualisations in a circular layout that wraps around the user in immersive environments. For example, the CAVE2 (see Figure 1.3) was one of the first VR setups to be used for immersive analytics [Feb+13], with an array of high-resolution displays supporting stereoscopic rendering for users wearing position-tracked polarised glasses. Since then, both with CAVEs and Head-Mounted Displays (HMD), researchers have tended to imitate this layout [Kwo+15; Cor+16; Cav+19]. Wraparound layouts allow users to have elements within arms' reach and reduce visual distortion of far-away elements [PBC16b].

Lastly, IA supports "embodied interaction", which refers to the ability to naturally involve one's physical body in interaction with technology, such as by gestures. In introducing the concept of "embodied interaction", Dourish [01] says, "how we understand the world, ourselves, and interaction comes from our location in a physical and social world of embodied factors." He further describes embodied

Fig. 1.3.: A picture of the CAVE2 hybrid reality environment [Feb+13].

interaction as moving interaction off the screen and into the real world. In IA, embodied interactions can be designed naturally with an explicit affordance, such as grabbing a visualisation with a tracked controller or deleting a visualisation via a "throw-away" gesture.

These advantages make IA an ideal platform for multi-view visualisation systems. In a multiple view system, one conceptual entity is investigated from the perspective of two or more different viewpoints [WWK00]. Usually, such multi-view visualisation systems require large display space so that users can still see the details of each visualisation. In immersive environments, the data can be rendered as an arbitrarily large representation on a virtually flat surface or extending into 3D. Also, such immersive multi-view visualisation systems can provide flexible layout options that allow users to freely control the display aspect ratio and distance to the visualisations. Moreover, users can use natural navigation techniques (e.g., physical walking) to switch the focus between different visualisations views, to see details (by stepping closer) or to get an overview of all the displays (by stepping back).

A small-multiples visualisation is a typical type of multi-view visualisation. In small-multiples visualisations, different data sets are represented using the same encoding [Mun14]. Small multiples are commonly used to perform visual comparisons through a tiled display of charts or models using the same axes and measure system [Tuf90]. Thus, they provide an overview of the data and allow for comparison with minimal interaction and without overloading the visual working memory [PW06]. In this PhD research, we choose the small-multiples visualisation as a starting point to investigate how to present and interact with visualisation views in such a multi-view visualisation system due to the coordinated feature among all the views.

1.1 Research Challenges

As introduced above, immersive environments may enhance visual perception and interaction of multi-view visualisations, contributing to effective and efficient sense-making and decision-making. Recent research has also explored and investigated how multiple visualisation views can be displayed and organised in such an environment [Bat+19; Sat+20; Luo+21; Luo+22]. However, there is little work systematically exploring the design options for visualisation view management in immersive environments.

For example, the display techniques in immersive environments vary from the traditional desktop displays in the aspect of rendering space, resolution, users' field of view, and viewing dimensions. Whether and how designers can adapt the existing design guidelines from desktop displays to immersive environments needs to be thoroughly explored and evaluated. Currently, most immersive visualisation system designers tend to imitate desktop displays, where visualisation views are rendered vertically at eye level with the same size as people used to have in desktop displays. Though this design has been approved to have decent performance for visual analytics, whether such a design exploits the full potential of the immersive technologies hasn't been explored. For example, immersive techniques allow visualisation views to be displayed on various surfaces such as walls [Feb+13; Kis+15; RFD21], furniture [Luo+21; Luo+22], tabletop [Zha+22; FSN20], floor [Sch+14; Cau+19], and even anywhere in the space around the user [Cor+17; Bat+19]. Thus, a systematical review and classification of the design space for immersive visualisation view management could guide future designers to understand the implications of such environments on spatial understanding.

Moreover, if visualisation views can be freely displayed in the space around the user, one of the research questions would be whether a curved arrangement that wraparound the user benefits the performance of visual analysis tasks. Compared to the traditional flat layout, curved displays can reduce the walking required to navigate them and create an egocentric perspective that all visualisation views have the same distance to the user. By arranging visuals to surround the user, as in modern CAVE2 environments [Feb+13], users can simply rotate to access the full display space. Such rotational navigation to change one's viewpoint may be less physically demanding than walking involved in a traditional flat layout. Recent studies have also reported a tendency to position visuals in a circular arrangement [Sat+20; Bat+19; Luo+22]. However, this user behaviour may be explained by an unwillingness to walk in the virtual environment. This might be because of the tethered headsets or unfamiliarity with the physical navigation in VR. Thus, wraparound displays are an attractive design choice but are they actually a good choice for immersive data displays?

On the other hand, since IA is a relatively new field, the interaction design possibilities have yet to be explored thoroughly. For instance, how typical interactions with visual information displays may be adapted from the traditional mouse and keyboard to modalities like mid-air hand or tracked 3D controller interactions. Just as views no longer need to be constrained to screens, interactions with visualisation views no longer need to be limited to our hands. Novel but natural interaction modalities have been explored in general Human-Computer Interaction (HCI), such as gaze [Col+16], foot [Shi+19; PR04; FL18], and the whole body [Kis+15; Wag+13]. These interactions are aligned with how we navigate and inhabit the world using our full bodies. However, these novel interactions have not been fully explored in the field of visualisation view management.

Thus, we argue that visualisation view management in immersive environments is important for data analysts to maintain and enhance their work efficiency by providing opportunities to make better decisions. A thorough exploration of the design space for immersive visualisation view management could also benefit future designers, researchers, and educators to express their creations and formalise design ideas. Therefore, this work aims to explore factors that may affect visualisation view management comprehensively and proposes novel interactions (see Figure 1.4) that allow people to explore and perform visual analysis tasks more effectively in immersive environments.

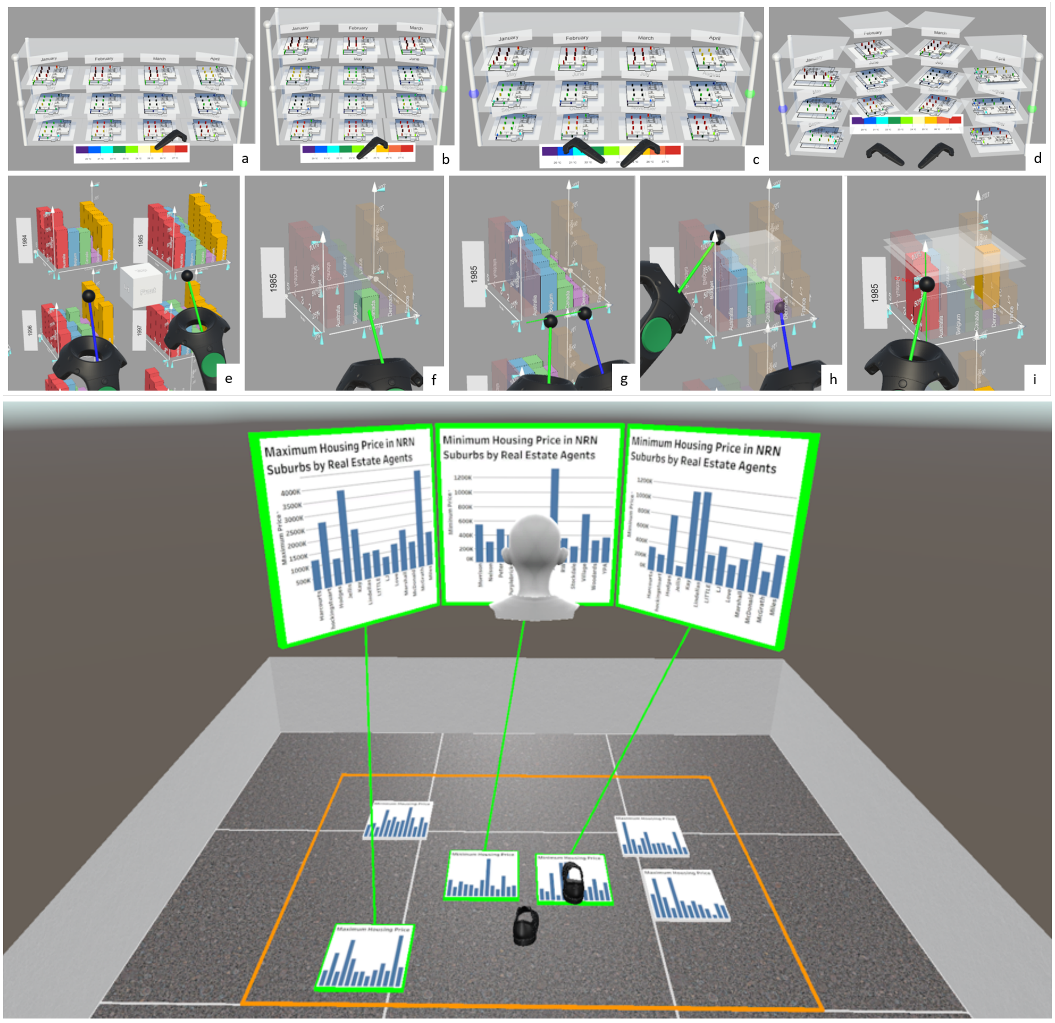

Fig. 1.4.: Novel interactions using mid-air gestures by tracked hand-held controllers (top) or foot positions (bottom) to select and arrange the visualisation views in virtual reality environments.

1.2 Research Objectives

The overarching research question that we seek to address in this project is as follows:

What factors influence and inform view management interaction design for multi-view data visualisations in immersive spaces?

A general overview of this PhD research is illustrated in Fig. 1.5. We first explore the adaptation of 2D small multiples visualisation on flat screens to 3D immersive space as our first Research Objective (RO) (details in Chapter 3). This exploration results in a design space for layout and interaction with small multiples in immersive environments (red-coloured items in figure 1.5). From this design space, we hypothesise that the display layout would make a difference in performance for data comparison tasks in an immersive multi-view visualisation system because the flat layout and curved layout in 3D space require different navigation methods, i.e., translational and rotational navigation, respectively. Thus, we set our second RO to evaluate the effect of the display curvature (details in Chapter 4, blue-coloured items in figure 1.5). The empirical findings from this evaluation lead us to test the effect of display layout on spatial memory (green-coloured items in figure 1.5). Spatial memory refers to the ability to remember the spatial location of elements of visualisations within the display space, which is crucial to support visual analytical tasks. Details of such evaluation and its empirical findings are presented in Chapter 5. Lastly (purple-coloured items in figure 1.5), we distil existing literature into a set of general but widely encompassing design dimensions as a framework by exploring and evaluating how to manage visualisation views on 3D surfaces or in 3D spaces (details in Chapter 6). We then illustrate how to use the design space by generating surfaces and prototypes evaluated via a user study. We also propose hybrid prototypes based on our design space and study results (details in Chapter 7). Detailed research sub-objectives are as follows:

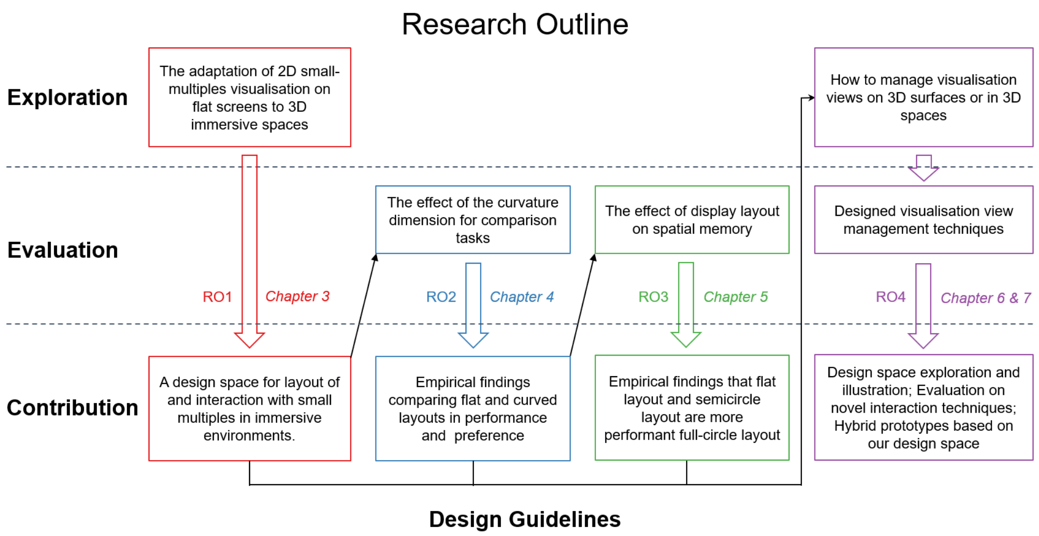

Fig. 1.5.: General overview of this PhD research and sub-objectives. The four columns illustrate four research objectives described in Section 1.2. The first two rows present exploration and evaluation performed for research gaps mentioned in Section 1.1. The last row states the research contributions after achieving each research objective (see details in Section 1.3).

1.2.1 RO1: Explore the opportunities for small multiples data display in immersive environments

Immersive environments benefit data visualisation by providing the ability to render data visuals in the 3D space around users, as well as the possibility of using embodied interaction instead of traditional mouse and keyboards. Thus, in Chapter 3, we want to take advantage of the abundant display space and explore the possible design space for immersive small multiples. We begin our exploration by focusing on adapting the techniques currently used in small-multiples data displays on conventional displays to immersive environments. We investigate the possible effects of this adaptation and begin to explore the new possibilities for small-multiple layouts offered by immersive environments.

1.2.2 RO2: Investigate the effect of layout curvature and the scalability of immersive small-multiples displays

In Chapter 4, we want to examine the effect of different layout curvatures (flat-wall, semicircular-wraparound, and circular-wraparound) on real visual analytical tasks that require comparison. We also want to test the scalability of the various layouts with respect to different numbers of small multiple visualisations (12 vs 36) while maintaining the height of the whole display.

1.2.3 RO3: Investigate the effect of layout curvature on spatial memory

We conjecture that the difference that we observe in users' ability to perform comparison tasks across small-multiples displays with different degrees of curvature may be due to their ability to remember the spatial location of elements of visualisations. We, therefore, in Chapter 5, dig into the wider-reaching question of whether and how spatial memory is affected by different display layouts.

1.2.4 RO4: Design a view management system with "natural" interactions in immersive spaces

Small multiples displays of data are typically regular grid arrangements of similarly sized and themed visualisations. However, modern data dashboards typically combine a variety of complementary visualisation styles in arbitrary configurations. This more general approach to combining many arbitrary views of data can be described as view management. General view management in immersive environments has been explored in the last twenty years [BFH01]. However, whether these guidelines can be applied to visualisation views still needs to be explored. For example, in a multi-view visualisation system, views may contain multiple semantic levels (e.g., overview + detail) for the information. Such views could also be coordinated to be interacted with at the same time. So far, most display techniques and interaction methods are adapted from traditional desktop displays, which might not be suitable for immersive environments or not utilise the potential of the display space. For instance, most immersive visualisation systems are hand-interaction based and tend to arrange visualisation views on a wall-shaped display. However, it remains unknown for the effect of other displaying and interaction techniques, such as the foot interaction for floor displays, on immersive analytics tasks. These novel interaction techniques may introduce benefits such as a natural feeling, ease of learning, and increased performance by enabling multi-modal interactions (e.g., foot and hands, gaze and hands).

We, therefore, aim to exploit the results from our own and others' previous research and explore multi-view visualisation in immersive environments in Chapters 6 and 7. As technology such as real-time body motion tracking stability improves, we believe that new and more "natural" ways to interact with multi-view visualisations become possible. We, therefore, begin to explore the possibilities of using the whole body to interact with views implicitly via body proxemics or using feet to interact with views on floor displays.

1.3 Research Contributions

In this thesis, we contribute to an exploration of design possibilities for small-multiples visualisations in immersive environments. We also investigated several design factors that influence view management design for small multiples data visualisation. From a series of user studies, we show that display layout has a strong effect on user performance for data comparison tasks. Then, we summarise the findings from our studies and propose a design space for visualisation view management. Finally, we demonstrate these design possibilities via hybrid prototypes.

1.3.1 An empirical evaluation and design implications for interactive small multiples visualisation in immersive spaces (RO1 and RO2).

In Chapters 3 and 4, we consider the adaptation of a common visualisation design pattern—that is very well studied on conventional desktop, handheld and wall screen displays—to immersive interaction spaces; namely *small multiples displays*, wherein a number of different data sets are represented using the same visualisation idiom in a tiled display to support easy comparison. We envision applications for immersive small multiples in domains that rely on the exploration of 3D data. For instance, changes in aircraft trajectories above an airport over different time periods may be analysed to reveal patterns in the efficiency of airspace utilisation and risks of collision. Another relevant domain is BIM, which is concerned with the management of a facility's digital information assets. Building managers may benefit by comparing temperature sensor readings and energy consumption over time to identify trends. Analysts may also be interested in data without a physical spatial embedding or abstract quantitative data, for instance, using 3D bar charts to compare wealth and productivity statistics across different populations (e.g., Gapminder [Tea19]). Based on a design space for immersive small multiples layouts, we develop a prototype implementation with features supporting the three use cases above (air traffic data, building information models, and abstract 3D bar charts). This implementation explores several interactions for manipulating 3D layouts and interacting with a variety of data visualisations. To help us to understand the benefits of different layouts, we run two comparison studies with different numbers of small-multiple data displays to compare layout curvature with different data types.

To summarise, the contributions of Chapters 3 and 4 include: (1) a design space for layout of and interaction with small multiples in an immersive environment; (2) a prototype system allowing us to explore layout and interaction designs; (3) two user studies evaluating the effect of introducing curvature into the shelves such that they wrap around the user; and (4) the finding that a flat layout is more efficient than curved with a small number of multiples although it requires more walking. With a large number of multiples, walking hinders the flat layout performance and user preference, in which fully enclosing circular shelves are particularly disorienting, but half-circle is a popular compromise.

1.3.2 An empirical evaluation on the effect of display layout on spatial memory for immersive spaces (RO3).

In Chapter 5, we study lower-level spatial memory tasks to see how spatial memory is supported by display layout. The hope is those clear findings in this regard can lead to more concrete design guidelines for immersive data visualisation and potentially other sensemaking activities in immersive environments. Spatial memory seems particularly relevant to recall and comparison tasks in visualisation because these tasks typically involve the comparison between multiple data encodings to identify patterns or anomalies. Since immersive environments allow data visualisations to be spread out over a large region, navigation between multiple objects for comparison requires users to remember their physical locations temporarily. If we can minimise the effort required for such context switches, users will switch more often to reduce demand on their visual working memory [PW06]. For instance, participants in our study (see Chapter 4) with small multiples seemed to find switching easier with a flat than with a curved layout [Liu+20]. Beyond data visualisation tasks, users' ability to remember the locations of objects in immersive environments has implications for many other applications, from group work to gaming [Nin+21; Muh15; GP18].

Apart from the empirical findings mentioned above, our research also presents a methodological contribution. This is the first rigorous study, inspired by the design of spatial memory tests from psychology, to test the effects of the layout of displays in immersive environments on spatial memory. We have also explored the effects of landmarks and the ability to have an overview as subordinate factors.

1.3.3 An empirical evaluation and design implications for visualisation view management in immersive spaces (RO4).

Several recent studies in the immersive analytics literature have allowed users to manually position views of data anywhere in the space around them. Generally, the data exploration tasks tested in these studies have focused on the static placement of visualisations centred at eye level in absolute room coordinates. However, more general work in HCI has the role of proxemics in interaction in immersive environments. Proxemics refers to the study of space and how we use it. Specifically, the way we arrange objects and ourselves in relation to space. These studies in proxemic interaction have identified zones relative to the user's body with different roles. Such interactions using different body parts affords various embodiment and kinesthetic cues for visualisation tasks, which has been suggested to affect spatial memory performance positively (e.g., touch vs. mouse [Jet+12; Tan+02], body vs. touch panning [Kli+13], body movement [Räd+13], and direct vs. indirect touch [PH16]).

In Chapter 6, we contribute to a comprehensive design space, which we call "DataDancing", for visualisation view management for 3D surfaces and spaces, where we characterise fundamental aspects such as presentation, reference frame, and interaction for data analytical tasks. Within this design space, we contribute to the investigation and implementation of several design considerations and an evaluation with a qualitative study. With this work, we hope to lay the foundation for future research and systems on visualisation view management in 3D surfaces and space.

1.4 Thesis Structure

We begin this thesis by reviewing the related research on immersive data visualisation and analytics, specifically focusing on view management for multi-view visualisations and embodied interactions in immersive environments (Chapter 2). Then, we present a design space for a typical type of multi-view visualisations called small multiples for 3D data (Chapter 3). Afterwards, we conducted a series of user studies to investigate the effect of display layout both for data comparison tasks (Chapter 4) and on spatial memory (Chapter 5). From the results of the studies, we expand our design space from the display layouts to a comprehensive view management perspective (Chapter 6), followed by an exploration and investigation of different interaction possibilities (Chapter 7). Finally, we conclude this dissertation with a discussion of the contribution and limitations of our research on immersive view management and provide our view on future research (Chapter 8).

2 Related Work

> *The need for any kind of data or information visualisation is to gain insights into the data and not just pictures or graphs.*
>
> — **Ben Shneiderman**
> (In Ben Shneiderman's Visualisation Mantra)

This chapter reviews related work on view management for immersive data visualisation. We first look into the emerging field of Immersive Analytics (Section 2.1). Then, we review the field of multi-view visualisation where visual analysis tasks are performed in systems using multiple views (Section 2.2). In such systems, it is essential to understand how to manage visualisation views, such as arranging and interacting with them. Thus, we investigate visualisation view management with a thorough review of the literature (Section 2.3). We discuss how this thesis relates to and contributes to the existing literature in each case.

2.1 Immersive Analytics

Recent work has explored how interacting with embodied data constructs and arranging them in a user's surrounding virtual space can enhance data exploration and understanding [Dwy+18]. For instance, Cordeil et al. [Cor+17] proposed a system, namely "ImAxes", to explore multidimensional data in a VR environment by manipulating virtual axes using natural interactions. In this system, users can create various visualisation idioms based on the arrangement of embodied virtual axes using direct manipulation, such as creating a parallel coordinates plot by moving two axes closely in parallel or a "throw-away" gesture for deleting a visualisation. Batch et al. [Bat+19] then use the same system to investigate embodied immersive analytics in applied economics. This work is conducted in the field (i.e., in the offices of an economics institution) and shows that participants were not affected by fatigue heavily and could use the tool efficiently without comprehensive knowledge of VR. Moreover, this study reveals that participants tended to stay in place during the data exploration phase and merely used the space in front of them. In contrast, they use the space around them better during the presentation phase. Smiley et al. [Smi+21] also extend the "ImAxes" system to AR and add dedicated tangible controllers. The authors explore the interaction possibilities using actuated controllers and conduct a collaborative user study. This study shows that participants could easily compose complex visualisations and present their findings using this embodied axes system.

Nevertheless, recent research in IA has demonstrated the benefits of applying immersive display technologies in the geographical area. Yang et al. [Yan+18] explore different ways to render worldwide geographic maps in VR. The authors investigate four interactive visualisations for geographic data and find that users can benefit from using exocentric maps in mixed-reality environments. They further explore a specific type of geographical map, origin-destination flow maps, in immersive environments [Yan+19]. This work suggests that using the third dimension can resolve visual clutter in complex flow maps. Satriadi et al. [Sat+22] extend the findings and develop tangible globes in an AR environment. The authors present a design space and implications of using tangible globes for data visualisation in AR. Satriadi et al. [Sat+20] investigate how people place and use immersive multi-view maps via an exploratory study. This study reveals that participants prefer and arrange multi-view maps in a spherical cap layout. Inspired by that research, Newbury et al. [New+21] present an example of an immersive flow map with novel embodied gesture interactions.

IA also benefits collaboration workspaces by immersing users in the same environment and sharing information in the same context. For example, Prouzeau et al. [PBC16a] propose using interactive wall displays in road-traffic control centres for interacting with real-time and simulated traffic data. The authors compare two visualisation techniques in terms of situational awareness of collaborators' activity. Lee et al. [Lee+21b] design a collaborative and co-located immersive data visualisation system with 2D and 3D visualisations, which allows users to freely position and author interfaces and visualisations in the space around the user (see Figure 2.1). Ens et al. [Ens+21b] design a novel system, namely "Uplift", to support casual, collaborative visual analytics via augmented reality displays. This system is co-designed with domain experts in building and facilities management. It shows the potential to bring together stakeholders with diverse knowledge and support complex interactions with and demonstrations of real-world data.

While many of the immersive systems described above allow for multiple views of data within an immersive environment, none of them systematically explore the design space for immersive multi-view visualisation. Inspired by the potential of

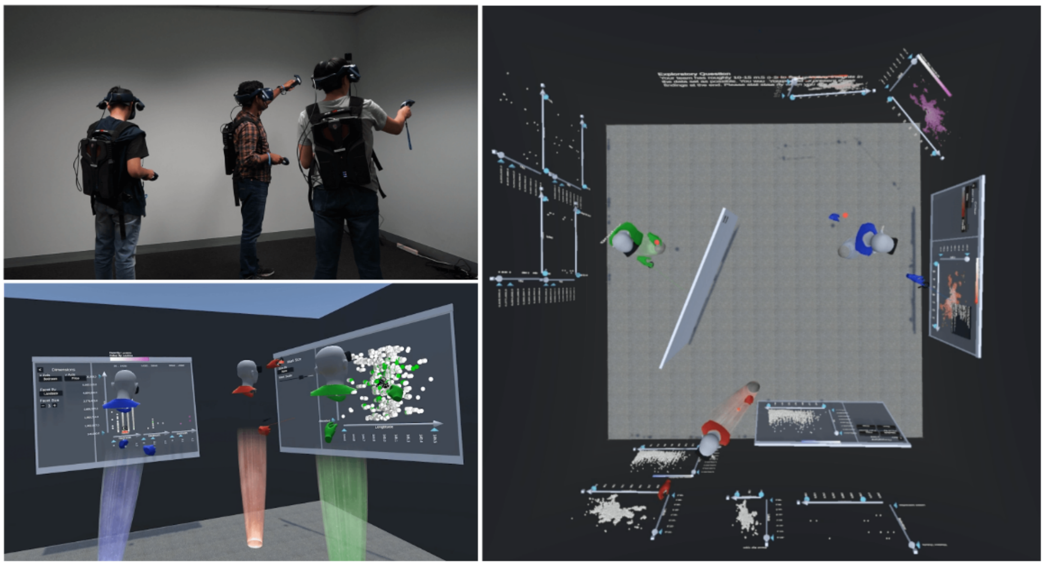

Fig. 2.1.: A collaborative immersive data visualisation system, namely “FIESTA” [Lee+21b]. This system allows users to freely author and position visualisation views in the space around them.

displaying visualisations in an ample 3D space allowing embodied data exploration, this thesis aims to leverage the benefits of such a virtual space to support the management of multi-view visualisations (see Section 2.2). That is, we focus on exploiting the usage of space around the user when designing visualisation presentations, such as the display layout that wraps around the user at arm’s length and using different display surfaces and spaces to render visualisation views. In addition, we explore various interaction possibilities, such as embodied manipulation and locomotion, which helps users to effectively and efficiently perform data analysis tasks.

2.2 Multi-view Visualisation

Multi-view or multi-form visualisation is a visualisation technique that has been established [Kel+94] and encouraged [Rob98] for a long time. Recent studies for such visualisation techniques explore design options on desktop displays. Javed and Elmqvist [JE12b] propose a visual composition model for the design of multi-view visualisations. The model contains four categories of ways to compose visualisation views (see Figure 2.2-top): juxtaposition (i.e., placing visualisations side-by-side), superimposition (i.e., overlaying two visualisations), overloading (i.e., using the space of one visualisation view to place another one), nesting (i.e., nesting the contents of one visualisation inside another one). The juxtaposed views are the most flexible and are often used in this thesis, such as placing multiple views side-by-side for comparison. Similarly, Gleicher et al. [Gle+11] propose a general taxonomy of visual comparison design with three categories (see Figure 2.2-bottom): juxtaposition (i.e., displaying visualisation views separately), superposition (i.e., overlaying views in the same place), and explicit representation (i.e., direct encoding connections between visualisation views). The authors further provide a survey of visualisation systems related to comparison and summarise the strengths and weaknesses of each displaying strategy. Based on this taxonomy, L'Yi et al. [LJS20] present a more recent systematic review of visualisation layouts designed to support comparison tasks and suggest several design guidelines for visual comparisons using multiple views. L'Yi and Gehlenborg [LG22] extend these guidelines and apply them to the genomics data. The authors identify the usability issues and discuss approaches to address them. Chen et al. [Che+20] present a study of how multi-view visualisations are designed in practice. They collect 360 design examples from related work and identify common practices around multi-view visualisation. They combine the findings and propose a multi-view visualisation system with interactive tools to explore the design space.

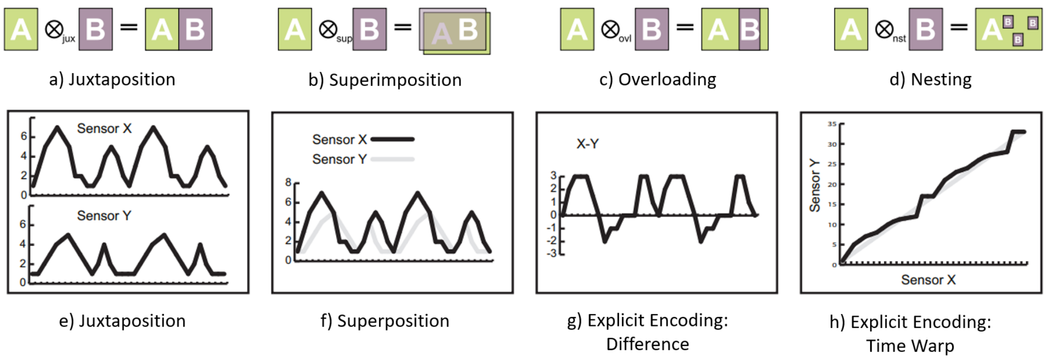

Fig. 2.2.: (top) Javed and Elmqvist [JE12b] visual composition model (a-d) and (bottom) Gleicher et al. [Gle+11] taxonomy for visual comparison (e-h).

These related works have demonstrated a systematic approach to display and interact with multi-view visualisations, especially for comparison tasks and especially on 2D screens of various sizes. This thesis distils the taxonomies discussed above and further explores the design space for multi-view visualisations in immersive spaces (see Chapters 3 and 6). The following sections will discuss an especially common type of multi-view visualisation, namely small multiples.

2.2.1 Small multiples on traditional displays

Small multiples are commonly used to perform visual comparisons through a tiled display of charts or models using the same axes and measure system [Tuf90]. That is, different data sets are represented using the same encoding [Mun14]. Thus, they provide an overview of the data but also allow for comparison with minimal interaction and without overloading the user's visual working memory [PW06]. That is, if all the data required for comparison is visible within the field of view then working memory is not required to retain information while the user navigates between views. In data exploration, small multiples have also been shown to provide a broader perspective on the data to avoid missing important information [EW13]. Further, compared to other techniques, small multiples have been shown to improve user performance for global time series tasks requiring the user to consider the entire display width [JME10]. Figure 2.3 shows an example of how small-multiples visualisation can be used for visual analytics.

Fig. 2.3.: An example of using small multiples for data analysis [TBL14]. The left part shows various graphs analysing trends. The right part shows in depth the samples of the current data trees. This figure shows small multiple views of various visualisation types and data from different hierarchical levels.

The visualisations in small multiples are traditionally arranged in a grid with a fixed and predefined order (see an example in Figure 2.4). Liu et al. [Liu+18] proposed reordering the grid to bring similar multiples together. Javed et al. [JME10] used a single column for small multiples of time series to ease temporal comparison. Also, Meulemans et al. [Meu+17] designed an algorithm to break the grid to match the multiples with geographic locations. A hybridisation approach of small multiples combines several visualisation types [Mac+03] to provide different perspectives on a graph [BW14] or to highlight differences between several maps [LKH10].

Display size limits the effectiveness of these systems using conventional screen-based displays because small-multiples visualisations position views side-by-side,

Fig. 2.4.: A space-time-attribute analysis system [Guo+06] shows a small multiples view of the US maps (top right)

requiring a lot of space to see all the details. Also, these screen-based multi-view systems described above assume traditional interaction modalities, such as mouse, keyboard or touch interactions. In our research, we want to adapt the existing design guidelines and interaction modalities from traditional screen-based displays to immersive displays and explore new design possibilities to enhance the performance of small-multiples visualisation.

2.2.2 Small multiples on immersive displays

On desktop displays, there may be insufficient screen space for effective small multiples [JE12a]. Research has focused on large displays for collaborative use of small multiples, e.g., for software maps [STD16] (see Figure 2.5); road traffic data [PBC16a]; and biological data [FIT+11]. Similarly, in VR, Johnson et al. [Joh+19] propose a system to visualise 3D small multiples on a flat layout (see Figure 2.6).

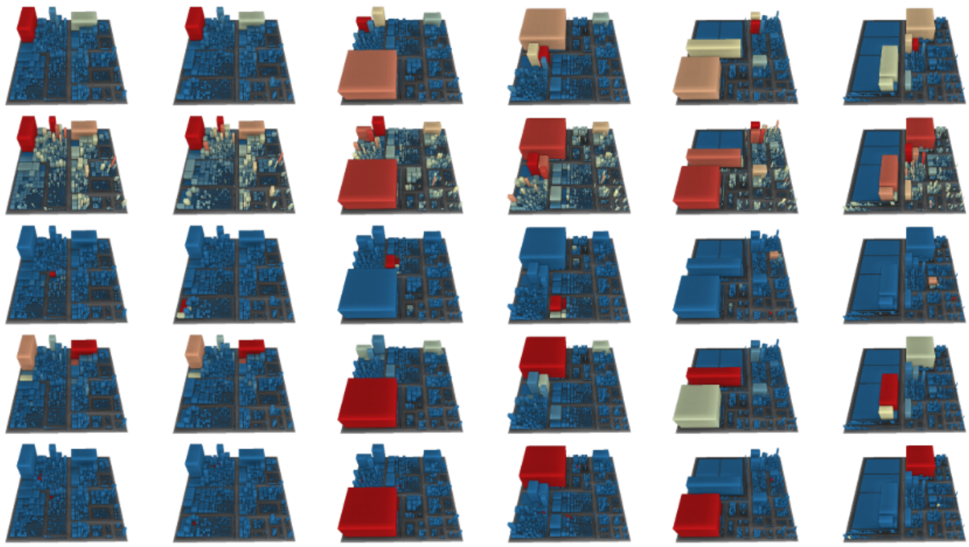

Fig. 2.5.: An example of interactive revision exploration using small multiples of software maps [STD16].

Despite the greater size, large displays only support the same flat grid layout on desktop displays. With VR or AR, other layouts are possible. In FiberClay, Hurter et al. [Hur+19] visualise small multiples on the ground, providing users with an overview of a dataset, with the focus presented directly in front. In "Encube", Vohl et al. [Voh+16] use a circular layout to visualise small multiples, allowing the visualisation of a large number of multiples (up to 80) without increasing the distance between the user and each multiple.

Other research has explored 3D spatial layouts of 2D information displays [EHI14] to support spatial memory [Gao+18] or analytic taskwork [EI17a]. For instance, Virtual Shelves [LDT09] distributes app shortcuts in an invisible hemisphere, which users can retrieve using spatial and kinaesthetic memory. Curved virtual "cockpit" [EFI14] or "amphitheatre" [Gao+19] display layouts distribute items equidistant from the user, making them easier to view or select [Xu+18]. Other layouts embed virtual displays in the physical environment [Ens+15; Fen+17], or situate them in 3D space around desktop monitors [Ser+15] mobile devices [Has+17] or smartwatches [Gru+15] to facilitate easy context switching.

While many design possibilities have been demonstrated in immersive environments, no study has been done to validate the performance of small multiples in 3D space. In our research, we will design and implement prototypes that demonstrate the

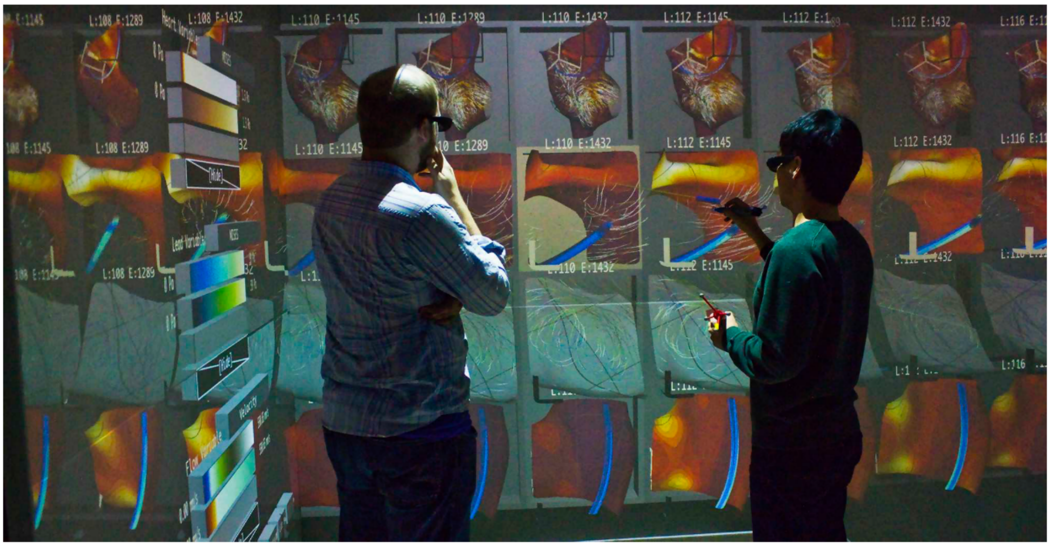

Fig. 2.6.: An example of Interactive and Zoomable small multiples technique for visualising 4D simulation ensembles in Virtual Reality [Joh+19].

design possibilities for immersive small multiples and evaluate the performance in further studies.

2.2.3 Interaction with multi-view visualisations

Interacting with multi-view visualisation is crucial to facilitate visual comparison and enhance decision-making. A popular technique used more generally in multi-view visualisation is brushing and linking [HS12]. With this technique, when a user selects points in one view, matching records in the other views will be selected. In Cerebral, Barsky et al. [Gar+08] extended the concept of linked views to navigation by applying pan and zoom to all views. Finally, in their tool Dream Lens, Matejka et al. [Mat+18] allow users to transition from small multiples to a superimposed view of several multiples.

In Encube [Voh+16], users can interact with the multiples using a handheld device. It allows them to rotate the multiples either globally or individually. Virtual Reality systems tend to favour direct spatial interaction techniques. In “ImAxes”, Cordeil et al. [Cor+17] propose using controllers to brush visualisations in coordinated views directly (see Figure 2.7). Following this initiative, we apply direct brushing and linking interaction in our prototype of immersive small multiples.

In our research, we adapt the existing display and interaction techniques for multi-view visualisations from traditional desktop displays to immersive spaces. We

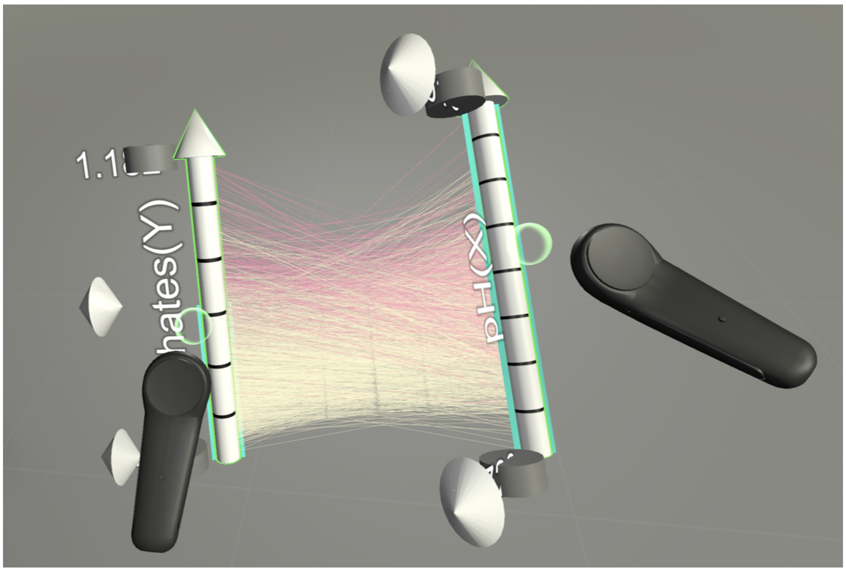

Fig. 2.7.: An interaction example of Immersive Analytics Toolkit [Cor+19]. The embodied axes can be grabbed and manipulated with standard controllers.

also consider recent studies on immersive multi-view visualisations and seek other potential design options for multi-view visualisation management. The design space exploration discussed in Chapters 3 and 6 is inspired by the literature discussed in this section.

2.3 Visualisation View Management

While working with multi-view visualisations both on traditional desktop displays and in novel immersive spaces, it is essential to manage such visualisation views within the display space. Good management of working visualisation views may boost user data analysis performance. For example, when comparing multiple visualisations they can be positioned side-by-side. Such juxtaposed views (see the term "juxtaposition" [Gle+11] described above) allow users to concentrate on sensemaking tasks by reducing the need to remember how to navigate between views (the spatial memory which will be discussed in Section 2.3.2). It may be straightforward to place visualisation views side-by-side on 2D desktop displays, but in 3D immersive spaces, there are many design opportunities for such view placement. On the other hand, interaction with visualisation views is also an important aspect of visualisation view management. How we adapt the existing interaction techniques on desktop displays to immersive spaces needs to be explored and evaluated.

View management in conventional 2D user interfaces can trace back to tiled window managers [CSI86; Tei84] and non-tiled window managers [BNB00]. These systems use non-overlapping methods and constraint-based algorithms to enhance the visibility of views. Visualisation views, like other virtual views or windows, require proper spatial arrangement and rendering techniques to ensure visibility within the users' field of view. However, for multiple views in 2D interfaces, this arrangement is limited by the size of the display, and we have to sacrifice the scale of the views to avoid overlapping, which might introduce a loss of information.

Recent off-the-shelf technology can track the human body and the environment, transforming the view display techniques from 2D surfaces to 3D space. View management in immersive 3D space has been explored for a long time [BFH01] (see Figure 2.8). By optimising the layout and appearance [AF03; Gra+12; GSH06; PAE08a; PAE08b; McN+19; Pro+19b], visibility relationships among different objects in 3D space can be maintained.

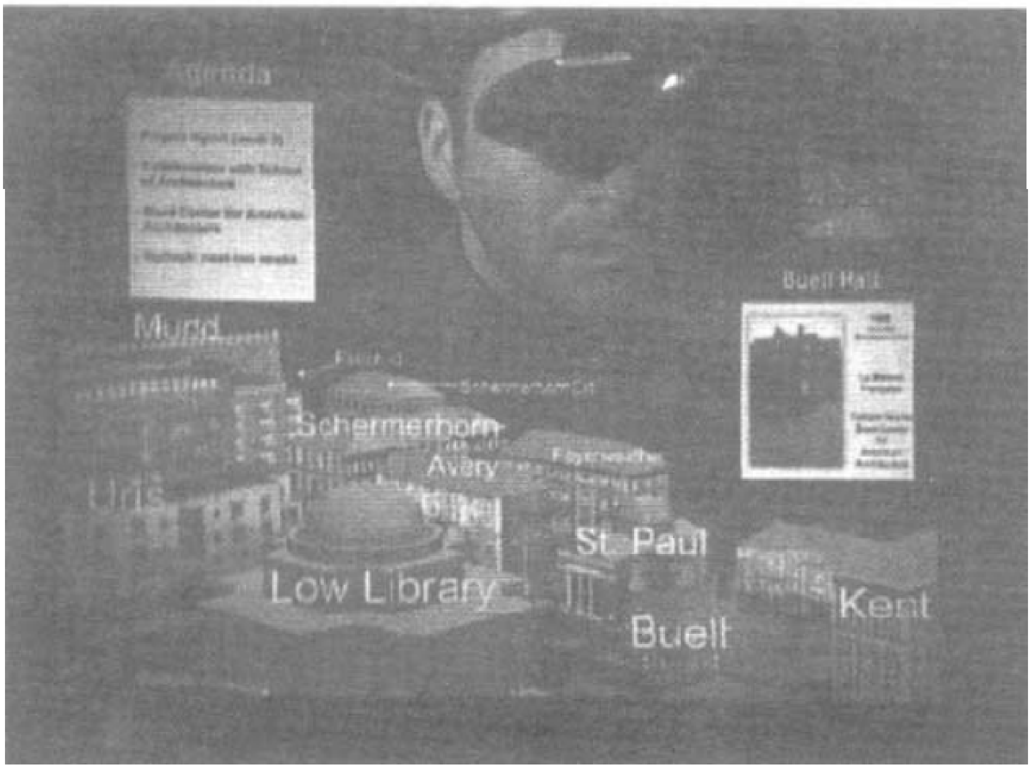

Fig. 2.8.: A figure from the research by Bell et al. [BFH01]. This figure shows how view management in the general user interface was performed in the early stage of augmented reality.

For instance, McNamara et al. [McN+19] explore and develop a technique for placing information labels in complex virtual reality environments. The authors use a novel eye-tracking-based technique to accurately gauge the user's attention. A series of user studies have shown that this technique improves users' performance on an information retrieval task while minimising obstruction of the virtual environments.

Similarly, Prouzeau et al. [Pro+19b] present a design space for routing visual links in immersive visualisations by optimising layouts based on the viewpoints of one or more users (see Figure 2.9). The authors introduce an algorithm to achieve such link layouts and illustrate its applicability in various use cases.

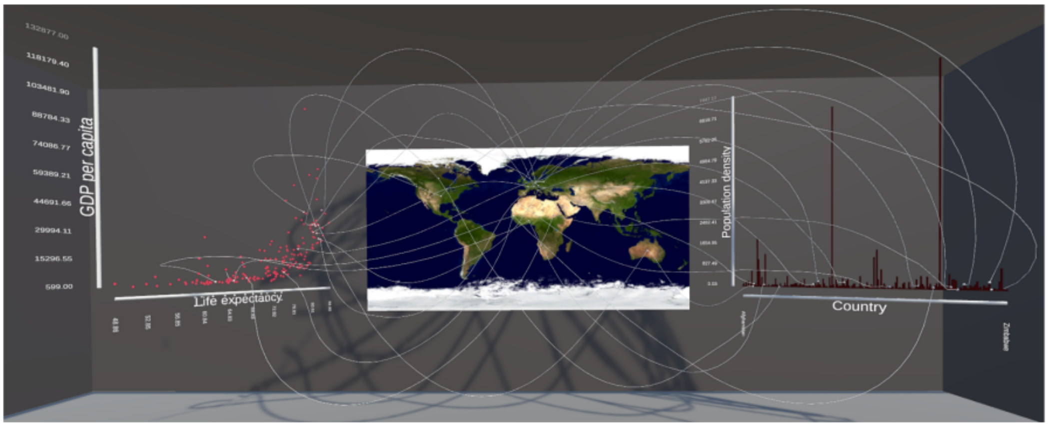

Fig. 2.9.: Visual links are displayed between virtual visualisations [Pro+19b]. Optimising the layout of visual links allows the visibility of each link in 3D space to be maintained.

In the context of immersive analytics [Mar+18] users are able to place visualisation views in the 3D space around them for data analytical tasks. Recent studies have explored how users utilise the space around them to place multiple views. Recent research explored the possibilities to display different types of visualisations in 3D space such as geospatial globes and maps [Sat+20; Sat+22; New+21] (see Figure 2.10) and space-time cubes [Zha+22].

Generally, the data exploration tasks tested in these studies have focused on static placement of visualisations centred at eye level in absolute room coordinates. However, immersive technologies can enable many more interactive spaces or zones, such as floor-referenced displays and body-referenced displays, which are underexplored. In this research, we aim to characterise fundamental aspects of view management in immersive spaces, such as presentation, reference frame, and interaction for data analytical tasks. In the following subsections, we focus on four aspects (display layout, spatial memory, frame of reference, and embodied Interaction) that may contribute to designing a view management system.

Fig. 2.10.: Multi-scale maps are arranged freely around the user in a virtual environment [Sat+20].

2.3.1 Display layout

The CAVE2 was one of the first VR setups to be used for immersive analytics [Feb+13], with an array of high-resolution displays that provide visualisations wrapping around the user. Since then, with CAVEs and HMD, researchers have tended to imitate this layout [Kwo+15; Cor+16; Cav+19].

Several recent VR visualisation studies that allowed participants to arrange their own display space have found that participants have a tendency to arrange the displays in a wraparound configuration. Batch et al. [Bat+19] found this effect in a longitudinal study of economists creating free-form visuals across multiple sessions. Satriadi et al. [Sat+20] found a similar effect for participants arranging multiview maps. Other recent research [Kob+21; Lis20; Luo+21; Luo+22] also found similar wraparound effects during document arrangement tasks.

For instance, Kobayashi et al. [Kob+21] present a prototype called SageXR and use it for a series of studies comparing the conventional physical and the novel HMD. In these studies, participants tended to surround themselves with data views. Likewise, Luo et al. [Luo+21] investigate how the physical surroundings might affect virtual content placement for collaborative sensemaking in Augmented Reality. The authors identify three patterns of the final layout from a user study. Again, participants preferred placing views in a circular layout based on their physical surroundings within the three patterns. In a follow-up research, Luo et al. [Luo+22] further categorise the spatial layout into nine different layouts based on the dependence on the physical environment (see Figure 2.11). These nine layouts show that views are generally placed in a grid using either flat, cylindrical, or furniture-aligned layouts.

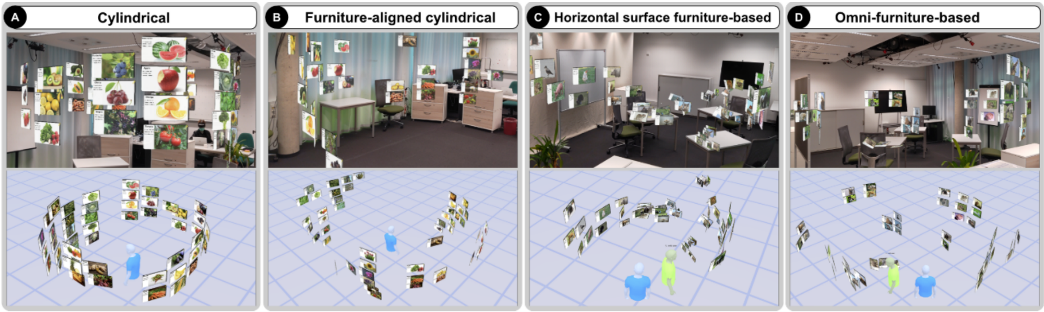

Fig. 2.11.: Four classified layouts in a user study investigating effects of physical furniture on view management [Luo+22]. The first layout is cylindrical, while the other three are furniture-based arrangements.

Wraparound layouts allow users to have elements within arm's reach and reduce visual distortion of far-away elements [PBC16b]. A flat layout would, in contrast, require more physical movements. Using a wall display, Shupp et al. [Shu+06] compared semi-circular with flat layouts in three different map tasks (search, route tracing and image comparison) and showed that the semi-circular one led to improved performance for search and route tracing but was inconclusive for comparison. In the Personal Cockpit, Ens et al. [EFI14] arranged a set of virtual displays equidistant from the user's shoulder to support direct input. They showed the importance of having this curved layout fixed in the world instead of moving with the user's body, as it could provoke incessant small movements. For Menu selection in AR, Lubos et al. [Lub+16] showed that such a curved layout is more efficient if centred on the wrist, thus at the border of the kinesphere, rather than on the head. In recent work, Reipschlaeger et al. [RFD21] proposed an immersive AR system to complement a physical flat display wall (see Figure 2.12). They explore a design space that includes a virtual extension to the display wall, which can wrap around the user. They hypothesised that this could reduce perspective foreshortening effects and bring the visuals closer to the user, but the prototype is not evaluated with a study.

To summarise, circular layouts have been proposed in various visualisation contexts and applications. Recent studies suggest that the curvature of the information displayed in immersive environments may affect task performance, but there is no clear explanation for these effects. In our research, we will study the effects of display layout on user performance for data analysis tasks. Specifically, we propose comparing a flat, semi-circle and full-circle layout for small-multiples visualisation comparison tasks in VR.

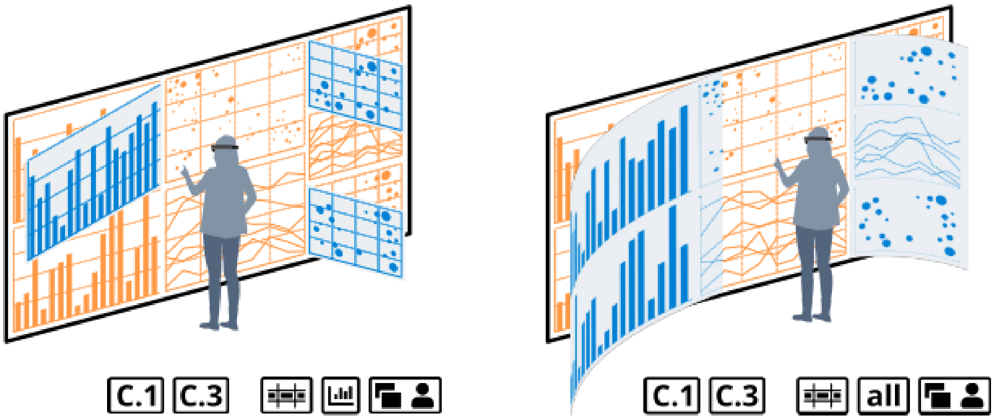

Fig. 2.12.: Visualisation techniques that augment virtual visualisations on a large wall display [RFD21]. These figures show hinged visualisations (left) and curved displays (right) that address the limited perception of faraway objects.

2.3.2 Spatial memory

Spatial memory is one of the spatial skills that people need to learn. Such spatial skills may not be essential on traditional desktop displays as the whole display may be within one's field of view. However, for 3D immersive spaces, such as in the VR environments, users have unlimited space to display visualisation views. The information about such environments and the spatial feature of visualisation views (e.g., position, orientation, and size) needs to be stored and used by users' brains to effectively and efficiently work in 3D environments. We call this ability: spatial memory.

Spatial memory collects and stores information about people's surrounding environment and facilitates navigation. It plays a part in both working memory (i.e., remembering the position and orientation of objects around a person) and long-term memory (i.e., building a mental map of specific locations). Our research focuses on spatial representation in working memory, as working memory is used to store and process information about the current environment. One well-known model of working memory is the multi-component model defined by Baddeley and Hitch [BH74]. Their Visuospatial Sketchpad model proposes a component of working memory that manages visual and spatial information about the current environment. While there is an interdependence between visual and spatial information, the visuospatial sketchpad treats these visual and spatial components as distinct [LL95]. There are two commonly-applied tasks to measure visuospatial capabilities in the working memory: (1) the visual pattern span, which focuses on the visual aspect of this

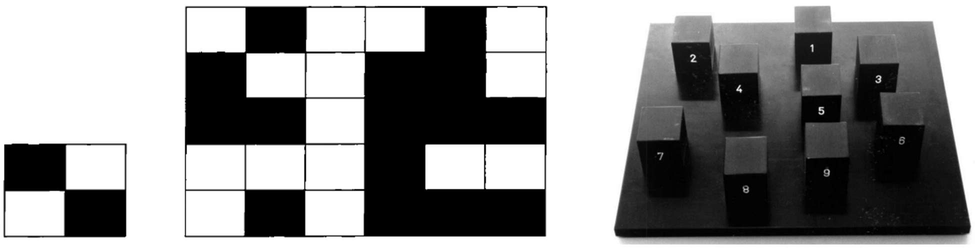

Fig. 2.13.: Two experiments from psychology studies: the Visual Patterns test [Del+97] (left) and the Corsi block tapping test [Cor73] (right). The Visual Pattern test is to measure the ability to recall visual patterns, while the Corsi block tapping test is used to investigate the spatial memory capacity.

memory [Del+97], and (2) the Corsi block tapping task [Cor73], which focuses mostly on the spatial aspect.

Specifically, the Visual Patterns test (VPT) investigates short-term visual memory (see Figure 5-left). In this test, participants see matrix patterns of black and white squares in a grid layout. Next, they need to memorise the checkerboard-like patterns in a fixed time. After each experimental trial, the complexity increases by expanding the grid size if participants recall the pattern correctly. A related test is the Corsi block tapping, which measures spatial memory capacity (see Figure 5-right). The initial Corsi test has nine identical blocks positioned randomly on a board. In each trial, the experimenter points to a series of blocks (one block per second) and then asks the participants to replicate the order on the board. Similar to the VPT task, the number of blocks pointed to on each trial increases as long as the participant continues to be successful, whereas incorrect responses end the task. Kessels et al. [Kes+00] further improved the Corsi block tapping task using a standardised administration and scoring procedure. They also found that this task can effectively assess visuospatial short-term memory in patients with brain damage.

Researchers in VR and HCI have since explored how spatial memory in both working and long-term memory can improve interfaces. With CommandMaps, Scarr et al. [Sca+12] showed that a spatial grid of commands is more efficient than hierarchical menus for expert users. Li et al. [LDT09] used the same technique in VR with the command visualised in an egocentric layout. This technique can be improved by the use of visual landmarks on desktops [UGC17], and in VR [Gao+18]. Virtual landmarks have also been shown to improve remote collaboration in AR as it provides common ground [MRR16]. Perrault et al. [Per+15] used the method of Loci to associate commands to specific physical locations. This is extended to virtual environments by Fruchard et al. [FLC18]. Using a similar method called the memory palace, Krokos et al. [KPV19] showed that spatial memory could provide more benefits in VR than on a desktop. Yang et al. [Yan+21a] also found that using a VR-based memory palace variant increased the effectiveness and performance of retrieving and retaining knowledge.

With Data Mountain, Robertson et al. [Rob+98] used the 3D location on an inclined plane to classify documents and showed that it improved the search for a specific document. Cockburn et al. [CM02] showed that the same technique in 2D is more efficient as less cluttered. And Jansen et al. [JSH19] showed that physical navigation and the availability of an overview also improved performance. Zagermann et al. [Zag+17] also used a similar task to investigate the effect of different input modalities and display sizes on spatial memory but did not report clear findings. In recent work, Friedrich et al. [FPM21] found a modest benefit to retrieval performance when users used locomotion to place windows.

In our research, we hypothesise that spatial memory is a significant component in visual sensemaking activity since moving between individual visualisations to compare them requires navigating back and forth between them. Therefore, in the follow-up investigation, we focus on whether spatial memory is significantly affected by layout curvature. Such a finding would help explain past observed differences in performance on more general visualisation tasks and provide clear guidance for using curved displays for sense-making tasks more generally.

2.3.3 Frame of reference

A reference frame acts as a coordinate system to support locating and orienting objects [Jer15]. Understanding each reference frame could help design efficient and effective interactions for immersive environments. In our research, we mainly discovered three frames of reference: the body/torso reference frame, floor reference frame, and "shelves" reference frame. Since all these frames of reference relate specifically to the virtual space in an immersive environment, we can call them spatial reference frames.

The body/torso reference frame is defined by the body's spinal axis and the forward direction perpendicular to the torso [Jer15]. Data references such as visualisations could be attached to users' hands, waist, and feet. Users can carry visualisations with them without grabbing or holding them. The most common scene for body reference frames is attaching visualisations on users' hands. For example, Prouzeau et al. [Pro+19a] propose two techniques to visually explore volumes within three-dimensional scatterplots in a virtual reality environment. These two techniques require using hand-held controllers to navigate the 3D virtual scatterplots. A virtual cutting plane is attached to the user's hand and provides feedback to users via different sensory channels, such as visual, vibrotactile and force feedback. Yang et al. [Yan+21b] also explore different techniques to interact with the 3D scatterplots in immersive environments. They evaluated four techniques in a user study, where participants used hand gestures to navigate and zoom the 3D scatterplot. In these techniques, a world-in-miniature design of the overview is attached to the user's off-hand controller. In another IA system developed by Lee et al. [Lee+19; Lee+21b], users can freely author and explore various visualisations with pre-defined tools attached to their virtual hands. This design allows users to find the tools and perform desired actions effectively and efficiently.

Other possible designs, such as carrying body-centric visualisations around the user, which has been explored in the interface designed by Ens et al. [EFI14] (see Figure 2.14). In this interface, users can directly interact with situated virtual windows around them. This interface leverages an empirically-determined spatial layout of virtual windows, displayed in a spherical layout in front of users within their field of view. The windows are body-centric and can move with users.

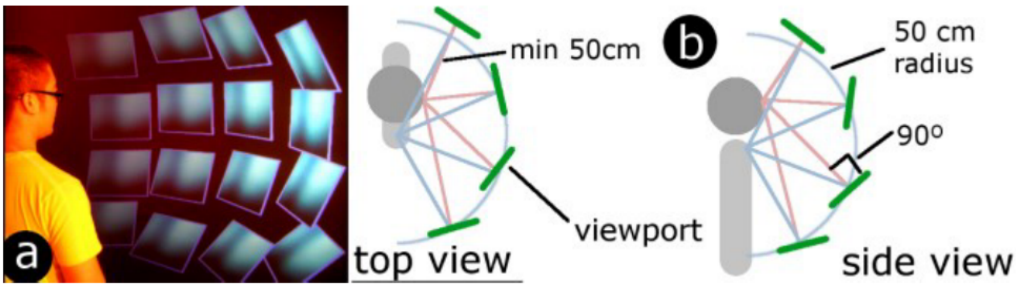

Fig. 2.14.: In personal cockpit [EFI14], users see a body-centric grid of views.

The floor reference frame is a mix of a virtual-world reference frame and a real-world reference frame. In virtual environments, we still need the physical floor for locomotion tasks [Wil+20]. Like the traditional visualisations attached to the wall, we can also attach them to the floor. These visualisations could be used as landmarks or overviews of the context. The upcoming question is how to interact with objects on the floor reference frame. A possible solution could be foot interaction and gestures [Shi+19; FL18; Jot+14; Vel+15] (see another example in Figure 2.15).

Although different reference frames, as discussed above, have been used in the general VR environment, there hasn't been any research yet that explores the possibilities of using these reference frames for visualisation views. In our research,

Fig. 2.15.: An example of using the floor as a reference frame for virtual objects [Sch+14].

we further classify and extrapolate these immersive reference frames in the design space for visualisation view management.

2.3.4 Embodied interaction

Researchers in the field of data visualisation have been interested in spatial interactions with visualisations afforded by large-screen touch interaction, advances in motion capture technologies, and commodity immersive headset displays. Many studies from the visualisation literature have investigated various designs for such "embodied" interaction with data, and there seems to be a tacit acknowledgement that there may be advantages over more traditional indirect interaction, for example, using a mouse. There is also much known in the Psychology research communities about spatial perception and cognition through direct testing of human ability.

Paul Dourish [01] defines embodiment as "the property of being manifest in and as part of the world". Subsequently, Dourish associates embodiment with phenomenology, which concerns "our experiences as embodied actors interacting in the world, participating in it and acting through it". In the context of HCI, our interest in *embodied interaction* concerns our experiences as "embodied actors" interacting with computers. Subsequently, using our physical environment and motor functions to interact directly or passively with computers.

Recently, many studies and applications have elements of embodied interaction in various visualisation techniques. For example, to present abstract data in 3D spaces, Ware and Franck [WF96] performed two experiments showing that motion cues from the embodied interaction help understand the visualisation. In works such as "ImAxes", Cordeil et al. [Cor+17] utilise handheld controllers for interactive authoring and exploration of multiple views of visualizations. Yang et al. [Yan+21b] evaluated several embodied navigation techniques (e.g., Overview+Detail and

Zooming) and found that these techniques provide benefits over standard locomotion support, but such benefits depend on the analysis tasks.

Several studies that explore displaying and interacting with 3D graph or network visualisation in immersive spaces have found that the depth and motion cues provided by the embodied navigation improve spatial comprehension and task effectiveness when working with larger graphs [Bel+03; Kwo+16]. However, Kotlarek et al. [Kot+20] found that 2D visualisations performed better than immersive visualisations for tasks that require spatial memory.

In the field of geo-visualisation, Newbury et al. [New+21] designed embodied gestures for multi-view map interactions (see Figure 2.16). Filho et al. [FSN20] evaluated an immersive space-time cube for intuitive movement trajectory data and found that the immersive version received a higher usability score and lower mental workload. Englmeier et al. [Eng+19] examined the impact of holding a virtual spherical visualisation in one's hands, discussing different handheld spherical displays. Satriadi et al. [Sat+22] similarly explored the interactions with tangible globes and proposed various ways of using them. Kirshenbaum et al. [Kir+20] explores the 3D representation of the terrain on actuated displays, which shows potential in physical geo-visualisation.

Fig. 2.16.: Embodied interactions in virtual reality can be performed naturally using handheld controllers. This figure shows how users can use embodied interactions to manipulate immersive flow maps using predefined gestures [New+21].

Other interaction techniques, such as direct-touch [Yu+12; Woź+14; Lóp+16], tangible [Bac+18], on-body [SBW12], eye-tracking [Hat+17], and mid-air gestures, are also likely to be within the umbrella of embodied interaction. Tonkin et al. [TOD11] compare consumers' visual behaviour and argue a difference in visual search performance between a physical store and a virtual shopping environment. Uddin et al. [UGL16] and Fruchard et al. [FLC18] present works by introducing hand gestures and on-body interaction for command selection in a spatial context.

In our research, we consider embodied interaction in our interaction designs, such as locomotion for navigation, hand gestures for data manipulation, and foot gestures for view management.

2.4 Conclusion

In summary, we reviewed immersive visualisation view management from the perspective of different factors in data display and interaction, which could influence the performance of data analysis tasks. Particularly the empirical evidence for display layout (Section 2.3.1) and spatial memory (Section 2.3.2). However, no research has evaluated these factors for view management tasks in immersive environments.

Moreover, there can be advantages to displaying visualisation views in immersive systems for data analysis tasks. Recent research for these systems commonly positions data displays in a wraparound configuration, such that the data displays surround the user's position. However, there are no clear guidelines for creators of these systems on this rather fundamental question of how to layout displays in immersive visualisation spaces. Moreover, there has yet to be a vast design space to explore the interaction design possibilities for interactive view management.

In this research, we aim to bridge this gap in the literature by exploring interaction design possibilities and providing a comprehensive design space for visualisation view management. In particular, we focus on the display layout of visualisation views on different frames of reference because it benefits from the immersive environment and may improve data analysis tasks.

3 A Design Space for 3D Small Multiples Visualisations

> *A small multiple is a design simultaneously enhancing dimensionality and information density.*
>
> — **Edward Tufte**
> (Data Visualisation Pioneer)

Currently, data visualisation—as with most interactive computing tasks—is overwhelmingly performed using flat screens. However, for data that is inherently 3D, such as aircraft trajectories or building models, this presents a problem, as rendering 3D data displays on screens is well known to suffer from issues of occlusion, perspective distortion and so on, and generally, a loss of information [Mun14].

On the other hand, as augmented and virtual reality (AR and VR) headset devices improve in tracking stability, field of view, and resolution, there is a real possibility that traditional screens may be cheaply replaced with wearable headsets that offer an immersive display of such 3D data. If headsets do replace screens, it presents both an opportunity and a challenge for data visualisation. It could be a paradigm shift in allowing immersive data visualisation in the context of other activities (i.e., situated analytics [Tho+18]). But it will also represent an interaction design challenge in translating everything we have learned about visualisation design on flat screens to the spaces around us. How do we adapt all common visualisation idioms and interaction techniques to take advantage of this space?

In this chapter, we consider adapting a typical visualisation design pattern that is well studied on screens to immersive interaction spaces, namely *small multiples displays*. Small multiple views are faceted subsets of a whole entity, represented using the same visualisation idiom in a tiled display to support easy comparison. As discussed in Section 2.2, small multiples displays are ubiquitous in many domains, e.g., stock market trading floors, scatterplot matrices, tiled medical images, etc. However, to our knowledge, layouts for small multiples have yet to be systematically explored or evaluated in 3D immersive environments.

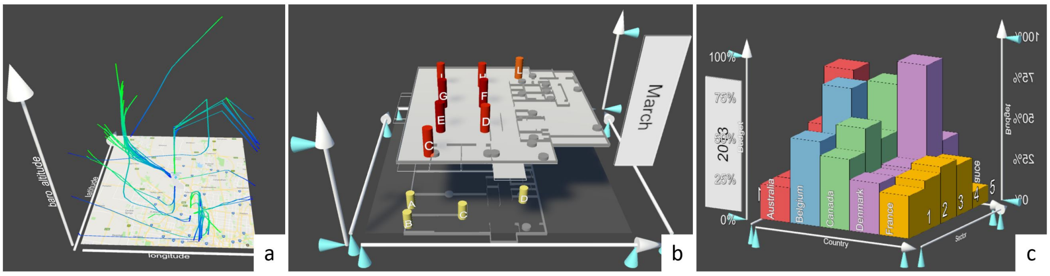

Fig. 3.1.: (a) Aircraft Trajectories; (b) Building Information Models (BIM); (c) Demographic indicators

Firstly, in Section 3.1, we envision applications for immersive small multiples in domains that rely on the exploration of 3D data. For instance, changes in aircraft trajectories above an airport over different time periods may be analysed to reveal patterns in the efficiency of airspace utilisation and risks of collision. Another relevant domain is BIM, which is concerned with the management of a facility's digital information assets. Building managers may benefit by comparing temperature sensor readings and energy consumption over time to identify trends. Analysts may also be interested in data without a physical spatial embedding or abstract quantitative data, for instance, using 3D bar charts to compare wealth and productivity statistics across different populations (e.g., Gapminder [Tea19]).

Next, in Section 3.2, we present a design space for displaying small multiples views in immersive environments, including dimension, curvature, aspect ratio, and orientation. We also propose a shelves metaphor to provide cues for interaction.

Lastly, based on a design space for immersive small multiples layouts, we develop a prototype implementation with interaction features supporting the three use cases in Section 3.1. This implementation explores several interactions for manipulating 3D layouts and interacting with the data visualisations.

3.1 Motivating Scenarios

Our design-space investigation is motivated by several real-world use cases of data with a natural 3D embedding (see Figure 3.1), that is difficult to present in small multiples on flat screens.

3.1.1 Aircraft Trajectories

Airport managers and air traffic analysts routinely analyse aircraft trajectories to assess the maximal capacity of an airport or before opening a new route. The use of 3D visualisations is very important as aeroplanes move in 3D space and important constraints apply on both latitude/longitude and altitude. In order to identify peak traffic periods, it is important for them to be able to compare the traffic hourly, daily or weekly. We are developing immersive visualisation techniques for this data with domain experts from the aviation industries in France and Australia.

3.1.2 Building Information Models (BIM)

With the use of the Building Information Modeling format, Facilities managers have more and more opportunities to visualise data coming from different building sensors (e.g., CO2, Temperature) overlaid on 3D CAD model of buildings. Seasonality is very important while looking at building data as the outside weather has a big influence on parameters like Air Conditioning and Lighting. It is then important for them to be able to aggregate and visualise their data per hour, day, month, etc. We are trialling small multiples displays with the Buildings and Properties department at our institution, as well as a major commercial supplier of building management systems.

3.1.3 Demographic indicators

When looking at demographic data like population, Gross Domestic Product (GDP), and spending in different areas, it is important to see both the temporal and spatial evolution (for instance by years and countries). The use of 3D bar charts in small multiples array allows for four dimensions of data to be viewed simultaneously, and potentially for trends involving more than two variables. For instance, in some countries, the population can increase with the GDP, while others will see their GDP decrease when the population increase. Demographic data from the GapMinder website [Tea19] is a popular and relatable baseline dataset in visualisation research.

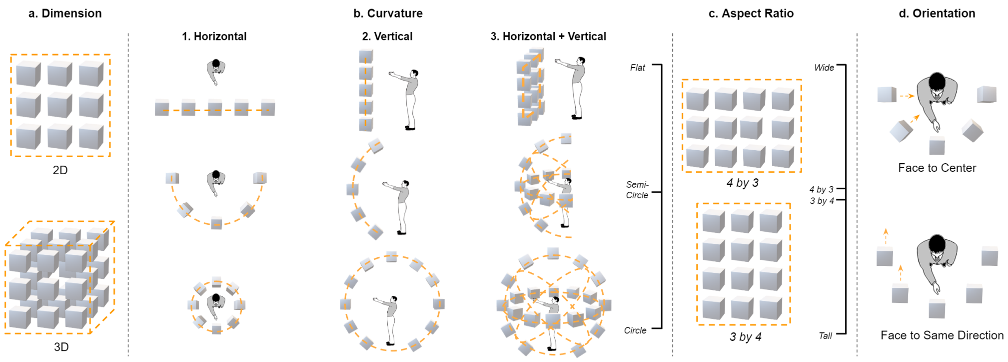

Fig. 3.2.: Immersive small multiples layout design space: (a) Dimension, (b) Curvature, (c) Aspect Ratio, and (d) Orientation.

3.2 Design Space for Immersive Small Multiples

While small multiples layouts have been explored in traditional flat-screen implementations, there is no existing design space to describe such layouts in 3D space. We identify 4 design dimensions that describe many possible layouts of small multiples for 3D data in immersive environments (see Figure 3.2):

3.2.1 Dimension

We refer to the dimensionality of the grid of small multiples. A One-Dimensional (1D) display would be a single row, 2D is the traditional grid used on screens, while 3D is a new possibility afforded by immersive environments, adding a depth dimension to the grid. Adding more dimensions allows more multiples to be compacted into a volume but stacking in the depth dimension will introduce occlusions.

3.2.2 Curvature

The curvature of the display allows multiples to wrap around the user, reducing the need for walking. However, users need to rotate their heads or body to navigate between multiples.

While curving a 1D layout is relatively straightforward, there are several possible ways to curve layouts in higher dimensions (e.g., curving a 2D layout into a cylinder or a sphere) either horizontally (see Figure 3.2-b1) or vertically (see Figure 3.2-b2). In such 2D curved displays, if a user stands at the centre point of the curvature, all multiples will have the same distance to the user.

3.2.3 Aspect ratio

Relates the number of multiples in each orthogonal dimension, e.g., a 2D array of 12 multiples can be arranged in ratios: 4×3, 3×4, 2×6, etc. In immersive environments, we usually limit the number of rows to be displayed but not the number of columns, because users usually perform 2D locomotion on floors, while they have limited freedom in the vertical axis.

3.2.4 Orientation

Refers to the relative orientations of the individual 3D data visualisations. Instinctively, one might align all the layouts to the same forward-facing direction, similar to flat-screen 2D layouts. However, with a curved layout (or potentially with a flat layout), rotating each visualisation to face the user may help them to more easily make comparisons.

3.3 A Shelves Metaphor

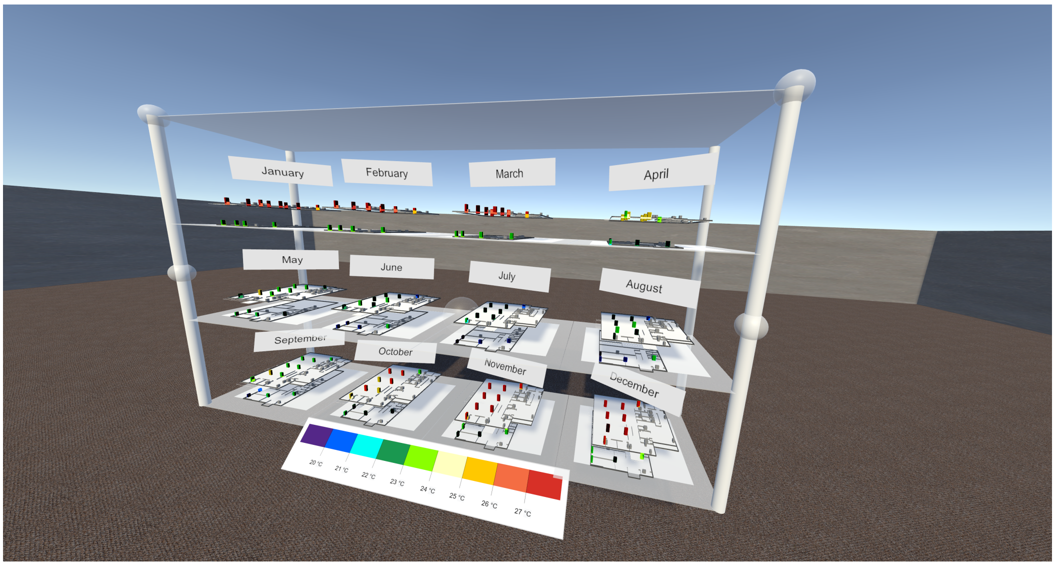

Fig. 3.3.: Small multiples presented in VR using a "shelves" metaphor.

Our design uses a *shelves* metaphor [LDT09] to provide cues for interaction. Fig. 3.3 shows the realisation of this metaphor in our prototype system. The shelf visuals provide affordances for users to understand and orient 3D small multiples and provide clear horizontal and vertical alignment of the small multiples to enhance spatial memory. Interactive elements, such as corner pillars, provide an interface for users to directly manipulate [Shn81] the display layout, for instance changing its *curvature* or *aspect ratio* to best suit the data and task. In the following section, we discuss how our implementation allows users to manipulate, brush and filter the data, with visual feedback coordinated across all of the multiples.

3.4 Prototype Implementation

We developed a VR prototype to explore the design space for immersive small multiples. It supports both manipulation of the layout and coordinated interaction with the small multiples.

3.4.1 Apparatus

We use an HTC Vive Pro room-scale VR device and the Unity development environment (2017.3.0f3). The prototype runs on a Windows 10 PC with an Intel I7 7800X (3.5GHz) processor and an NVIDIA GeForce GTX 1080 (32GB RAM) graphics card. We leverage VRTK [Bod18] for interactive components, and IATK [Cor+19] for rendering for the small multiples data visualisations. The code is available on GitHub [Liu19].

3.4.2 Interacting with Shelves

In addition to walking around the data and viewing it from different perspectives, users can reconfigure the layout of the small multiple by "grasping" and manipulating different components of the shelves' visible form. Affordances for layout operations are revealed to users by visible "handles" on the pillars or shelves, which also provide visual feedback during manipulations. Since the shelf is too large for users to easily reach the pillars, the handles can be manipulated from a distance through a ranged pointing gesture with the Vive controllers. Pointing rays extend from each controller to provide additional visual feedback. Implemented operations include changing the layout aspect ratio, curvature, height, detail level, or shelf position.

Aspect ratio. By grabbing one of the front shelf pillars, the shelving unit can be "stretched" or "compressed" horizontally (see Figure 3.4-a, b). As the shelf width changes, the multiples automatically rearrange themselves to fit the new aspect ratio, with animated movements between shelf positions.

Curvature. Grabbing both front pillars simultaneously allows the shelf to be "bent", adjusting the layout curvature (see Figure 3.4-c, d). The shelves can be adjusted continuously between a straight layout and a half-circle configuration.

Height. Grabbing the top corner of either pillar allows users to "stretch" the shelves vertically. This adjusts the height of the shelving unit, and accordingly the space between shelves, but without changing the aspect ratio.

Detail level. With some data sets, such as BIM data, users may want to adjust the level of semantic detail shown. Pressing a button on the controller increases the separation between the floors of the building model, i.e., creating an "exploded" view.

Shelf position. Grabbing a handle in the centre of the shelving unit allows users to move the entire layout horizontally or vertically. This can be used to get a closer view of distant multiples, for instance, the far edges or lower shelves, without walking or crouching.

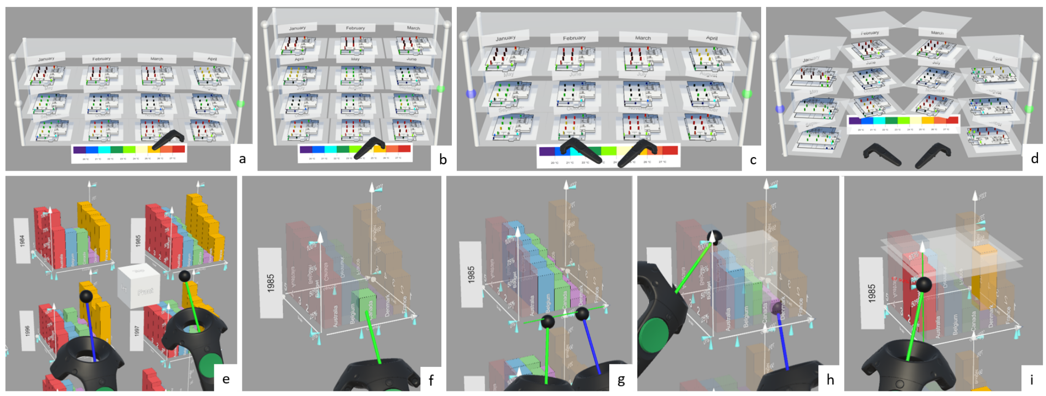

Fig. 3.4.: Interactions with the shelf layout (top) and contained data visualisations (bottom): (a,b) adjusting layout aspect ratio by "grabbing" and moving a shelf post, (c,d) adjusting layout curvature by moving both posts, (e) rotating multiples via the ViewCube [Kha+08], (f) brushing a single data point, (g) brushing an axis using both controllers, (h) brushing a volume selection on all axes, (i) filtering on the y-axis with cutting planes.

3.4.3 Interacting with Data

We implemented several operations for interacting with the 3D data visualisations to allow us to investigate the use of the small multiples layouts with data analytics tasks. These include selection, rotation, brushing, filtering and a ruler tool. These operations (except for selection) are coordinated so that manipulating any single data visualisation results in the same effect applied to all multiples.

Selection. Users can select one of the small multiples, either by moving the controller near and pressing the trigger button or by using the controller's ray from afar (see Figure 3.4-f).

Rotation. To view the data visualisations from different sides, users can press both controllers triggers to present a view cube [Kha+08] (see Figure 3.4-e). Users can then manipulate the cube rotation, which is reflected across all multiples.

Brushing. Brushing [HS12] allows users to select one or more data points on a single visualisation, and see the selection linked across all coordinated views. We provide several brushing methods. Users can brush a single data point with a pointer that extends from the controller (see Figure 3.4-f). The bimanual interaction of a pair of sliders on any axis brushes a range in one dimension (see Figure 3.4-g). Finally, a bimanual gesture within a data volume brushes a cube-shaped region on all 3 axes at once (see Figure 3.4-h).

Filtering. A pair of cutting planes can me moved along the vertical axes to select a specific range of values (see Figure 3.4-i).

Ruler tool. When touching the vertical axis of a data visualisation the pointer is annotated with a numeric value (see Figure 3.4-i) supporting detailed height comparisons across multiples.

3.5 Conclusion

In this chapter, we present a design space exploration for an interactive small multiples display for 3D data in immersive environments. The design space characterises four main design factors to display immersive small multiples. This exploration also leads us to develop novel interaction techniques and contributes to design guidelines for immersive small multiples visualisations.

We first demonstrate the motivating scenarios for three types of 3D data (time-series trajectories, BIM models, and 3D bar charts), whose design cannot be fully adapted from traditional flat screens. We then show four design dimensions to present immersive small multiples, a "shelves" metaphor to provide cues for interaction design, and several interaction design possibilities.

In the following chapter, we investigate one factor in this design space, the curvature of the layout, to study its effect on user performance for data comparison tasks using the implemented prototypes.

4 Effects of Display Layout for Data Comparison

> *Curving the display so that it 'wrapped' the user would make the display 'immersive'.*
>
> — **Gary K. Starkweather**
> (American Inventor, the Godfather of printing tech)

The CAVE2 was one of the first VR setups to be used for immersive analytics [Feb+13], with an array of high-resolution displays that provide visualisations wrapping around the user. Since then, both with CAVEs and HMD, researchers have tended to imitate this layout [Kwo+15; Cor+16; Cav+19]. Moreover, several recent VR visualisation studies [Bat+19; Sat+20; Kob+21; Lis20; Luo+21; Luo+22] that allowed participants to arrange their own display space have found that participants have a tendency to arrange the displays in a wraparound configuration.

Wraparound layouts allow users to have elements within arm's reach and reduce visual distortion of far-away elements [PBC16b]. A flat layout would, in contrast, require more physical movements. While proposed many times in such design explorations, it seems the effectiveness of such a wraparound visualisation has until recently been rarely studied. On the other hand, recent studies suggest that curvature of information displays may affect task performance [Shu+06], but there is no clear explanation for these effects.

In this chapter, we focus on the question of whether user performance is significantly affected by layout curvature. In Section 4.1, we first present a user study to compare three layout curvatures (*Flat*, *Quarter-Circle*, and *Half-Circle*) using two different datasets (demographic data and Building Information Modelling (BIM) data). In Section 4.2, we show a second user study to test the scalability of the result from the first study with more views involved. In the second study, we also replace the *Quarter-Circle* layout with a *Full-Circle* layout to investigate the effects of participant rotation. In each section, we also discuss the results and suggest design guidelines for the display layout of immersive small multiples.

4.1 User Study 1: Layout Comparison

It is unclear how the layout of small multiples in immersive spaces impacts the performance of users in a visual comparison task. Therefore, we evaluate three different layouts with two different datasets for such tasks. The design of this experiment has been preregistered on Open Science Framework (OSF) [Liu+19a].

4.1.1 Task

Our task consists of visual comparison between pairs of visualisations that are part of a small multiples display. More specifically, participants have to compare the value of two specific data points between two specific multiples in a total of 12 multiples placed in a 2D shelves with a grid of 4 columns and 3 rows.

We test three layouts (LAYOUT): *Flat*, *Quarter-Circle*, and *Half-Circle*. We focus on horizontal curvature, similar to existing large displays, to prevent a combinatorial explosion. We chose not to evaluate a full circle layout, because with just 12 multiples, either the circle will be too small, or the distance between columns too large.

To provide generalizable results, we include two common data sets in our studies: *Bar*, which is a typical representation of multi-dimensional, non-spatial 3D data, and *BIM*, which contains data that has a spatial reference frame such as a floor plan.

Finally, we vary the locations of the multiples to compare within the grid, controlling for the distance between the two that need to be compared. In one condition, *Short*, the two multiples are at a Manhattan distance of 1 or 2, meaning that participants can do the task with both multiples simultaneously in their field of view. In the second one, *Long*, the Manhattan distance was 4 or 5.

Dataset. We use one dataset for each DATASET condition. The data for *Bar* is 12 indicators for 10 years and 10 countries from the GapMinder website [Tea19] (see Figure 4.1-top). One multiple represents the evolution of one indicator for 10 countries over 10 years. For the *BIM* dataset, we took inside temperature data from a building at our institution. There are 25 temperature sensors in this building. We aggregated the temperature by month for each sensor. Each multiple shows the mean temperature for one month for each sensor (see Figure 4.1-bottom). The questions were created manually by the authors.

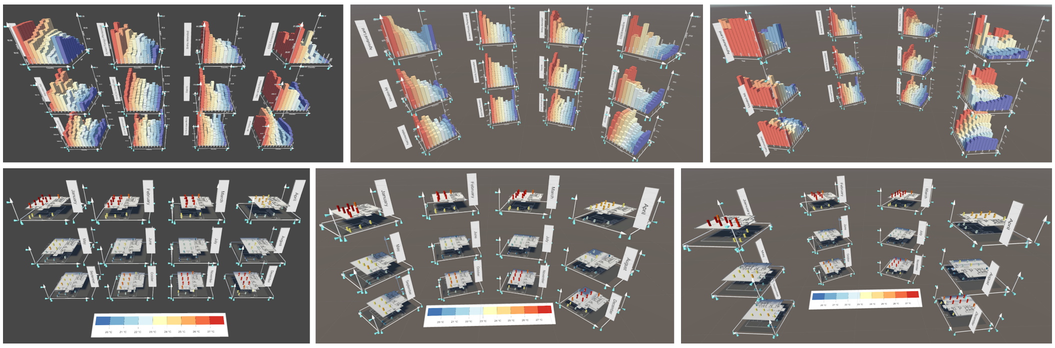

Fig. 4.1.: Two visualisation idioms used in this study: 3D bar charts (top) and BIM models (bottom). Three layout curvatures as the main study condition: flat (left), quarter-circle (middle), and semi-circle (right).

4.1.2 Study Design

We used a within-subjects design with 3 factors: 3 LAYOUT (*Flat*, *Quarter-Circle* and *Half-Circle*) × 2 DATASET (*Bar* and *BIM*) × 2 COMPARISON DISTANCE (*Short* and *Long*). There were 2 repetitions for each combination, which yielded a total of 288 trials with 12 participants.

To limit the time spent in VR and mitigate the possible effects of simulator sickness, we kept the study duration to a maximum of 1 hour. To further balance the experiment time and possible learning effects, we decided to use a Latin square design to counterbalance the order of LAYOUT and DATASET only while leaving the COMPARISON DISTANCE with a fixed order, that is, participants did *Short* first and then *Long* within each condition.

Based on a pilot study (4 participants), the related work and our design space, we formulate a number of hypotheses. Hypotheses D1 and D2 are related to the difficulty of the task, L1-2 consider the effect of layout on performance, M1-2 are related to participants' movement and P1 relates to participants' preferences.

We expect participant performance (time and accuracy):

D1 – will be better with *Short* comparison distance than *Long* - because for *Short* they will be more easily able to have both visualisations in view;

D2 – will be better with less abstract data in the visualisation (i.e., *BIM* better than the *Bar*);

L1 – will be better for *Short* distance, *Half-Circle* layout over other layouts - because it should involve the least participant movement to see both visualisations simultaneously;

L2 – will be better for *Long* distance, *Flat* layout over other layouts - because it allows participants to step back to see both visualisations simultaneously;

In terms of participant movement, we expect:

M1 – greater distance covered with *Flat* layout than *Quarter-Circle* and *Half-Circle* ones.

M2 – more back and forth movement between the two multiples with the *Quarter-Circle* and *Half-Circle* than *Flat*.

For preference we expect:

P1 – *Quarter-Circle* will be preferred over either *Half-Circle* (requires too much rotation) or *Flat* (requires too much movement).

4.1.3 Procedure

After completing the consent form and a demographic questionnaire participants were trained with three interaction techniques: rotation, brushing and filtering. Each study block (i.e., one LAYOUT and one DATASET) followed the same process: the eye tracker was calibrated; followed by two training trials; then four experiment trials; and then a short questionnaire regarding the condition.

At the beginning of each trial, participants were asked to position themselves at a centre position indicated on the ground. Then the question was displayed and they had time to read it. They then had to press a controller trigger to reveal the small multiples and begin the task. By pressing the trigger again, they stopped the task, the small multiples disappeared and they could answer the question by choosing their answer in a menu. They had a maximum of 60 seconds to do the task, after which the small multiples disappeared and they had to choose an answer.

In our initial pilots, we found participants spent an inordinate amount of time finding the two visualisations named in the question. We wanted to focus in this study on participants' ability to compare visualisations at a distance rather than the spatial search task, which is not specific to visualisation. We, therefore, highlighted the two visualisations for comparison from the beginning of the trial.

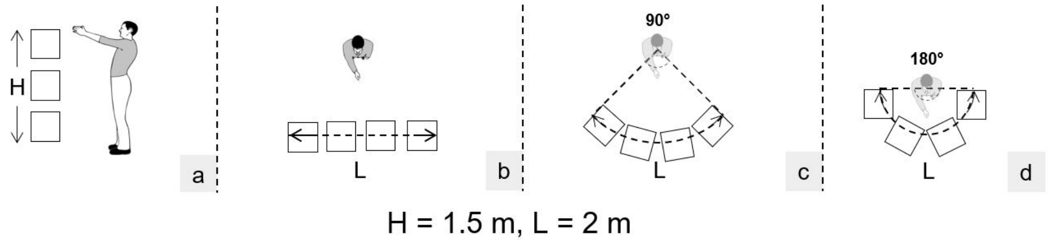

Fig. 4.2.: The shelf configuration: (a) shelf height, (b) flat shelf length, (c) quarter-circle shelf arc length, (d) half-circle shelf arc length

4.1.4 Apparatus and Participants

We used the apparatus and prototype described in the "Implementation" section. The only difference was that all interactions with the shelf itself were blocked. Each small multiple's size is $0.4\ m^3$. The horizontal and vertical offset between each pair of small multiples is $0.15\ m$ (see Figure 4.2). The shelf height was adjusted dynamically so that the top edge of the top multiple was aligned with the participant's eye level (based on pilot studies). The only available interactions were: brushing, filtering and rotation of the small multiples.

We recruited 12 participants (7 males and 5 females. mean age=27.5 and SD=4.7). 4 participants had already experienced VR 2 used Small Multiples before and 5 had experience with brushing and linking techniques.

4.1.5 Measures

We recorded completion time (i.e., the time between pressing the trigger after reading the question until pressing the trigger to give their answer) and accuracy (whether the participants found the correct answer or not) for each trial. In the analysis, we are actually looking at the percentage of wrong answers for each condition. At the end of each block of trials with the same LAYOUT, preference was measured using a ranking. They were also asked about their strategy to solve the task. Participants' head was tracked during the entire experiment, which we use to calculate the distance they travelled during trials. Finally, we use an eye-tracker to find the object they looked at. From this information, we count the number of times they switched between the two small multiples under comparison.

4.1.6 Results

Overall task difficulty between COMPARISON DISTANCE and DATASET conditions is shown in Figure 4.3. The remaining results were analysed for each DATASET individually, as we are more interested in the nuances of each condition than the overall effects. Results for time, accuracy, distance and gaze are shown in Figure 4.4, and participant rankings of the different layouts are shown in Figure 4.5.

Statistical Method. Following APA recommendations [Ass09], we report our analysis using estimation techniques with confidence intervals and effect sizes (i.e., not using p-values) following recent precedents in HCI [Wil+15; BAI17]. Our confidence intervals were computed using BCA bootstrapping, and the term *effect size* here refers to the measured difference of means. Error bars in our charts reporting means are computed using all data for a given condition. When comparing means, we average the data by participants/groups and compare the three conditions globally by computing the CI of the set of differences. A difference is considered as significant when the CI of the difference does not cross 0. In our charts, we display the computed CI of the differences. While we make use of estimation techniques, a p-value-approach reading of our results can be done by comparing our CIs spacing with common p-value spacing as shown by Krzywinski and Altman [KA13]. No corrections for multiple comparisons were performed [Per98; Cum13]. All the results reported in the analysis are significant.

Difficulty. Participants were faster ($\sim$ 3 seconds) to answer questions with *Long* than with *Short*, however, this difference may be attributed to a learning effect, since participants always completed the *Short* condition first. We did find any difference between the two conditions in accuracy. Participants were faster ($\sim$ 25 seconds) to answer questions on the *BIM* condition than on the *Bar* one. Accuracy is also a little lower ($\sim$ 6%) in the *Bar* condition than with the *BIM* one.

Bar Dataset

Time. Overall, participants were faster to complete the task with the *Flat* layout (*Quarter-Circle* was ~ 6 seconds slower, *Half-Circle* ~ 8 seconds slower). When we look at the different COMPARISON DISTANCE, we can see that there is a difference only for the *Long* comparison distance with participants being faster by $\sim$ 9 seconds compared to the *Quarter-Circle* and 14 seconds with the *Half-Circle*.

Accuracy. Overall, participants were less accurate with the *Quarter-Circle* layout (0.3 against 0.1 for the *Flat* and 0.12 for the *Half-Circle*). This difference is present

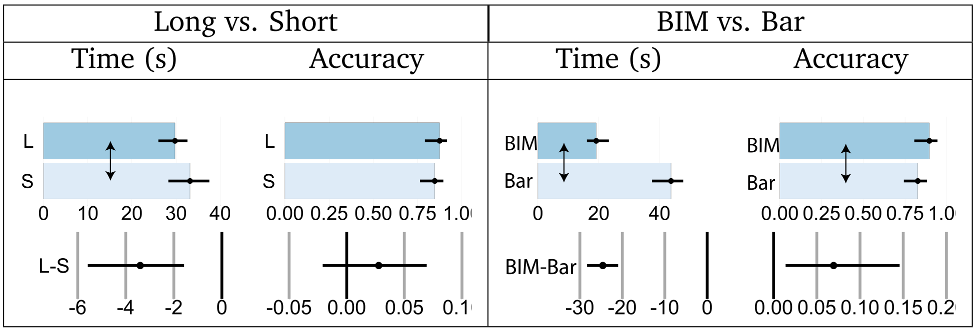

Fig. 4.3.: The top bars compare *Long* (L) and *Short* (S) conditions (left), and *BIM* and *Bar* conditions (right). The bottom charts show corresponding 95% CIs for the mean differences. Arrows indicate a significant difference between the two conditions.

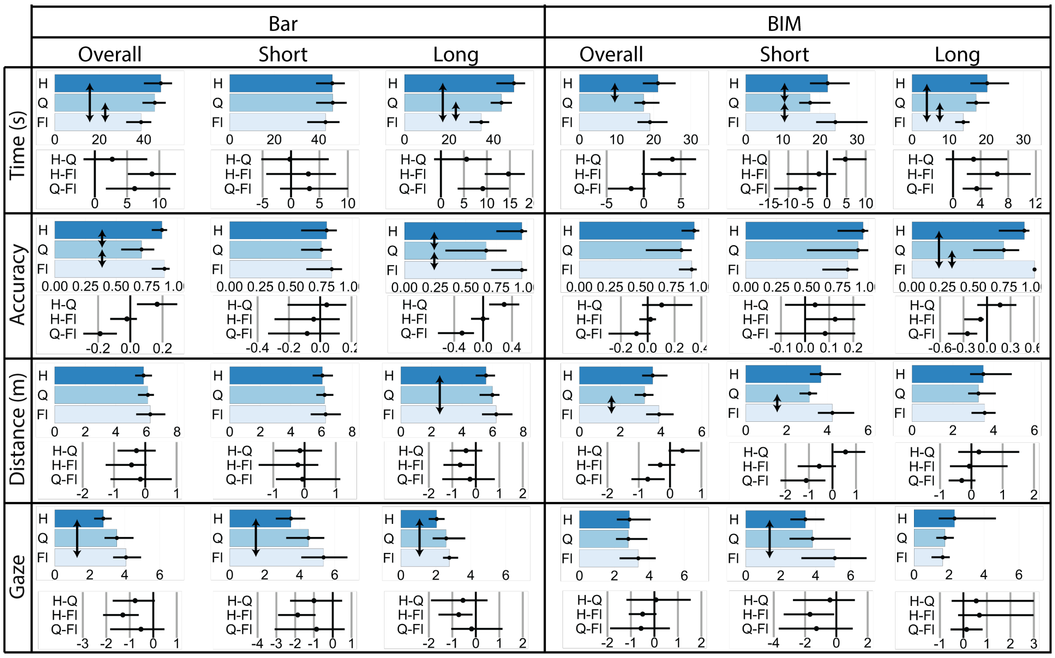

Fig. 4.4.: The top chart of each pair shows Means and CIs for all measures for Layout (Flat (Fl), Quarter-Circle (Q) and Half-Circle (H)) across conditions. The bottom chart shows 95% CIs for the mean differences between Layouts. Arrows indicate significant differences between conditions.

for the *Long* comparison distance, where participants have an error rate of 0.3 with the *Quarter-Circle* layout against one of 0.04 with the two others.

Travel Distance. Overall, we did not see any difference in the distance participants travelled during trials between the different layouts. We do find a difference for the *Long* comparison distance between *Flat* and *Half-Circle* layout ($\sim$ 0.7 m with *Half-Circle*).

Gaze Change. Overall, participants did 1 more back-and-forth between the two multiples with the *Flat* layout than with the *Half-Circle* one. This is reflected in both conditions with a similar effect.

Preferences. When we look at the ranking of the LAYOUT, we can see that 5 participants ranked *Quarter-Circle* first, against 4 participants for the *Flat* and 3 for the *Half-Circle*. Six participants ranked the *Flat* and the *Half-Circle* layouts last, against none for the *Quarter-Circle* one. In their comments, a few participants said that the *Flat* layout required too much walking (3/12), but one mentioned that it was possible to easily have an overview, without rotating. The rotation with the *Half-Circle* layout was considered an issue by some participants (5/12). Finally, the *Quarter-Circle* was considered a good compromise between walking and rotating (6/12).

BIM Dataset

Time. The only difference found is between the *Quarter-Circle* and the *Half-Circle* layout (*Quarter-Circle* faster by 4 seconds). If we break by COMPARISON DISTANCE, the *Quarter-Circle* layout was slightly faster for the *Short* comparison distance ($\sim$ 6 seconds against the *Flat* and 4 seconds against the *Half-Circle*), while *Flat* was faster for the *Long* comparison distance ($\sim$ 6 seconds against the *Half-Circle* and 3 seconds against the *Quarter-Circle*).

Accuracy. Overall, there is no difference between the three LAYOUT. There is also no difference for the *Short* comparison distance. For the *Long* comparison distance, participants have a lower error rate with the *Flat* layout (0.0) than with the *Quarter-Circle* (0.25) and the *Half-Circle* (0.09).

Travelled Distance. Overall, there is a difference between the travelled distance between the *Quarter-Circle* and the *Flat* ($\sim$ 0.7m). The same difference can be seen for *Short* comparison distance ($\sim$ 1.1m), and additionally, there is a difference between the *Quarter-Circle* and the *Half-Circle* layout ($\sim$ 0.5m). No difference can be observed for the *Long* comparison distance.

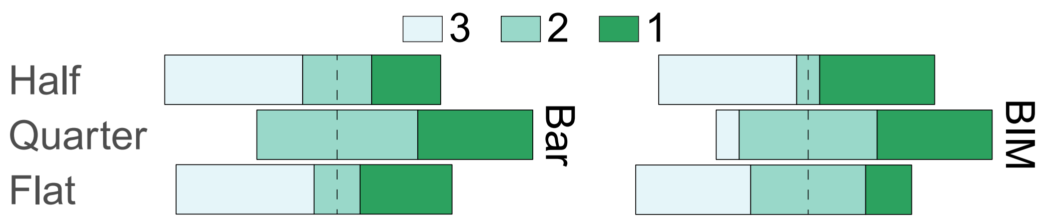

Fig. 4.5.: Result of the ranking for the three layouts for the Bar condition (left) and BIM condition (right).

Gaze Change. Overall, we can not find any difference between the number of back-and-forth switches between the two multiples. We can only see a difference in the *Short* in which participants did almost 2 more switches with the *Flat* than with the *Half-Circle* one.

Preferences. Six participants ranked *Quarter-Circle* and *Half-Circle* layout first, against 2 for *Flat*. Only 1 ranked *Quarter-Circle* layout last, against 5 for *Flat* and 6 for *Half-Circle*. Similar to *Bar*, participants found walking an issue with *Flat* (4/12) but liked the overview that it allowed without rotation (3/12). Rotation in *Half-Circle* was also considered an issue (6/12), and *Quarter-Circle* was a good compromise between walking and rotation (8/12).

4.1.7 Discussion

The fact that participants were faster with the *Long* condition than with *Short* is interesting (rejecting *D1*). This might be due to several phenomena, including a learning effect due to participants completing *Short* first in each condition, but also due to only 12 small multiples being insufficient to really force much movement. On the other hand, participants were clearly faster in *BIM* condition than in *Bar* (confirming *D2*), which is expected due to the number of candidate data points for comparison.

Regarding performance in *Short*, participants were faster with *Quarter-Circle* for the *BIM* dataset (Rejecting *L1*). No other difference was found regarding time or accuracy. The layout in the *Short* condition probably does not impact performance.

In *Long* condition, participants were faster and more accurate for both datasets with *Flat* layout (supporting *L2*) despite reporting that they found they had to walk more. In fact, analysis of tracked movements revealed only a small increase in movement (there is a difference of only 0.7 meters against the *Half-Circle* with the *Bar* dataset) which likely did not significantly affect their completion times. Also, we found that participants routinely found positions such that their field of view included both multiples under comparison.

Overall, regarding the distance travelled by participants, there is only a difference with the *BIM* layout (M1 partially confirmed), and it is rather small (between 0.5 and 0.7 meters shorter than with the *Flat* layout). This may be due to the low number of multiples which means that participants do not have to walk much to closely inspect all of them. Regarding the number of gaze switches between the two multiples, we can see a global difference only in the *Bar* condition, and it shows that there is more with the *Flat* layout than with the *Half-Circle* one (rejecting M2). Plumlee and Ware explain that the less costly switches are in visual comparison, the more users are going to use them. This is in order to limit the load on their visual working memory. In our case, this seems confirmed by the finding that it is less easy to find a position where users can transition between the two multiples with the *Half-Circle* layout than with *Flat*.

Finally, participants stated that the *Flat* provides a good overview of the data and that they can easily see all of the multiples at once and keep them in their peripheral view when they focus on one, which is not possible with the two other layouts.

4.2 User Study 2: Large Scale Comparison

The first user study indicated performance advantages of the flat layout, as it provides a broad overview without the need for rotation, despite the need for some walking. We conducted a second user study to determine whether these findings scale to a more extreme design, with a larger layout containing more multiples (from 12 to 36, with 12 columns and 3 rows). To better understand the effects of participant rotation, we also included a full-circle condition (and thus, removed the *Quarter-Circle* layout). Prior work in multi-display environments recommends never placing displays behind the user [SB05], however, we are interested to see if this holds true in an immersive setting where the user is standing, rather than sitting. The design of this experiment has been preregistered on OSF [Liu+19b].

4.2.1 Tasks

We have two tasks in this follow-up study. In both tasks, each multiple presents a 3D bar chart. The first task is the same as in the first study, it is a visual comparison between two multiples. In this study, we have only one condition in which the multiples are at a Manhattan distance of 7 or 8.

For the second task, we wanted participants to have to look at all multiples. We decided to go with a task in which participants have to find the maximum value for a specific bar in the small multiples.

Dataset. We used a dataset inspired by the world indicator dataset used for the *Bar* condition in the previous study. Each multiple represented the value of 5 indicators for 5 countries for a specific year (see Figure 4.1). Contrary to the previous experiment, the data were simulated in order to easily create one with a maximum value. The questions were created manually by the authors.

4.2.2 Study Design

We used a within-subject design which consisted of: 3 LAYOUT (*Flat*, *Half-Circle* and *Full-Circle*) $\times$ 2 TASK (*Comparison* and *Max*). There were 3 repetitions of each combination, which yielded a total of 216 trials for 12 participants. A Latin square was used to counterbalance the order of LAYOUT. As we did not intend to compare the two TASK, the order was fixed. Participants started with the *Comparison* task.

As this is an exploratory study (we removed a condition to try a new task), we did not have strong hypotheses regarding the performance of each LAYOUT. Our goal was to observe the nuances of each and how they compare to each other. However, the metric and the analysis methods were determined before the study: we explore the effect of LAYOUT performance, movement, gaze and preference.

4.2.3 Procedure

The procedure is similar to Study 1, except the maximum task time is increased to 90 seconds. For the *Max* task, no multiples were highlighted as participants should look at all of them.

4.2.4 Apparatus and Participants

We use the same apparatus and prototype as in Study 1. However, we adapted the shelf configuration for the large scale. Each small multiple's size now is $0.3\ m^3$.

The horizontal and vertical offsets between small multiples are 0.18m and 0.15m, respectively. The shelf height was adjusted dynamically as in study 1.

We recruited 12 participants (5 male, 7 female; mean age=26.1 with SD=3.9); 4 participants returned from Study 1; 8 had already experienced VR; 5 had used Small Multiples before, and 5 had experience with brushing and linking techniques.

4.2.5 Measures

We use the same statistical method and take the same measure as in Study 1. Using the head tracking data, we calculated the amount of time participants spent walking (over 1.8 km/h), which we called *Walking Time*. Finally, using the eye tracker data, we calculated the distance between the participants and the object they are looking at. We then calculate the amount of time they spent looking at objects that are more than 1 metre away (*Time looking at distant objects*).

4.2.6 Results

Results regarding time, accuracy, distance, gaze change, walking time and distance between participants and objects are presented in Figure 4.6, and Figure 4.7 shows the results of the participant ranking of the different layouts.

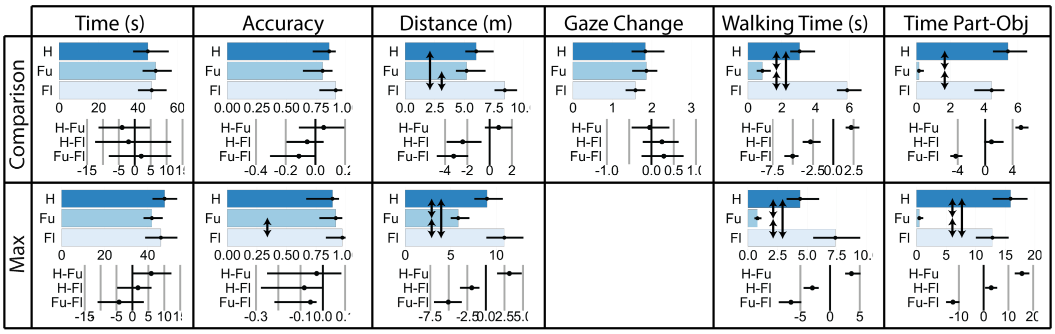

Fig. 4.6.: In each cell, the top bars show Means and CIs for all measures for Layout (Flat (Fl), Half-Circle (H) and Full-Circle (Fu)) across conditions. The bottom charts show Corresponding 95% CIs for the mean difference. Arrows indicate a significant difference between the two conditions.

Comparison Task

Time. We do not observe any difference in completion time between the three LAYOUT.

Accuracy. We do not observe any difference in accuracy between the three LAYOUT. However, there may be a difference between *Full-Circle* and *Flat*, with participants being more accurate with *Flat*, but it is not significant.

Travel Distance. Participants travelled more with *Flat* than with *Half-Circle* (∼2.4m) than with *Full-Circle* (∼3.2m).

Gaze Change. We did not find any difference between the number of gaze switches between layouts.

Walking Time. Participants spent more time walking with the *Flat* layout than with *Full-Circle* (5 seconds more) and *Half-Circle* (3 seconds more). They also spent more time walking with *Half-Circle* than with *Full-Circle* (2 seconds more).

Time looking at distant multiples – Participants spent less time looking at distant multiples with *Full-Circle* than with *Flat* (4 seconds less) and *Half-Circle* (5 seconds less).

Preferences. 5 participants ranked *Flat* first, against 4 participants for *Half-Circle* and 3 for *Full-Circle* . Only 1 ranked *Half-Circle* last, against 4 for *Flat* and 7 for *Full-Circle*. In the comments, participants found that walking with *Flat* was an issue (7/12), but some thought that this layout allowed for a good overview of the multiples (3/12). For *Half-Circle*, some participants also complained about walking (4/12), and one specifically mentioned that walking "around" was not convenient. Finally, the main issue mentioned for *Full-Circle* was that it was hard to locate the graphs to compare (despite them being highlighted) because they had to do a 180 degrees rotation (8/12).

Max Task

Time. We do not observe any difference in completion time between the three LAYOUT.

Accuracy. Participants were slightly more accurate with *Flat* than with *Full-Circle*, with a difference of 0.05. There seems to be a difference between *Flat* and *Half-Circle*, with participants being more accurate with *Flat*, but it is not significant.

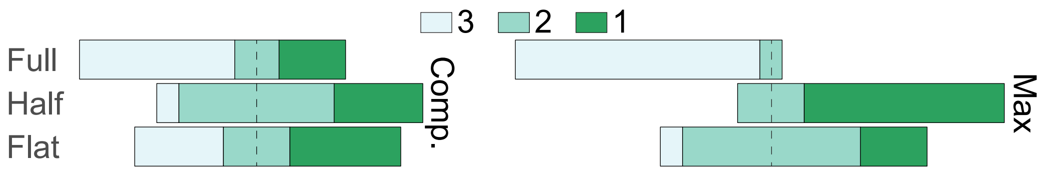

Fig. 4.7.: Result of the ranking for the three layouts for comparison (left) and max task (right).

Travelled Distance. Participants travelled more distance with *Flat* than with *Half-Circle* (∼1.9m) than with *Full-Circle* (∼5m). They also walked more with *Half-Circle* than with *Full-Circle* (∼3.2m).

Walking Time. Participants spent more time walking with *Flat* than with *Full-Circle* (7 seconds more) or *Half-Circle* (3 seconds more). They also spent more time walking with *Half-Circle* than with *Full-Circle* (4 seconds more).

Time looking at distant multiples – Participants spent less time looking at distant multiples with *Full-Circle* than with *Flat* (12 seconds less) and *Half-Circle* (16 seconds less). They also spent less time with *Half-Circle* than with *Flat* (3 seconds less).

Preferences. 9 participants ranked *Half-Circle* first, against 3 participants for *Flat* and none for *Full-Circle* one. No participant ranked *Half-Circle* layout last, against 1 for *Flat* and 11 for *Full-Circle*. With *Flat* layout, participants liked that they could easily get an overview of the multiples (3/12), but not the fact that they had to walk a lot (5/12); for instance, one participant commented "I wish I could perform less physical walking. Panning the vis would be great in this case." Some participants thought *Half-Circle* was a good compromise as it provided an overview without too much walking and rotation (4/12). In accordance with that, some participants stated that the *Full-Circle* layout did not provide them with an overview at a glance, and required too much rotation (4/12).

4.2.7 Discussion

The results from both tasks are very similar. We cannot see significant differences between different layouts regarding time and accuracy. For the *Comparison* task, this could mean that the better performance of *Flat* in the previous experiment is countered here by the greater number of multiples. This explanation is supported by the fact that participants had to walk a greater distance, costing additional time. A similar effect has been observed by Shupp et al. when comparing flat and curved physical displays on search and path tracing tasks [Shu+06]. However, their findings suggested that curved display leads to better performance while our results do not provide statistically significant evidence reproducing this result in our VR environment.

So participants, in both tasks, spent more time walking in the *Flat* layout, but also in the *Half-Circle* one. Additionally, they spent more time looking at distant objects, this could mean that they seized the opportunity to step back and get an overview of the multiples, which is not possible in the *Full-Circle* layout.

Finally, participants preferred, for both tasks, the *Half-Circle* layout. Their comments explained that it was a good compromise between walking and rotation and that it allows for an overview at a glance by taking a step back. Participants identified that rotation in the *Full-Circle* layout was disorienting and made it harder for them to locate specific multiples. Similar to the *Half-Circle* layout, *Flat* was appreciated for its easy-to-access overview, but the amount of walking necessary was considered an issue. Interesting future work would be to explore techniques to reduce walking, like panning of the shelf, and VR teleportation. Similar work has been done on wall displays, and they showed that while users tend to favour Virtual Navigation [JH15] (in our case it would be panning the shelf or teleportation), physical navigation leads to better performance [Bal+07; JH15; Liu+14] as it improves spatial memory [Räd+13]. These studies involved flat wall displays, the influence of curvature on this issue would also be an interesting future direction.

4.3 Conclusion and Future Work

Our user studies revealed that the performance of different layouts is dependent on the number of multiples displayed. With a small number, a *Flat* layout is more performant, even if it is not the users' preferred one, due to the amount of walking required. With a significant increase in the number of multiples, the difference in completion time was less noticeable. However, participants complained about disorientation with *Full-Circle* and that it made locating a specific multiple difficult. It was also an issue that *Full-Circle* made getting an overview at a glance difficult. On the contrary, the *Flat* layout allows users to easily obtain an overview of all the multiples but requires too much walking. Regarding all these issues, the *Half-Circle* provided a good compromise and was preferred by participants.

There is a future opportunity to explore the curvature design space. For instance, vertical curvature has been used to support direct input in joint-centred layouts [Lub+16]. It would also be interesting to study the impact of interaction techniques that avoid walking, like VR teleportation or virtual panning of the shelf. However, this may also be less natural, and disorienting and may impede any kinesthetic memory effect – but all of these aspects would need to be teased apart in low-level studies.

5 Effect of Display Layouts on Spatial Memory

> *Spatial memory is the ability to remember where you put something.*
>
> — **George Robertson et al.**
> (In a 1998 paper introducing the concept of Data Mountain to evaluate spatial memory for document management)

In immersive systems for data visualisation, it is common to position data displays in a *wraparound* configuration, such that the data displays surround the position of the user [Bat+19; Lis20; Lee+21b; Sat+20]. This design choice may descend from early room-size projection VR systems (e.g., the CAVE [Cru+92]), capable of projecting stereo imagery in every direction the user may face. Arranging the visuals to completely surround the user, as in modern CAVE2 environments [Feb+13], is then a fairly logical way to utilise the display capability. A display that fully surrounds the user may also have the advantage that the user can simply turn on the spot to navigate. Such rotational navigation may be less physically demanding than walking to change one's viewpoint in a traditional flat layout. Direct manipulation with immersive interface elements is also well-suited to a wraparound configuration, as arranging objects around a common centre point reduces the effort needed when reaching from object to object [EHI14; Lub+16]. Another source for this design choice to 'wrap' the visuals around the user may be VR headsets that are tethered (connected by a physical cable to a PC). Headset tethers physically limit the distance a user can comfortably walk and introduce a fear of tripping over the cable and can therefore be a disincentive for users to walk any significant distance.

Recent results from multiple studies that allow users of immersive visualisation systems to freely create visualisations have reported that people tend to position visuals in a circle at arms' length around them [Bat+19; Lis20; Lee+21b; Sat+20]. Some of the research has therefore concluded that circular arrangements of data visualisations around users should be supported as a key aspect of immersive visualisation systems. But once again, an alternative explanation for this observed

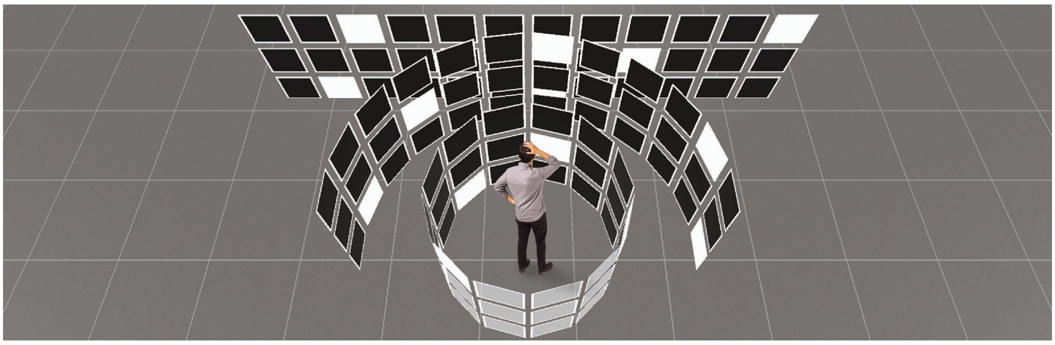

Fig. 5.1.: The extensive 3D space surrounding users in immersive environments allows for various display layouts. In this research, we consider layouts which wrap around the user to varying degrees: Flat, Semi-Circle, and Full-Circle. We hypothesise that the degree of curvature affects users' spatial memory during navigation. We explore this hypothesis through a sequence of studies.

user behaviour may be an unwillingness by users to walk in the virtual environment due to a tether or unfamiliarity with physical navigation in VR. It should also be noted that the immersive studies above typically involved free-form data exploration, rather than controlled data understanding tasks – so the observed user preference for wraparound displays in these contexts does not necessarily indicate support for analysis tasks.

While there is some evidence from existing work that display curvature affects visualisation tasks, these findings are overall rather inconclusive. To give a couple of examples, a study by Shupp et al. has shown advantages of curved 2D displays in path-following tasks on maps [Shu+06] but was inconclusive for comparison tasks. While a recent study by us [Liu+20] with small multiples in VR found that participants were able to perform visual comparison and search tasks better with flat displays than wraparound displays. As a result, there are no clear guidelines for creators of immersive visualisation systems on this rather fundamental question of how to layout displays in immersive visualisation spaces. In their concluding remarks, Liu et al. hypothesise that the effects of layout curvature on spatial memory may help to explain their observed differences, but to our knowledge, no existing studies have tested whether curvature of information displays influences spatial memory.

In this chapter, we study lower-level spatial memory tasks to see how spatial memory is supported by display layout. The hope is those clear findings in this regard can lead to more concrete design guidelines for immersive data visualisation and potentially other sensemaking activities in immersive environments. Spatial memory seems particularly relevant to recall and comparison tasks in visualisation, because these tasks typically involve the comparison between multiple data encodings to identify patterns or anomalies. Since immersive environments allow data visualisations to be spread out over a large region, navigation between multiple objects for comparison requires users to temporarily remember their physical locations. If we can minimise the effort required for such context switches, users will switch more often to reduce demand on their visual working memory [PW06]. For instance, participants in Liu's study with small multiples seemed to find switching easier with a flat than with a curved layout [Liu+20]. Beyond data visualisation tasks, users' ability to remember the locations of objects in immersive environments has implications for many other applications, from group work to gaming [Nin+21; Muh15; GP18].

In Sections 5.2 and 5.3, we present two user studies to test the effect of different display layouts (*Flat* vs *Full-Circle*, *Flat* vs *Semicircle*) by investigating user's ability to recall locations of items within the layout for a straight-forward visuo-spatial memory task. As detailed in Section 5.2.6, results of the first study clearly show that participants are able to recall room-scale patterns of cards more accurately with a *Flat* than a *Full-Circle* display layout. Subjective feedback also reports better performance and less mental effort and frustration with the *Flat* than the *Full-Circle* layouts. In Study 3 we also introduced conditions with visual modifiers to try to isolate the effect of physical navigation from other differences between *Flat* and *Full-Circle*, such as the possibility of getting an overview by stepping back from *Flat* or the obvious landmarks provided by the edges of the *Flat* layout. Neither of these visual modifiers made a significant difference, meaning that the primary benefit of *Flat* over *Full-Circle* is likely the physical navigation, i.e., walking rather than rotation. The results from the second study show non-significant differences between the *Flat* and the *Semicircle*. However, our participants prefer the *Semicircle* layout suggesting it is a good compromise between the *Flat* and *Full-Circle* layouts. Overall the findings from our two studies suggest that, when the tasks depend on the user's spatial memory of the layout, layouts of the information displayed in immersive environments that completely surround the user should be avoided.

Apart from the empirical findings as mentioned above, our research also presents a methodological contribution. This is the first rigorous study, inspired by the design of spatial memory tests from psychology, to test the effects of the layout of displays in immersive environments on spatial memory. We have also explored the effects of landmarks and the ability to have an overview as subordinate factors. We hope this research will establish a connection between spatial memory and analytic tasks in information visualisation, and be used as a foundation for future work expanding this fundamental topic.

5.1 Studying Spatial Memory

This section details the historical context and rationale for studying spatial memory for immersive visualisation and for our chosen task. While past work in data visualisation explored the effects of layout in the context of high-level visual data analytics tasks, either qualitatively [Bat+19] or quantitatively [Liu+20], their conclusions regarding spatial memory were inconclusive due to the confounds introduced by the complex nature of such tasks. Thus, we choose an abstract task, which is adapted from two common tasks developed by psychologists to assess visuo-spatial memory: the visual memory span task [LZB90; WSP87], and the Corsi block tapping task [Cor73].

In the visual memory span task as used by Logie et al. [LZB90] and Wilson et al. [WSP87], participants were presented with a grid pattern of squares (half filled with black and half with white) for a short duration. They were then asked to reproduce this pattern on an empty grid. The difficulty was increased over time by adding two squares incrementally. The Corsi block tapping task is similar to the visual memory span task but requires participants to recall a specific sequence. In this task, participants are asked to tap a set of blocks (among 9) in a specific order. The first task begins with two blocks, and the number of blocks is incremented by one every time participants successfully recall the pattern. The experiment ends when the participants fail twice.

In summary, spatial memory has been shown to influence interface performance both on desktops and in VR. We can also see that the interface itself has an impact in this spatial memory (2D vs. 3D, the impact of navigation, etc.). However, little is known about how the arrangement of visual elements in the space around the user in VR environments affects their working memory, for example, whether certain layouts reinforce or detract from spatial memory. In this research, we take a further step in this direction and assess the impact of the layout of visual elements on spatial memory in VR. This requires participants to move within the tracked volume, which allows us to easily vary conditions across factors such as the degree to which the layout of grids wraps around the participant.

5.2 User Study 3: Flat Versus Full Circle

Our initial study focuses on examining the effectiveness and efficiency (see 'measures' subsection below) on a task that requires spatial memory with a comparison of *Flat*

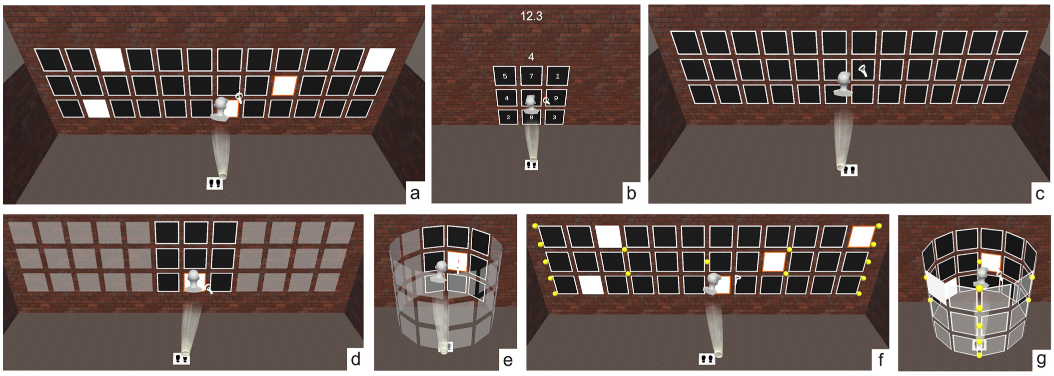

Fig. 5.2.: (top) In the study, participants had to remember 5 cards highlighted in a grid in a learning phase (a), then they performed a distractor task to decay short-term memory (b), and finally in a recall phase, they had to select the memorised cards in an empty grid (c). (bottom) The between-subjects VISUAL MODIFIER factor has three levels: *Regular* (a), *Restricted FoV* (d,e), and *Landmark* (f and g) for both layouts.

and *Full-Circle* layouts. While we are also interested in studying partial-wraparound layouts, early pilot testing with a visuo-spatial memory task led us toward a minimal study design with 2 conditions per participant in order to limit their exposure to VR. Thus we first investigate our primary research questions with these two 'extreme' cases before including *Semicircle* layouts in a follow-up study.

To limit the time spent in VR and mitigate possible effects of simulator sickness, we keep the study duration relatively short (to a maximum of 1 hour). Due to high inter-participant variability, we limited our design to a single factor and controlled the remaining variables. Thus, we use a single task difficulty with a fixed size grid (3 rows x 12 columns) and a fixed number of items that need to be recalled (5 items), as described below.

5.2.1 Task

We use a grid of 36 virtual cards arranged into 12 columns and 3 rows, as shown in Figure 5.2. This arrangement follows the 'large scale comparison' study design of our past studies [Liu+20], which used 36 small multiples in a 3x12 grid. In each task, participants must learn and recall the locations of 5 cards, which is slightly higher than the known capacity of visuo-spatial working memory (4 objects) [LV97]. The number of cards to recall was chosen to control the level of difficulty after pilot tests (using 3–6 cards) and power analysis. As described in Section 5.1 the task chosen for our study is inspired by this past work.

Each card is 0.4×0.4 m, with horizontal and vertical offsets of 0.1 m between each pair (Fig. 5.1). The *Flat* layout has a width of 5.9 m and a height of 1.4 m (see Figure 5.2-a). The circumference of the *Full-Circle* layout is equal to the width of the *Flat* layout, resulting in an approximate radius of 0.95 m. With this radius, the cards are within arm's reach and thus, we speculate that walking will be minimised (see Figure 5.2-e,g). Similar dimensions of wraparound layout (i.e., an approximately arms-length radius) are also observed to emerge naturally from user placement of objects in exploratory studies from [Bat+19; Sat+20; GSL21], as discussed in Section 2.3.2. The height of the *Full-Circle* layouts is the same as the *Flat* layouts. The participant starting position in the *Flat* layout has a 0.95-meter distance to the centre of the layout grid while the starting position of the *Full-Circle* layout is the centre point of the circle.

To reduce variability in the study data, we create a fixed sequence of patterns for the grids by generating them in a constrained-random manner and then validating them manually. There are 3 constraints for the generation: (1) no 2 adjacent cards can be included in the same pattern; (2) at least 1 card is included on each row to balance the pattern vertically; and (3) at least 2 cards are included on each side (left or right) to balance the pattern horizontally.

Each trial is divided into 4 phases: *preparation*, *learning*, *distraction*, and *recall*. In the *preparation* phase, participants are required to stand at the starting position facing forward, as indicated by a pair of footprints. Once in position, participants trigger the *learning* phase (Figure 5.2-a) by pressing a button on the controller. In this phase, a pattern of 5 white cards is revealed in the grid. Participants are given 15 seconds to tap each white card with a controller held in their dominant hand. Changes to the card boundary colour provide feedback to track participants' progress in this learning phase. Specifically, a green border means the card has been tapped which helps participants ensure they touch each white card. Also, an orange border means the card has appeared within the participant's point of view; although this is primarily for experimenters as participants will only see cards when they already have an orange border.

Since short-term memory decays within 15–30 seconds [AS68], we include a *distraction* phase lasting at least 15 seconds between the learning and recall phases. In this phase, a distractor task requires participants to tap a new set of randomly numbered cards in a given sequence (Figure 5.2-b). Participants will see a countdown timer on top of the task board. During the distractor task, if participants have tapped the wrong cards or idled for 3 seconds, they will be penalised by adding 3 seconds to their current timer.

Finally, in the *recall* phase, participants are asked to recreate the pattern shown in the learning phase by tapping on an empty layout. We do not set a time limit for this phase (Figure 5.2-c). Participants need to confirm their answers by pressing a button on the controller. The number of correctly selected cards is then shown to them.

5.2.2 Design

Layout. The primary motivation of this study is to examine the effect of layout on participants' ability to recall the locations of items within the layout. As described above, we design two layouts with extreme curvatures: *Flat* and *Full-Circle* (see Figure 5.1).

Visual Modifier. In a visual and spatial memory task, as the one described above, we expect the *Flat* layout to provide some advantages over the *Full-Circle* one. First, participants can take a step back to get an overview of the *Flat* wall, which is not possible in the *Full-Circle* layout. The *Flat* layout also provides implicit landmarks at its edges and corners. While prior work suggests benefits of explicit landmarks [Gao+18; Gao+21; UGC17], we speculate that, to some extent, this result is also generalised to implicit landmarks. To evaluate the impact of these advantages on participants' performance, we include a VISUAL MODIFIER factor that will either (1) limit the capabilities of an overview of the layout (*Restricted FoV*), (2) add landmarks to the grid (*Landmark*), or (3) leave the two layouts unchanged (*Regular*). The *Restricted FoV* condition reduced the benefit of *Flat* layout over *Full-Circle* by only showing cards on the three nearest columns from the participant (see Figure 5.2-d,e). The other columns show only semi-transparent backgrounds in place of the cards. The *Landmark* condition adds a set of yellow spheres in fixed positions on the grid as landmarks (see Figure 5.2-f,g). This design was inspired by a similar study by Gao et al. [Gao+18]. To help orient users, we put a different number of landmarks in different positions: middle (*Flat*) or front (*Full-Circle*) with a single landmark, left/right edges (*Flat*) or back (*Full-Circle*) with 5 landmarks, and 2 landmarks in-between (see Figure 5.2-f). These visual modifiers are enabled in both the learning and recall phases.

Our study design is a 2 (LAYOUT) x 3 (VISUAL MODIFIER) mixed-factors study. LAYOUT is treated as a within-subjects factor with 2 conditions (*Flat* and *Full-Circle*). VISUAL MODIFIER is a between-subjects factor with 3 conditions (*Regular*, *Restricted FoV*, and *Landmark*). Each participant performs both LAYOUT but only one VISUAL MODIFIER. The reason for our mixed-factor study is that a fully within-subject study would result in an excessive amount of VR exposure for participants, especially while doing a cognitively intensive task.

In total, we collect data from 648 completed trials (12 participants $\times$ 9 repetitions $\times$ 2 LAYOUTS $\times$ 3 VISUAL MODIFIERS). We treat LAYOUT and VISUAL MODIFIER as independent variables. Dependent variables include completion time, cards accuracy, Manhattan distance of the errors, walking distance, head positions and rotation angles, and subjective ranking.

5.2.3 Participants and Apparatus

In total, we recruit 36 participants (18 males and 18 females; mean age = 25.11, $SD = 3.89$). All participants are students from our university. Each VISUAL MODIFIER group consists of 12 participants with the same male and female ratio (6 males and 6 females). Of the participants, 22 have at least some experience with VR and 3 of them rate themselves as VR experts. Participants sign up voluntarily and are rewarded a gift card (A$20) and small gifts (candies and chocolates) as a sign of appreciation.

We run our study using a tethered HTC Vive Pro in a 10 m x 5 m empty room. We develop our study software using the Unity development environment (2019.3.0f3). We leverage VRTK [Bod18] for interactive components. The prototype runs on a Windows 10 PC with an Intel I7 7800X (3.5GHz) processor and an NVIDIA GeForce GTX 1080 (32GB RAM) graphics card. The source code is publicly available and may be downloaded via GitHub: [Liu22b].

5.2.4 Procedure

After completing a consent form and demographic questionnaire, participants are given a verbal explanation of the trial workflow. Next, participants put on the VR headset and performed a series of training scenes such as interactions and the trial workflow. After that, participants complete the trials with the two LAYOUT conditions in alternating order. The order of the starting layout is also counterbalanced. Participants first complete 2 practice trials (one with each LAYOUT condition), followed by 3 blocks of 6 trials each. Participants are asked to remove the VR headset to take a short break between blocks. Following the completion of all 20 trials, participants complete a short questionnaire with (1) NASA-TLX [Har06], (2) rankings on LAYOUT preference, and (3) the general strategy they use to complete the tasks. The total study duration is about 45 minutes, including roughly 30 minutes in VR. All participants complete the full set of trials successfully.

The experiment environment includes surrounding walls, carpet floor, a starting position sign, and the experimental grid, as shown in Figure 5.2. The starting position and surrounding walls are visible at all times during the experiment.

The vertical position of the grid is adjusted using a standard calibration for every participant before the experimental trials. It is used to normalise the individual height differences and make sure that every participant has the same ability with the controls for selection. These configurations are adapted from Liu's work [27] and validated through our pilot testing of different variations.

5.2.5 Measures

For each trial, we record the number of correctly chosen cards, along with their positions in the grid. We also record the *Recall Time* taken to select the 5 cards in the *recall* phase. The *Recall Time* is calculated from the start of each *recall* phase immediately after the timer of distractor task ends, to the time the participant presses the button on the controller to indicate task completion and see the results. In our analysis, we use two methods to measure participants' recall accuracy: *Cards Incorrect* and *Manhattan Distance Error*.

Cards Incorrect measures the average number of cards selected incorrectly in each trial (also expressed as an open unit interval). To reveal deeper granularity in the responses, we further include the Manhattan Distance Error measure, which measures the sum of Manhattan distances from incorrectly selected cards to the correct cards. The Manhattan distance is a common distance matrix for discrete space and has been used more often to vectors that describe objects on a uniform grid [Liu+20; Gao+18; SCG13], than other distance measurements, such as a Euclidean distance. Because the selection is non-sequential, there are many possible solutions to this measure, so we take the solution with the minimum distance as calculated using the Hungarian Algorithm [Kuh10].

Participants' head pose is tracked throughout each trial and is used to calculate the *Walking Distance* travelled by participants, *Head Rotation*, and *Head Pointer Intersections* with the plane of the wall display.

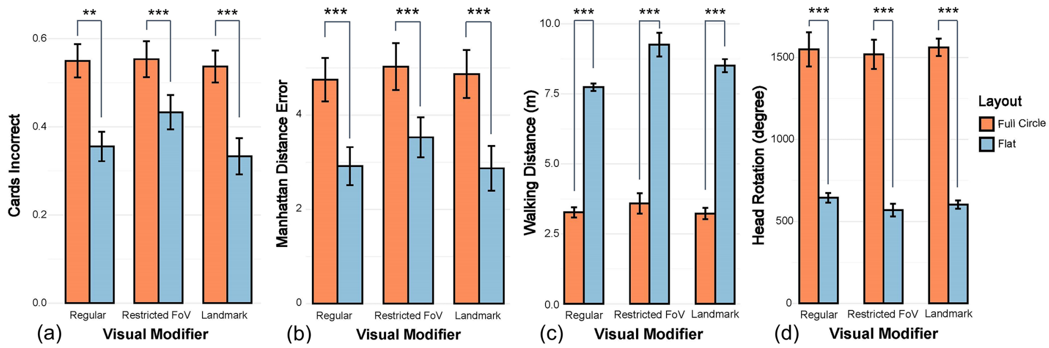

Fig. 5.3.: (a) Cards Incorrect (lower is better), (b) Manhattan Distance Error (lower is better), (c) Walking Distance, and (d) Head Rotation between the VISUAL MODIFIER factor within the *Flat* layout and *Full-Circle* layout. Error bars denote standard error. Asterisks in this figure and the following figures represent the level of significance: * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$.

5.2.6 Results of Study 3

We report on the following measures: First, we include three performance measures, (1) *Cards Incorrect*, or proportion of cards chosen incorrectly in each trial; (2) (optimal) *Manhattan Distance Error* between the participants' answers and the solutions; and (3) *Recall Time*, total time of the recall phase. Then we include three physical movement measures collected during the learning phase: (4) *Walking Distance* travelled by participants; (5) *Head Rotation* performed by participants calculated by cumulative angular distances from their tracked head movements; and (6) *Relative Head Position* compared with the projection of the participant head pointer on the plane of the wall display. Lastly, (7) subjective measures include overall *Preference*, as well as the *Mental* and *Physical* workload of participants.

For the *Cards Incorrect*, *Manhattan Distance Error*, *Time*, *Travelled Distance*, and *Head Rotation*, we first assess the normality of the data using the Shapiro-Wilk normality test. Then we assess the homogeneity of variances by Levene's test and sphericity. When the criteria are met, we use a mixed ANOVA to test the differences between the VISUAL MODIFIER independent groups whilst subjecting participants to repeated measures within the two LAYOUT conditions. A t-test is used to compare the means of LAYOUT pairs within each VISUAL MODIFIER condition.

When the data is not normally distributed, we use a Kruskal-Wallis test to compare the data against the VISUAL MODIFIER factor. We also use a Friedman test to compare the data against the LAYOUT factor. For the *subjective measures*, we use Kendall's W test for each VISUAL MODIFIER condition to see the significant effects between the LAYOUT variables.

Cards Incorrect. The data for the incorrect cards are normally distributed and meet the assumption of homogeneity of variances. The mixed ANOVA test shows no significant effect of VISUAL MODIFIER ($p = 0.48$, effect size $\eta_G^2 = 0.04$) among *Regular* ($mean = 0.45$, $SD = 0.16$), *Restricted FoV* ($mean = 0.49$, $SD = 0.15$), and *Landmark* ($mean = 0.44$, $SD = 0.17$). However, it shows a significant effect of LAYOUT factor ($p = 2.28 \times 10^{-10}$, effect size $\eta_G^2 = 0.32$), with a lower overall error for *Flat* ($mean = 0.37$, $SD = 0.13$) vs *Full-Circle* ($mean = 0.55$, $SD = 0.13$). A closer inspection in Figure 5.3-a shows the results of paired T-tests of the LAYOUT factor for each VISUAL MODIFIER group.

Participants on average have a *Cards Incorrect* rate of 0.36 ($SD = 0.12$) in the *Regular-Flat* condition, and a *Cards Incorrect* rate of 0.55 ($SD = 0.13$) in the *Regular-Full-Circle* condition. A paired T-test reports a significant difference between the two conditions ($p = 1.02 \times 10^{-3}$, effect size $|d| = 1.58$).

Participants on average have a *Cards Incorrect* rate of 0.43 ($SD = 0.13$) in the *Restricted FoV-Flat* condition, and a Cards Incorrect cards rate of 0.55 ($SD = 0.14$) in the *Restricted FoV-Full-Circle* condition. A paired T-test reports a significant difference between the two conditions ($p = 1.68 \times 10^{-4}$, effect size $|d| = 0.87$).

Participants on average have a *Cards Incorrect* rate of 0.33 ($SD = 0.14$) in the *Landmark-Flat* condition, and a *Cards Incorrect* rate of 0.54 ($SD = 0.13$) in the *Landmark-Full-Circle* condition. A paired T-test reports a significant difference between the two conditions ($p = 3.67 \times 10^{-5}$, effect size $|d| = 1.52$).

Manhattan Distance Error. The Manhattan Distance provides a secondary evaluation of the error measure. Whereas *Cards Incorrect* provides an absolute measure, Manhattan Distance rewards card selections by summing the distance from the selected cards to the correct ones.

The data for the *Manhattan Distance Error* is normally distributed and meet the assumption of homogeneity of variances. The mixed ANOVA test shows no significant effect of VISUAL MODIFIER factor ($p = 0.73$, effect size $\eta_G^2 = 0.02$) among *Regular* ($mean = 3.83$, $SD = 1.74$), *Restricted FoV* ($mean = 4.28$, $SD = 1.75$), and *Landmark* ($mean = 3.87$, $SD = 1.96$). However, the mixed ANOVA test shows significant effect of LAYOUT factor ($p = 1.33 \times 10^{-11}$, effect size $\eta_G^2 = 0.25$), with a lower overall error for *Flat* ($mean = 3.10$, $SD = 1.50$) vs *Full-Circle* ($mean = 4.88$, $SD = 1.65$). Figure 5.3-b shows the paired T-test of the LAYOUT factor for each VISUAL MODIFIER group.

The *Manhattan Distance Error* is on average 2.92 ($SD = 1.40$) in the *Regular-Flat* condition, and 4.75 ($SD = 1.59$) in the *Regular-Full-Circle* condition. A paired T-test

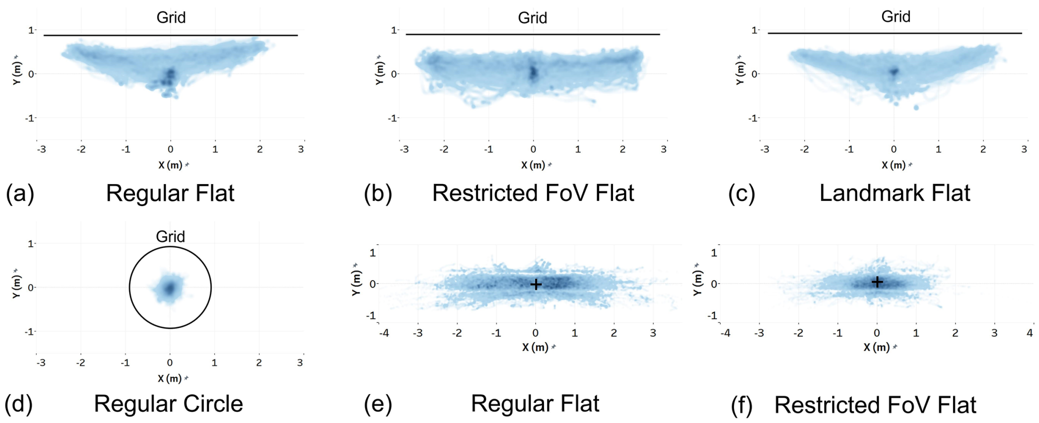

Fig. 5.4.: Density maps showing participants' positions during the learning phase in (a) *Regular* condition, (b) *Restricted FoV* condition, (c) *Landmark* condition for *Flat* layouts, and (d) *Regular* condition for *Full-Circle* layouts. And density maps show where the participant head pointer (ray cast from headset's forward direction) intersects the plane of the wall display, relative to the user's head position in (e) *Regular* condition and (f) *Restricted FoV* condition during the learning phase for *Flat* layouts.

reports a significant difference between the two conditions ($p = 8.29 \times 10^{-4}$, effect size $|d| = 1.22$).

The *Manhattan Distance Error* is on average 3.53 ($SD = 1.48$) in the *Restricted FoV-Flat* condition, and 5.03 ($SD = 1.73$) in the *Restricted FoV-Full-Circle* condition. A paired T-test reports a significant difference between the two conditions ($p = 1.90 \times 10^{-4}$, effect size $|d| = 0.93$).

The *Manhattan Distance Error* is on average 2.87 ($SD = 1.64$) in the *Landmark-Flat* condition, and 4.87 ($SD = 1.77$) in the *Landmark-Full-Circle* condition. A paired T-test reports a significant difference between the two conditions ($p = 1.06 \times 10^{-6}$, effect size $|d| = 1.17$).

Recall Time. The recall time data is not normally distributed. The Kruskal-Wallis test shows no significant effect of VISUAL MODIFIER factor ($p = 1$, effect size $\eta^2 = 0.03$) among *Regular* ($mean = 21.77$, $SD = 12.31$), *Restricted FoV* ($mean = 28.04$, $SD = 17.33$), and *Landmark* ($mean = 24.92$, $SD = 9.87$). The Friedman test shows no significant effect of LAYOUT factor ($p = 0.05$, effect size $W = 0.11$) between *Flat* ($mean = 24.55$, $SD = 12.83$) and *Full-Circle* ($mean = 25.27$, $SD = 14.47$).

Walking Distance. Overall, we use a non-parametric test to analyse the walking distance data because the data in each condition is not normally distributed. The Kruskal-Wallis test shows no significant effect of VISUAL MODIFIER factor ($p = 0.52$, effect size $\eta^2 = -0.01$) among *Regular* ($mean = 5.50$, $SD = 2.35$), *Restricted*

FoV ($mean = 6.43$, $SD = 3.19$), and *Landmark* ($mean = 5.87$, $SD = 2.80$). The Friedman test shows significant effect of LAYOUT factor ($p = 1.97 \times 10^{-9}$, effect size $W = 1$) between *Flat* ($mean = 8.50$, $SD = 1.16$) and *Full-Circle* ($mean = 3.36$, $SD = 0.89$). Figure 5.3-c shows the paired T-test of the LAYOUT factor for each VISUAL MODIFIER group.

Participants travel on average 7.74 ($SD = 0.47$) meters in the *Regular-Flat* condition, and 3.27 ($SD = 0.63$) meters in the *Regular-Full-Circle* condition. The data are normally distributed in this condition. A paired T-test reports a significant difference between the two conditions ($p = 3.05 \times 10^{-10}$, effect size $|d| = 8.06$).

Participants travel on average 9.26 ($SD = 1.47$) meters in the *Restricted FoV-Flat* condition, and 3.59 ($SD = 1.26$) meters in the *Restricted FoV-Full-Circle* condition. The data are not normally distributed in this condition. The Friedman test shows a significant difference between the two conditions ($p = 5.32 \times 10^{-4}$, effect size $W = 1$).

Participants travel on average 8.51 ($SD = 0.81$) meters in the *Landmark-Flat* condition, and 3.23 ($SD = 0.70$) meters in the *Landmark-Full-Circle* condition. The data are normally distributed in this condition. A paired T-test reports a significant difference between the two conditions ($p = 1.04 \times 10^{-11}$, effect size $|d| = 6.99$).

Figure 5.4-a, b, and c show density maps of all user positions (top view) collected during the learning phase for the *Flat* layout. The origin represents the start position. We can see that, in general, participants step back further than the starting position in all conditions, especially in the *Regular* condition. This is indicated by the second dark spot below the origin. Moreover, we can also see that the participants tend to move left and right in the *Restricted FoV* condition, while moving directly to the card patterns in the other two conditions. This might explain why they form different density patterns on the graphs. On the other hand, user positions (top view) collected during the learning phase for the *Full-Circle* layout don't differ much among the VISUAL MODIFIER conditions. Figure 5.4-d shows an example of the density plot of users' positions in the *Regular* condition (density maps for the other full circle conditions appear similar and are omitted).

Head Rotation. The data for the Head Rotation during the learning phase is normally distributed. The mixed ANOVA test shows no significant effect in the VISUAL MODIFIER factor ($p = 0.75$, effect size $\eta^2_G = 0.01$) among *Regular* ($mean = 1097$, $SD = 531$), *Restricted FoV* ($mean = 1044$, $SD = 539$), and *Landmark* ($mean = 1082$, $SD = 510$), but a significant effect in the LAYOUT factor ($p = 3.25 \times 10^{-20}$, effect size $\eta^2_G = 0.83$) between *Flat* ($mean = 605$, $SD = 111$) and *Full-Circle* ($mean = 1544$,

$SD = 287$). Figure 5.3-d shows the paired T-test of the LAYOUT factor for each VISUAL MODIFIER group.

Participants perform on average 644 ($SD = 103$) degrees of head rotation in the *Regular-Flat* condition, and 1549 ($SD = 362$) degree in the *Regular-Full-Circle* condition during the learning phase. A paired T-test shows a significant difference between the two conditions ($p = 4.82 \times 10^{-7}$, effect size $|d| = 3.41$).

Participants perform on average 569 ($SD = 134$) degrees of head rotation in the *Restricted FoV-Flat* condition, and 1519 ($SD = 310$) degree in the *Restricted FoV-Full-Circle* condition during the learning phase. A paired T-test shows a significant difference between the two conditions ($p = 4.82 \times 10^{-7}$, effect size $|d| = 3.98$).

Participants perform on average 602 ($SD = 87$) degrees of head rotation in the *Landmark-Flat* condition, and 1562 ($SD = 182$) degree in the *Landmark-Full-Circle* condition during the learning phase. A paired T-test shows a significant difference between the two conditions ($p = 7.35 \times 10^{-11}$, effect size $|d| = 6.72$).

Relative View Position. Figure 5.4-e,f show density plots of the Relative View Position, calculated by projecting the head pointer (ray cast from headset's forward direction) onto the *Flat* grid, with the head position as the origin point. This helps us to investigate how frequently participants look at far away or nearby objects. We use a density map to observe the density of the relative positions for *Flat* layouts. The *Landmark* condition (density map omitted) has a similar plot as the *Regular* condition, while there are differences between the *Restricted FoV* condition and the *Regular* condition.

Results show that the range of head rotation was smaller with the *Restricted FoV* than in the *Regular* condition, which means that participants look more often at the objects near them than the object far away in the *Restricted FoV* condition compared with the other VISUAL MODIFIER conditions.

Subjective Rating. Overall, for the learning phases, 28 out of all 36 participants prefer the *Flat* layout, while for the recall phases, 31 out of all 36 participants prefer the *Flat* layout (see Figure 5.5-d,e, and f). Figure 5.5-a, b, and c show Kendall's W test for each VISUAL MODIFIER condition.

For the NASA-TLX scores in the *Regular* condition, Kendall's W test shows significant effects for mental ($p = 7.0 \times 10^{-3}$, effect size $r = 0.61$), performance ($p = 7.0 \times 10^{-3}$, effect size $r = 0.61$), effort ($p = 0.03$, effect size $r = 0.38$), frustration ($p = 8.0 \times 10^{-3}$, effect size $r = 0.58$), and overall mean ($p = 4.0 \times 10^{-3}$, effect size $r = 0.69$). The

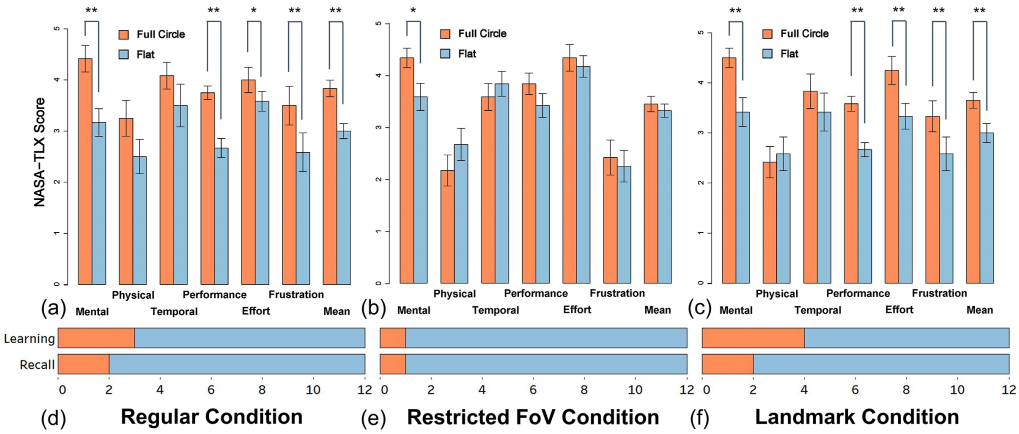

Fig. 5.5.: Participant responses on the NASA-TLX for each layout in (a) *Regular* condition, (b) *Restricted FoV* condition, and (c) *Landmark* condition. Participant preference for each layout in (d) *Regular* condition, (e) *Restricted FoV* condition, and (f) *Landmark* condition. In the NASA-TLX, performance was rated in reverse order (lower is better). Error bars denote standard error.

results show that the participants perform the best in the Flat layout with the least mental effort and frustration.

For the NASA-TLX scores in the *Restricted FoV* condition, Kendall's W test shows significant effects for mental effort only ($p = 0.02$, effect size $r = 0.45$). The results show that the participants perceived the combination of *Flat* layout and *Restricted FoV* as the least mentally demanding compared to other conditions.

For the NASA-TLX scores in the *Landmark* condition, Kendall's W test shows significant effects for mental ($p = 3.0 \times 10^{-3}$, effect size $r = 0.75$), performance ($p = 3.0 \times 10^{-3}$, effect size $r = 0.75$), effort ($p = 5.0 \times 10^{-3}$, effect size $r = 0.67$), frustration ($p = 8.0 \times 10^{-3}$, effect size $r = 0.58$), and overall mean ($p = 4.0 \times 10^{-3}$, effect size $r = 0.69$). The results show that the participants perform the best in the Flat layout with the least mental effort and frustration.

5.2.7 Discussion

Our accuracy results suggest that the use of *Flat* layout leads to better user performance than *Full-Circle* layout. In the *Flat* layout condition, participants made less errors, as measured by *Card Incorrect* and *Manhattan Distance Error*, than the *Full-Circle* layout condition. We found no significant difference in recall time between the two layout conditions. These results support our initial conjecture that spatial memory is an important factor in the findings of our study [Liu+20] showing that *Flat* better-supported complex visualisation tasks than *Full-Circle*.

Looking at the density maps in Figure 5.4, we notice that participants seemed to take a step back during the task to get an overview of the workspace in the *Flat* layout for both the *Regular* and *Landmark* conditions (this was not possible in the *Restricted FoV*). This could suggest that the positive results of the *Flat* layout may be due to the ability of participants to get an overview of the workspace. To understand the contribution of this overview effect in our observed results, we included the *Restricted FoV* condition in our study. In this condition, our results indicate that the *Flat* layout still leads to better performance compared to the *Full-Circle* one meaning that the overview provided by the *Flat* is not the main reason for the difference between the two layouts.

Comments from participants mentioned another potential explanation: with its corners, the *Flat* layout provides natural landmarks that can support participants' spatial memory (the corners were also visible in the *Restricted FoV* condition). This is confirmed by Uddin et al. [UGC17] and Gao et al. [Gao+18], where they found that artificial landmarks play an important role in assisting spatial memorisation and retrieval of items in a grid of interface components. Therefore, in the *Landmark* condition, artificial landmarks were added in both layouts to limit any such inherent advantage of the *Flat* one. Our results in this condition still indicate significantly better performance with the *Flat* layout; therefore eliminating landmarks as the main factor for the difference between the two layouts.

In summary, our results suggest that the main impact of the type of layout on spatial memory is not due to either overview or landmarks. Rather, the analysis of the tracking data in our study shows that the *Full-Circle* layout condition requires more head rotation than the *Flat* layout condition. Participants confirmed this by mentioning that the *Full-Circle* was more disorienting (P2, P8, P20, and P25), and made locating elements more difficult (P8, P24, P33, and P36). This effect is also supported by the fact that the rotation participants performed during and after the learning phase facilitated errors as a result of an inaccurate update of spatial mental representation [Wal+02]. Given all of the apparent advantages of the *Flat* layout, it is no surprise that it was preferred by most participants. Therefore, our study points to the conclusion that disorientation due to the rotational movement required to explore the workspace using the *Full-Circle* layout is the main factor that impacts spatial memory.

5.3 User Study 4: Flat Versus Semicircle

Study 3 shows that *Flat* layouts outperform *Full-Circle* layouts and are preferred by participants in all 3 VISUAL MODIFIER conditions. However, our research [Liu+20] reports that participants also prefer the *Semicircle* layouts. It is reasonable to hypothesize that such a *Semicircle* arrangement [Shu+06; HXW20; Cav+19] is a good compromise between *Full-Circle* and *Flat*. We, therefore, run another study to investigate the effects on Visio-spatial memory between the *Flat* layout and *Semicircle* layout.

5.3.1 Task

The *Flat* condition has a width of 5.9 m and a height of 1.4 m, which is the same as study 3. The *Semicircle* condition has an approximate radius of 1.9m, which results in an arc length the same length as the width of the flat grid. The starting position in the *Flat* layout has a 1.9-meter distance to the grid while the starting position of the *Semicircle* layout is the centre point of the semicircle. The task and the procedure are the same as in Study 3.

5.3.2 Design

We conduct a within-subjects design study with the LAYOUT (*Flat* and *Semicircle*) as the main independent variable. All participants complete the full set of trials successfully. In total, we collect data from 216 trials (12 participants $\times$ 9 repetitions $\times$ 2 LAYOUTS). Dependent variables are the same as the study 31 including completion time, card accuracy, Manhattan distance of the errors, walking distance, head positions and rotation angles, and subjective ranking.

5.3.3 Participants and Apparatus

In total, we recruit 12 participants (6 males and 6 females; mean age = 24.42, $SD = 2.50$) from our university. All participants were students and did not participate in our study 3. 6 participants have at least some experience with VR and 1 of them rate himself as a VR expert. Participants sign up voluntarily and are rewarded a gift card (A$20) and small gifts (candies and chocolates) as a sign of appreciation. We use the same apparatus as in study 3.

5.3.4 Measures

Measures for study 4 are similar to study 3. For each trial, we record the number of incorrectly chosen cards, along with their positions in the grid. We also record the *Recall Time* taken to select the 5 cards in the answer phase. In our analysis, we use two methods to measure participants' recall accuracy: *Cards Correct* and *Manhattan Distance*.

Participants' head poses are also tracked during the duration of each trial, which we use to calculate the *Walking Distance* travelled by participants and *Head Rotation* during trials. In the post-study questionnaire, the subjective task load is measured using questions derived from the NASA-TLX [Har06]. Participants also indicate their preferred layout and were asked about their strategy to solve the task.

5.3.5 Results of Study 4

For quantitative measures, we use the same statistical test method as the first study. Measures are broken down into three categories for reporting, as follows.

Performance: (1) *Cards Incorrect*, or proportion of cards chosen incorrectly in each trial; (2) (optimal) *Manhattan Distance Error* between the participants' answers and the solutions; and (3) *Recall Time*, total time of the recall phase.

Learning Phase: (4) *Walking Distance* travelled by participants; (5) *Head Rotation* performed by participants calculated by cumulative angular distances; and (6) *Relative Head Position* compared with the projection of the participant head pointer on the plane of the wall display.

Subjective: We collected *Preference*, as well as the *Mental* and *Physical* workload of participants.

Cards Incorrect. The data for the incorrect cards are normally distributed. Participants on average have an incorrect cards error rate of 0.34 ($SD = 0.12$) with the *Flat* condition and an incorrect cards error rate of 0.36 ($SD = 0.12$) with the *Semicircle* condition (see Figure 5.6-a). A paired T-test doesn't find a significant difference between the two conditions ($p = 0.95$, effect size $|d| = 0.20$).

Manhattan Distance Error. The data for the Manhattan Distance Error between the participant answer and the solution is normally distributed. This distance is

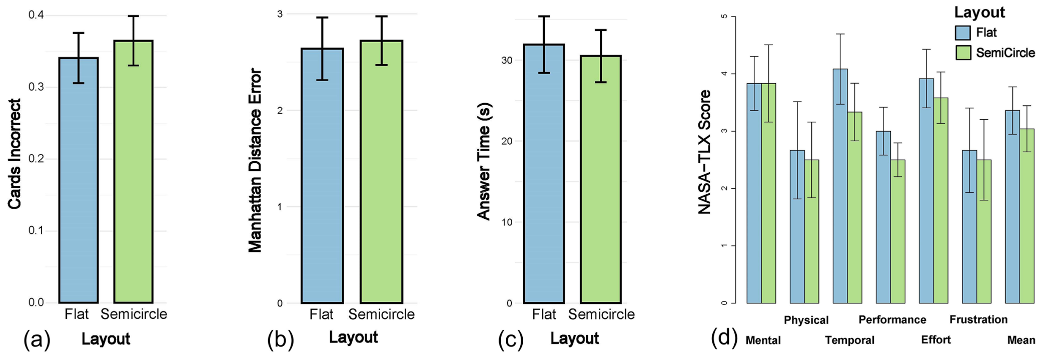

Fig. 5.6.: (a) Cards Incorrect (lower is better), (b) Manhattan Distance (lower is better), (c) Recall time during the recall phase, and (d) Each participant's responses on the NASA-TLX in *Flat* layout and *Semicircle* layout. In the NASA-TLX questionnaire, performance was asked in reverse order (lower is better).

on average 2.64 ($SD = 1.13$) with the *Flat* layout, and 2.72 ($SD = 0.88$) with the *Semicircle* layout (see Figure 5.6-b). A paired T-test doesn't find a significant difference between the two conditions ($p = 0.78$, effect size $|d| = 0.08$).

Recall Time. The data for the time taken to select the cards in the recall phase is normally distributed. On average, participants took 31.92 ($SD = 12.11$) seconds to select the cards the *Flat* condition, and 30.50 ($SD = 11.18$) seconds in the *Semicircle* condition (See Figure 5.6-c). A paired T-test doesn't find a significant difference between the two conditions ($p = 0.41$, effect size $|d| = 0.12$).

Walking Distance. The data for the Walking Distance during the learning phase are normally distributed. During the learning phase, participants travel on average 9.38 ($SD = 0.70$) meters in the *Flat* condition and 6.74 ($SD = 0.61$) meters in the *Semicircle* condition (See Figure 5.7-a). A paired T-test shows a significant difference between the two conditions ($p = 4.62 \times 10^{-9}$, effect size $|d| = 4.02$).

Figures 5.7-c and d show density maps of all user positions (top view) collected during the trials. The origin represents the start position. We can see that, in general, participants spend similar time on the original position and on the path to touch the cards between the two layouts.

Head Rotation. The data for the Head Rotation during the learning phase is normally distributed. During the learning phase, participants perform on average 592 ($SD = 81$) degrees of head rotation in the *Flat* condition, and 782 ($SD = 133$) degrees in the *Semicircle* condition (See Figure 5.7-b). A paired T-test shows a significant difference between the two conditions ($p = 4.47 \times 10^{-6}$, effect size $|d| = 1.73$).

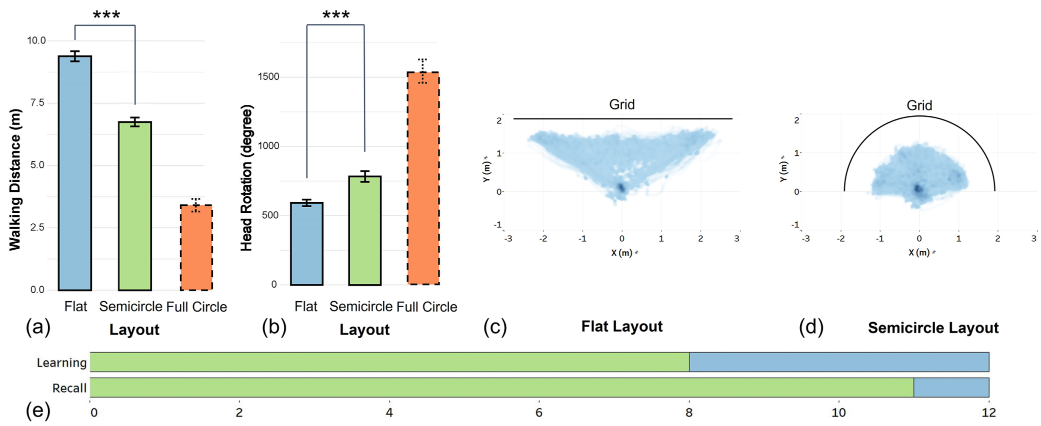

Fig. 5.7.: (a) Walking distance and (b) Head rotation in *Flat* layout and *Semicircle* layout during the learning phase (dashed bars represent mean walking distance and head rotation in study 3 for *Full-Circle* layout). Density plots for participants' positions during the learning phase in (c) *Flat* layout, (d) *Semicircle* layout. And (e) Subjective preference in two layouts. Error bars denote standard error.

Subjective Rating. Overall, for the learning phases, 8 out of 12 participants prefer the *Semicircle* layout, while for the recall phases, 11 out of 12 participants prefer the *Semicircle* layout (See Figure 5.7-e). Figure 5.6-d shows the NASA-TLX score assessed by all participants for each LAYOUT condition. The Kendall's W test showed no significant effects among these criteria. From the figure, we can see that *Semicircle* layout is rated higher than *Flat* layout in all criteria, which supports our finding on the preference for the *Semicircle* layout.

5.3.6 Discussion

Contrary to what has been shown by Shupp et al. [Shu+06] on their spatial memory study in wall-displays environments, we did not find any difference between the *Flat* and *Semicircle* layout. A notable number of participants prefer the *Semicircle* layout and mention that *Semicircle* layout is easier to see and memorise than *Flat* layout (P3, P5, P8, P10, and P11). They feel it is easier to rotate their heads than walk around to browse (P8). However, some participants report that *Flat* layout has the benefit of providing a complete overview (P4, P6, and P7) but requires more time to touch and memorise than *Semicircle* layout (P1, P2, and P6). The mixed feedback indicates a balance of pros and cons for these two layout types, which may be the reason for their similar performance.

Overall, the *Semicircle* layout provides less walking distance but more head rotation than the *Flat* layout. *Semicircle* layout is a compromise between the *Flat* layout and *Full-Circle* layout and our follow-up study does not show a significant negative impact on spatial memory due to the limited rotation required by *Semicircle* layout.

5.4 Limitations and Future Work

One limitation of our study design is that our *Full-Circle* wraparound condition only tests views with a close distance. While the diameter of around 2 metres is chosen to keep the same grid size as in the *Flat* layout, enabling arms to reach the distance between the participants and the grid, and minimise the need for walking (and therefore physical effort), we don't know if the effect on spatial memory remains the same in another wraparound layout such as CAVE2 environments. Also, to limit the experiment duration and participant fatigue we only test one study setup with 36 (3x12) cards and one task difficulty level: memorising a pattern of 5 cards. As discussed in Section 5.2.1, the study setup follows our past studies [Liu+20], where 36 small multiples were used in a 3x12 grid, while the task difficulty level was chosen after extensive piloting to find a level difficult enough but doable. Another limitation of our study design is that we choose to focus on one type of selection technique: direct tapping. As shown on both small [Tan+02] and large 2D displays [Ebe+09], the type of input to select an element (either up-close or from a distance) has an influence on spatial memory. Future work should explore the impact of remote selection techniques such as hand pointer or gaze on spatial memory compared to the direct tapping method we use.

There are, of course, several more factors that should be taken into account in future studies. Firstly, we can summarise from the two studies that among the three layout types, *Flat* layout requires the most translational movement while *Full-Circle* requires the most head rotation. While our result suggests that full body rotation has a negative effect on spatial memory, further studies could help to isolate the limits of rotation more precisely or whether walking could have a beneficial kinaesthetic memory effect. Secondly, the current experiment relies purely on the physical navigation of the participants to interact with the virtual world. However, the effects on spatial memory of physical navigation versus virtual navigation (such as zooming and panning) for this particular task are unknown. Finally, we feel it is important to explore the connection between spatial memory and analytic tasks in information visualisation. While immersive environments provide users with more 'space to think' [Lis20] than traditional displays, designers must be able to understand the implications of such environments on spatial understanding, when creating tools to facilitate user understanding.

Our study was conducted in Virtual Reality such that the participants could not see any background of their real-world environment. It would be interesting to see how well our results carry over to Augmented Reality headsets, where additional landmarks from the environment may be visible behind the virtual imagery [Luo+21; Luo+22]. We would also expect that the more limited field of view provided by existing AR headsets compared to the VR headsets, would place greater demands on spatial memory, though the technology continues to improve.

5.5 Conclusion

In this chapter, we contribute two user studies, each of which evaluates the effect of display layout on spatial memory in immersive environments. We use an abstract task in both studies using layouts of 2D cards based on visuo-spatial memory studies from psychology to determine which layout leads to the best retention of card patterns. In the first study, we examine the effects of the *Flat* layout and the *Full-Circle* layout on spatial memory with a mixed-factors study. This study focuses on the two extremes of the layout curvature spectrum as the within-subjects factor. We also investigate the subordinate factors in this study such as the overview advantage of the *Flat* layout and the natural edges and corners of the *Flat* layout as a between-subjects factor. The result shows that the *Flat* layout outperformed the *Full-Circle* layout with better accuracy. Moreover, the subjective result shows that the participants perform the best in the *Flat* layout with the least mental effort and frustration. This general result held regardless of the subordinate factors (visual modifiers) that we introduced, implying that the main factor that influences the performance is the type of physical navigation. In other words, walking in front of a *Flat* display is less detrimental to spatial memory than rotation.

In study 4, we test whether the *Semicircle* layout provides a good compromise. It reveals no significant difference between *Flat* and *Semicircle* while participants prefer the *Semicircle* layout. Our work [Liu+20] has suggested that *Semicircle* layout provides advantages over *Flat* in terms of reduced total walking distance and perspective distortion without requiring the full rotation navigation of *Full-Circle*. Our finding suggests that these advantages of *Semicircle* can be achieved with no significant negative impact on spatial memory.

In summary, the clear takeaway from our studies is that full wrap-around displays and the rotation required to navigate them are disorienting to users and should be used with caution for immersive information presentation. This finding is contrary to use patterns we see emerging in the literature, so we hope this research will influence future system implementers to be aware of this limitation, and further research to find nuance.

6 A Design Space for Visualisation View Management

> *We are especially interested in decisions that determine the spatial layout of the projections of objects on the view plane. We refer to these decisions as view management.*
>
> — **Steven K. Feiner**
> (In a 2001 paper introducing the concept of view management in augmented reality)

In emerging immersive systems for data visualisation, it is becoming common practice to display multiple visualisation views on wall or tabletop arrangements [Sat+20; Lee+21b; Zha+22]. This design choice may be a straightforward adaptation from traditional physical pin-up wall and table arrangements as well as conventional 2D windowing systems, allowing the user experience to be transferred seamlessly from existing 2D surfaces. Such flat display layouts may also benefit users' spatial memory [Liu+22] so that they can easily switch their focus between multiple views for comparison tasks. But wall arrangements require walking to shift focus from view to view, or stepping back to obtain an overview. They leave space immediately around the user wasted. In immersive environments, visualisation views can be displayed in any layout in 3D space, such as a cylindrical layout [Luo+22] or a spherical layout [Sat+20]. Moreover, by enabling users to move visualisation views, users may freely create their preferred layout in the 3D space around them.

Apart from allowing us to use space differently, immersive technologies offer the opportunity to work with visualisation views with natural embodied interactions. Users can directly manipulate views using tracked devices and body parts, such as hands, feet, or the whole body. Hand interactions are commonly used to interact with views on eye-level displays. However, in situations where both hands are occupied or where interaction targets are positioned out of arm reach, other body parts—such as feet—may provide alternatives to conventional hand interaction for accessible input [Vel+15]. Also, feet can provide additional input channels for assisting other modalities in complex tasks [Col+16]. However, foot interaction has not previously been explored in the field of visualisation view management.

The whole body can also be used as an additional modality to support implicit tasks using proxemic interaction [BMG10; Gre+11; MG12; Jak+13]. The position and orientation of the user's body can be considered as input for view management. These novel interaction design possibilities represent a significant shift from everything we have learnt about interaction with flat screens.

This chapter introduces *DataDancing*[1], a design space for visualisation view management, presenting a framework that identifies important aspects in whole-body interaction (including feet) for designing view management systems. This design space is derived from a systematic literature review of immersive visualisation prototypes and systems with multiple views, focusing on both the presentation of and interaction with visualisation views for 3D surfaces and spaces.

From this design space, we extrapolate a variety of view management prototypes, each demonstrating a different combination of interaction techniques and space use. These range from common wall and table arrangements to novel foot and floor interaction.

6.1 DataDancing: A Design Space for Visualisation View Management

DataDancing presents a design space for visualisation view management. It identifies important aspects for displaying visualisation views on 3D surfaces or in 3D spaces and for interacting with visualisation views via whole-body interaction (including feet). This chapter discusses and exploits such a design space that distils existing literature into a set of general but widely encompassing design dimensions as a framework for designers, researchers, and data analysts to express their creations and formalise design ideas (proposed in Section 6.1). The dimensional organisation also helps understand existing designs by grouping and categorising them (discussed in Section 6.2). By contrasting and comparing these, designers gain insights into general patterns and identify gaps in the framework where designs do not yet exist. Ultimately, designers can then use this information to assist with the creation of new designs, either by applying the strengths of existing patterns to the correct

[1] A witty reference to the popular movie *Dirty Dancing*: "Nobody puts Data in a corner!"

contexts or, through experimentation, by altering one or more dimensions and then imagining the resulting implications.

6.1.1 Approach

We develop our design space using methodology formalised in Zwicky's General Morphological Analysis [Rit98] and which has been applied to HMD interface design by Robinett [Rob92], as well as immersive information space design by Ens [EHI14]. This method generates a set of orthogonal geometric design space dimensions as a set of defined taxonomical concepts. The resulting theoretical matrix offers a framework for comparing and contrasting concepts. The methodical filling-in of this structure makes it easier to classify already-existing works, distinguish between ideas, and locate potential directions. In summary, we follow three methodical steps, as per [EHI14]:

- Review existing designs to distil a set of characteristic dimensions;
- Categorisation of existing designs among these dimensions to identify both gaps and common usages;
- Generation of new designs through an analytic process of combining and altering design choices.

6.1.2 Paper Selection

This design space is the product of an extensive review of literature related to visualisation view management and spatial interaction, beginning with a search for papers exploring visualisation view management in 3D spaces, extending or existing fully beyond the limits of a conventional display screen. We filter the literature selection with the following criteria: (1) Our design space focuses on designs involving immersive information spaces. Thus, we exclude designs for real-world object placement. (2) We target designs involving planar information spaces and thus exclude designs that do not explicitly discuss 2D workspaces, for example, those that involve managing 3D workspaces through a 2D display. (3) We exclude papers that do not introduce distinct differences from previous designs, for example, using an existing design in a new context or focusing on the technology for implementing a known design.

The literature search began with the past five years' proceedings of CHI, UIST, ISS, VR and VRST. We also conducted a tree search of references and citations of seminal papers on displaying visualisation views in 3D space and spatial interaction frameworks (e.g., [Liu+20; EHI14; HS12; Gre+11; Wag+13; Lee+22]). The final list, containing 55 papers, is likely not exhaustive, but from these, we are able to draw a representative selection of designs. (A complete list of all designs in our survey, along with their dimensional classifications, can be found in the supplementary materials.)

From the papers in our literature review, we distilled a set of design dimensions using a bottom-up, open-coding approach. We begin with candidate dimensions that fit the concepts found in the literature, followed by an iterative process to filter, combine, and refine these into a set small enough to manage in a concise framework yet containing enough dimensions to make it useful. We eliminate dimensions (1) that could be split into a combination of lower-level dimensions (e.g., spatial reference frame could be split into the dimension, curvature, and orientation), (2) that were later incorporated into other dimensions (e.g., view orientation could be incorporated into view movability), or (3) that were not directly related to the problems discussed in our evaluation and implementations (e.g., interaction dynamics, input type, and interaction continuity). Such excluded dimensions could be considered in future research.

This process results in eleven design dimensions, listed in Figure 6.1. We assign the dimensions into two main categories: *View Presentation* and *User Interaction*, which are further organised into four groups, two for each category, based on the strongest dependencies between them. This categorising and grouping is used to organise several resulting design recommendations.

6.1.3 View Presentation — Space Perception

The space perception category refers to the understanding of the spatial relationship between the user and visualisation views. This category covers three design dimensions: *Perspective*, *Proximity*, and *View Movability*.

Perspective – This refers to the cognitive judgement of view locations, whether from an egocentric perspective [Sat+22; Sat+20; Luo+22] (visualisation view is relative to users) or an exocentric perspective (visualisation view is relative to an external *Frame of Reference*). Ens et al. [EHI14] also use this term to define the relative viewpoint between the observer and the environment.

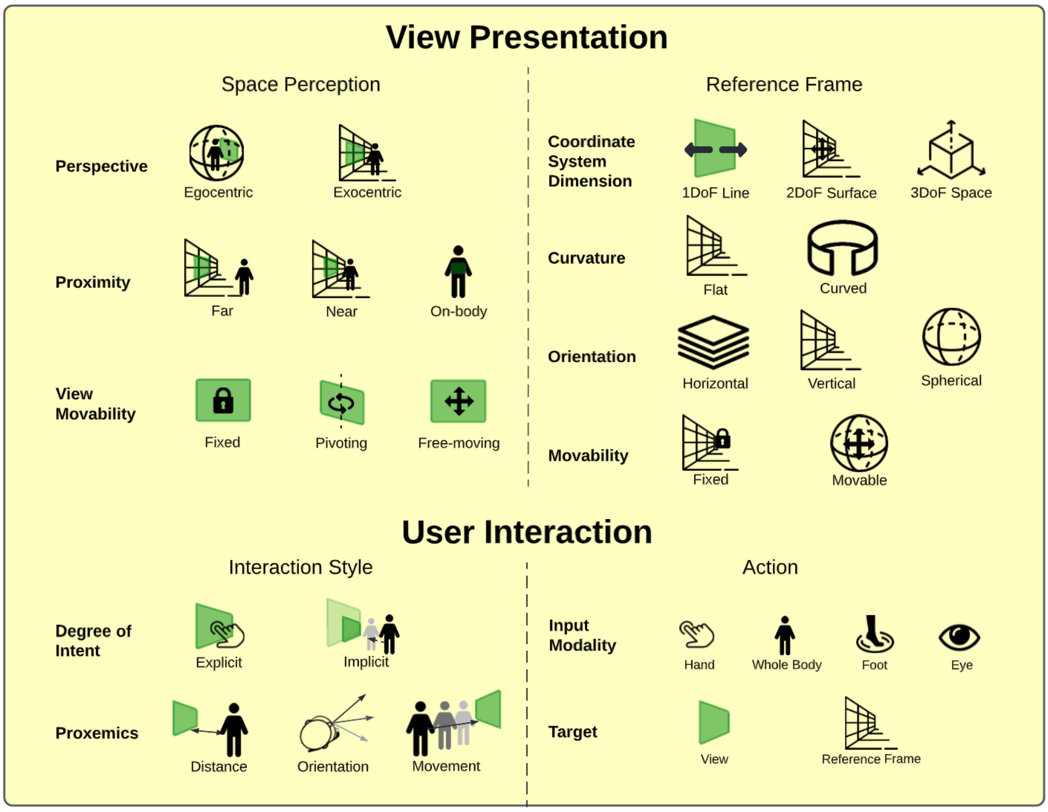

Fig. 6.1.: A design space illustration for visualisation view management for 3D surfaces and spaces. In this design space, we propose seven design dimensions in two categories for visualisation view presentation (top) and four design dimensions in two categories for user interactions with views (bottom).

Proximity – This describes the distance relationship between people and visualisation user interfaces. We adapt and borrow a set of proxemic regions defined by Hall [HH69] and neuropsychologists [HS04; ES06], and used by Ens et al. [EHI14]: far [HXW20] (extrapersonal space far from users and outside their arm's reach), near (peripersonal space surrounding users within arm's reach), onbody [HBW11; Wag+13; FLC18] (matching pericutaneous space directly on the body surface).

View Movability – This indicates whether each visualisation view is *fixed*, *pivoting*, or *free-movable* during the view management tasks. Fixed views help users to build a static mental model, utilising their spatial memory for navigation [RFD21; Liu+20; HXW20], while free-movable views may increase the effectiveness of comparison tasks, since users could bring views close to each other [Luo+22; Lee+21b; Cor+17; New+21]. The pivoting views usually update their orientations but remain in the same position. This presentation can be found in the body- or head-synchronised systems [EFI14; Bil+98], where views always face the user to reduce the distortion caused by a far distance. The movability of views overall facilitates an interactive and collaborative environment.

6.1.4 View Presentation — Frame of Reference

In this thesis, we use the term *Frame of Reference* to denote a coordinate system that serves as a basis to locate and orient visualisation views, such as the wall for the wall displays or the table for the tabletop displays. This term has been used in related work, indicating that visualisation views in the same 3D space could have different *Frame of Reference*. Our thesis considers multiple views on the same reference frame to be one coordinate system rather than multiple coordinate systems, each with one view. This category contains four reference frame characteristics: *Coordinate System Dimension*, *Curvature*, *Orientation*, and *Movability*.

Coordinate System Dimension – This describes the dimension of the coordinate system. We define three dimensions based on the degrees of freedom (DoF) of the *Frame of Reference*: 1 DoF Line (Linear *Frame of Reference*, where views can only be moved along one axis in the coordinate system [Bil+98]), 2 DoF Surface (Surface *Frame of Reference*, where views can be moved along two axes), and 3 DoF Space (Space *Frame of Reference*, where views can be moved freely along all three dimensions in the space).

Reference Frame Curvature – This describes the curvature of the *Frame of Reference* geometry: flat or curved. A curved geometry would include any curved layout, such as a semi-circle (180 degrees) or a full circle (360 degrees) [Liu+20; Sat+20; New+21] arrangement. While curving a 1D layout is relatively straightforward, there are various possible ways to curve layouts in higher dimensions (e.g., curving a 2D layout into a cylinder or a sphere).

Reference Frame Orientation – This dimension describes the orientation of the *Frame of Reference*. The reference frame can be horizontal, such as displaying visualisation views on roofs, floors, and tabletops [Zha+22; Kra+20]. It can also be vertical, such as presenting visualisation views on the furniture and traditional wall displays [Kis+15; RFD21; Liu+20]. The uncommon spherical orientation refers to the emerging findings from recent user studies [Sat+20], where participants prefer positioning visualisation views in a spherical cap wrapped around them.

Reference Frame Movability – The view *Frame of Reference* may be *movable* or *fixed* with respect to another given frame of reference. By moving the whole *Frame of Reference* of views, users may translate the views together while preserving their relative layout. Most head-up displays allow visualisation views to follow the users' field of view by moving the frame of reference [Sat+22; Cor+20]. On the other hand, fixed *Frames of Reference* are the common default, i.e., views fixed relative to a world-fixed reference point.

6.1.5 User Interaction — Interaction Style

Degree of Intent – This denotes the intent of the interaction. We borrow the dimension from related work [Sch99; JLK08; Lee+12; Bad+16], where the explicit interaction is defined as an action that is initiated by user [Lee+12] and aimed primarily at interacting with a computer system [Sch99; Bad+16]. On the contrary, implicit interaction is described as user actions that are not primarily aimed at interacting with a computer system [Sch99; JLK08]. Existing view management systems predominantly employ explicit interaction, such as conventional mouse drags and clicks, touchscreen taps and swipes, and novel embodied manipulations in immersive environments [Cor+20; Sat+20; New+21]. Implicit interaction, on the other hand, is a more novel approach. With the emergence of the whole body tracking techniques, proxemics can be used to mediate user interaction, where systems proactively react when users are close to the system [BMG10; Gre+11].

Proxemics – In general, proxemics refer to the study of space and how we use it. In the HCI field, Greenberg et al. [Gre+11] defined five categories of proxemics for ubiquitous interaction: distance, orientation, movement, identity, and location. We adapt these five categories, keeping the three that show high relevance for the view management interactions. First is distance-based proxemic interaction. For instance, in the evaluation study by Badam et al. [Bad+16], view scaling is controlled by the distance of the user from the display. Jakobsen et al. [Jak+13] also illustrate a distance-based semantic zoom technique. Ghaemi et al. [Gha+22] propose a novel transformation that changes the geometry of maps based on their proximity to users. The second is orientation, which is usually based on the rotation of the user's head or the whole body. Badam et al. [Bad+16] mapped the orientation of the user's head with the panning tasks. Jakobsen et al. [Jak+13] exploited the orientation of the whole body relative to the display to select between different views. Lastly, the movement of the user can also be used to change the encoding of visual representations. Badam et al. [Bad+16] proposed to use the movement of multiple users to merge or split views, while Jakobsen et al. [Jak+13] showed an example of changing a dynamic query slider by moving.

6.1.6 User Interaction — Action

Input Modality – The input modality dimension covers a wide range of interaction modalities available. These include the head, hand, whole body, foot, and eye. We focus on different human parts in this design space. Head input usually uses the tracking information of head-mounted displays, such as position and rotation. Hand input refers to the tracked hand-held devices such as controllers or gloves [SZ94]. Whole-body interaction is related to the previous proxemics design dimension, where interactions are performed based on the relative distance, orientation, or movement of a user's body to the display.

Foot interaction is a novel interaction modality and has been explored in the general HCI field, such as in the exploration of foot gestures [Vel+15; FL18], command selection using foot gestures or direct selection [SV16; Cau+19], and locomotion interfaces [Shi+19; Wil+20; Hay+19]. However, Pakkanen and Raisamo [PR04] found that feet are applicable for tasks not requiring high accuracy and fast execution time but are still, on average, less accurate and slower than hands for non-accurate spatial tasks.

Eye or gaze interaction exploits gaze input or eye tracking. the eye as an input modality provides fast but inaccurate responses [WM86]. Also, gaze input often relies on an awkward dwell-time approach [SR95]. Thus, eye input is often used within multi-modal input, for instance, eye and foot [Hat+17; Kla+15; Jot+14].

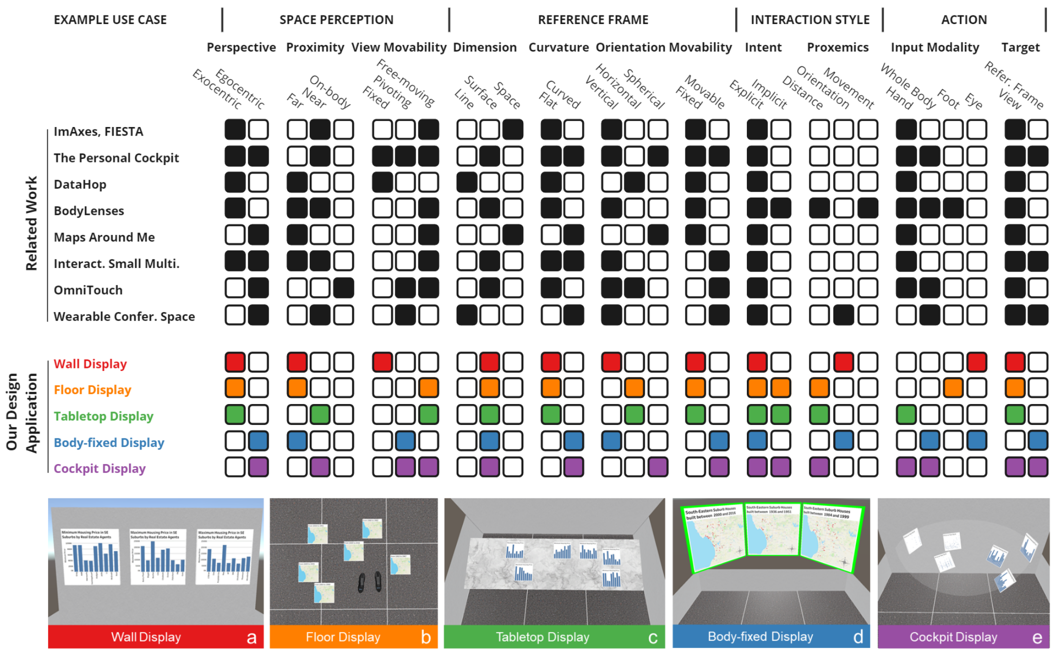

Fig. 6.2.: Use cases from literature (top row) or proposed by us (middle row). In these tables, a filled cell indicates the design dimension option used. The bottom five figures illustrate implemented prototype surfaces as design applications adapted from recent research: (a) Wall Display, (b) Floor Display, (c) Tabletop Display, (d) Body-fixed Display, and (e) Cockpit Display. (Best viewed in colour)

Target – This dimension describes the target of the action, whether users interact with views or the *Frame of Reference* of views. For example, a group of views can be manipulated as a single object when users interact with the reference frame of those views, such as moving the wall will cause all the views on the wall to move in unison.

6.2 Design Space Application

We develop our DataDancing design space to aid future designers as well as to direct our own research. In this section, we go over how our design space can be utilised to classify, contrast, and facilitate the development of both previous and new designs. From existing applications (see Figure 6.2-Related Work), we distilled five categories of designs of display surfaces for visualisation view management (see Figure 6.2-Our Design Application). These range from the common wall and table arrangements to the novel floor and cockpit layouts. To demonstrate the descriptive potential of our design space, we map the eleven design dimensions encompassing view presentation and interaction to each of these categories. This provides us with a methodical approach to compare and contrast these different designs. We also discuss the possible user interactions with these five categories of display surfaces in this section. (In the discussion below, references to design space dimensions are denoted in `Courier font`.)

Wall Display – This first category has the largest number of applications. These are primarily derived from conventional wall-sized large screens or displays, which are typically fixed, 2-dimensional surfaces that are flat and vertically positioned. Although several data visualisation systems exploit curved wall-sized layouts [Cru+92; Feb+13; Liu+20], flat layout wall displays (see Figure 6.2-a) were used in most of the design concepts we found. Because the Wall Display normally serves a large display area at the user's eye level, it is often used as the main display when multiple surfaces are involved. However, positioning visualisation views at eye level also limit the use of space around the user. Visualisation views on the Wall Display are usually fixed. They are usually perceived as an exocentric `Perspective` and far from the user to provide a full overview. Recent example applications for view management systems include: PersonalAR [RFD21], BodyLenses [Kis+15], DynamicNetwork [LAN19], Immersive Small Multiples [Liu+20], Fiesta [Lee+19], VisualLinks [Pro+19b], Immersive Space to Think [Lis+20], and Dynamic Network Plaid [LAN19].

Floor Display – Floor-based interactions have been widely explored in HCI research, which roughly consists of four groups: (1) projection based system such as Kickables [Sch+14], drone.io [Cau+19], and HMD Light [Wan+20]; (2) sensor only, foot-centric systems such as smart floor [OA00], Z-tiles [Ric+04], and SmartCarpet [Gla+07]; (3) underfoot displays or projections such as Multitoe [Aug+10]; and (4) floor-based signage using a glass surface with a capacitance system such as TapTiles [Dal13]. Generally, in these applications, people were able to use the interface with little prior training. However, most foot-based interaction techniques require high-precision tracking capability for human feet or the whole body.

In our exploration of foot interactions for visualisation view management, we use the floor as a *Frame of Reference* similar to the Wall Display, except that Floor Display is horizontally positioned (see Figure 6.2-b). Another difference from the Wall Display is that individual views on the Floor Display can be freely moved. However, similar to a far Wall Display, the views are outside of arm's reach. The primary disadvantage of the Floor Display is that its *Frame of Reference* requires users to frequently look down, which may cause much higher neck fatigue than the Wall Display.

Tabletop Display – Placing visualisation views on the top of a virtual table provides a natural way to interact with them within easy reaching distance (see Figure 6.2-c).

The horizontal flat surface also contributes to the convenience of manipulating views by hand. Within our design space, the Tabletop Display display follows a similar path across the design dimensions to the Floor Display (see Figure 6.2-Our Design Application). The main difference is in `Proximity`, which has significant implications in the `User Interaction` side of our design space; views on the Floor Display cannot be easily interacted with by hands, while users can directly touch and move the views on a Tabletop Display. Recent design applications from related work include: TimeTables [Zha+22], immersive space-time cube analysis [FSN20], and immersive heatmaps study [Kra+20].

Body-fixed Display – This category covers novel displays that have a set of large views curved around the user's position. Typically, the views maintain a far distance relative to the user. The frame of reference is movable, thus the views create an egocentric configuration that moves with the user and is pivoted to face the user at all times. This display is relatively static, similar to the head-fixed display in AR applications [Fei+93], in-Situ Visual Analytics [EI17b], and even for the default menu of Hololens AR devices, where the menu window is always in the user's field-of-view. These head-fixed displays, however, restrict the display capacity within the user's field-of-view. However, in our current exploration of the Body-fixed Display, we always place visualisation views relative to the user's torso. This design not only creates an egocentric `Perspective` but also maximises the rendering capability around the user. The `Geometry` of this body-fixed *Frame of Reference* varies, but a common example would be a 2D vertical cylindrical layout (see Figure 6.2-d).

Cockpit Display – This design category is inspired by the Personal Cockpit [EFI14], where users have an arm-reachable panel to interact with (see Figure 6.2-e). The main difference from the Body-fixed Display category is that these views are closer to the user and can be freely moved and are always pivoted to face the user, thus can be easily rearranged using one's hands. Recent studies on visualisation view management have also found that participants tend to position views in an egocentric wraparound layout [Sat+20; Luo+22; New+21] but in absolute room coordinates. We argue that for visualisation view management tasks, especially for individual use, a body-fixed cockpit display would benefit more from being able to move around freely with the views.

6.2.1 Interacting with Surfaces

One of the objectives of this research is to explore the range of possible interactions with the proposed surfaces described above for view management tasks and to describe these interactions using our design space. We consider the following interactions in our implementations following the metaphor of 'DataDancing'.

Regarding the `Degree of Intent`, we enable both implicit and explicit interaction styles for those designed surfaces that have manipulative visualisation views, including the Floor Display, Tabletop Display, and Cockpit Display. The explicit interactions cover regular selection, navigation, and free manipulation, while the implicit interactions could enhance the affordance (e.g., implicit highlighting) and may increase efficiency (e.g., implicit selection). The other two surfaces (Wall Display and Body-fixed Display) are designed to be viewed from a far distance. Thus, explicit navigation should be provided.

One of the common implicit interaction methods is via proxemics. We exploit the spatial relationship between the surfaces and different parts of the user's body by enabling different proxemics dimensions. For instance, views can be selected implicitly as the user approaches, based on their distance from the user's whole body or the gaze. For view management tasks that require hands or feet to interact with views, the views can similarly be selected implicitly according to the distance from the hands or feet.

We also investigate novel foot interaction to interact with views arranged on the Floor Display. A variety of foot interactions have been discussed in HCI literature, such as using foot gestures [Hat+17; SV16; Vel+15; FL18; Wil+20], via various sensors (e.g., pressure sensors) [KJC18; RE06; YXL05; Mat+13], and external devices [Kla+15; Jot+14]. However, foot interaction has not been explored for interacting with data views. We propose that simple foot gestures such as sliding and tapping are efficient with view management tasks such as moving and selection, respectively. Pressure sensors could also be used to increase an input dimension to differentiate functionalities, such as walking for navigation and tapping for selection.

Finally, the `Target` of the interaction action can be easily identified among the five surfaces. For instance, the visualisation views on all surfaces but Body-fixed Display can be directly interacted with, while the Body-fixed Display and Cockpit Display support interactions with surfaces themselves, such as rotating them or carrying them around.

6.3 Conclusion

This chapter introduces *DataDancing*, a design space for visualisation view management, presenting a framework that identifies important aspects in designing view management systems and proposes relevant interaction techniques, focusing on the presentation of and interaction with visualisation views. From this design space, we extrapolate a variety of view management prototypes, each demonstrating a different combination of interaction techniques and space use. These range from common wall and table arrangements to novel foot and floor interaction.

With this work, we hope to lay the foundation for future research and systems on visualisation view management in 3D surfaces and space. In the next chapter, we will further explore and evaluate interaction design possibilities based on our proposed design space.

7 Exploration and Evaluation of Interactions for Visualisation View Management

> *The next evolution of VR would be where you participate physically in that VR world, and not just sitting down.*
>
> — **Nelson Gonzalez**
> (Co-founder of Alienware Inc.)

The main aim of this work is to explore and evaluate how to manage visualisation views on 3D surfaces or in 3D spaces. To achieve this, we design and implement four VR prototype systems that encompass the various surfaces and interactions discussed in section 6.2. We then compare and contrast the interaction affordances of these designs with a qualitative study. This user study aims to formalise our design space, evaluate the proposed interactions on various display surfaces, and gain insights from real visualisation view management tasks.

7.1 User Study 5: View Management Interaction Exploration

7.1.1 Study Design

In order to simulate a real working environment for visualisation view management tasks, we design tasks that require participants to interact with visualisation views on the designed prototype surfaces, such as views on the Wall Display and Floor Display. Then, following the design guidelines proposed by Munzner [Mun14, Chapter 12] for multiple shared encoding views and the example of a multi-view overview-detail visualisation tool designed by Craig and Kennedy [CK03], we consider two fixed

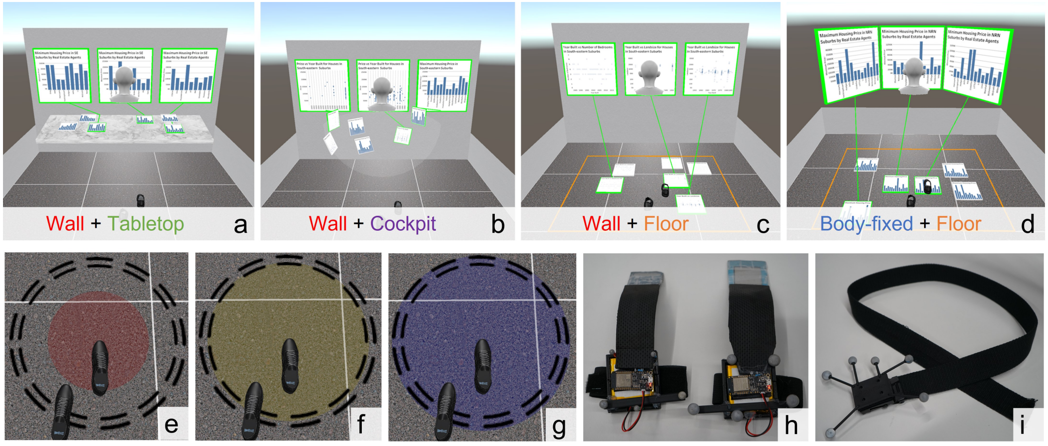

Fig. 7.1.: The top figures show the four prototypes that were explored and evaluated in our qualitative study: (a) Tabletop Display + Wall Display, (b) Cockpit Display + Wall Display, (c) Floor Display + Wall Display, and (d) Floor Display + Body-fixed Display. The bottom figures first illustrate a colour indicator attached to the participant's virtual foot to reflect their foot pressure to the floor in (e)-(g) and two external physical devices used in the study to track (i) the waist and (h) the feet with sensors to obtain foot pressure to the floor.

semantic levels for the information contained within the views: *Landmarks* and *Detailed Views*.

Landmarks are less detailed views that outline a lot of data values [Mun14, Chapter 6]. They are designed in this user study as small views (20cm x 20cm) for participants to interact with using their hands, feet, or whole body. These views display only the visualisation title and visual marks with normalised visual channels (see views on the table in Figure 7.2). *Detailed Views* , on the other hand, are large views (1m x 1m) that cannot be manipulated directly. These views contain full visualisations for use in analysis and sensemaking (see views on the wall in Figure 7.2).

In our evaluation, the *Landmarks* are used as proxies for manipulating coordinated *Detailed Views*. Users can interact with the *Landmarks* directly, and positions of *Detailed Views* are managed by the system based on the relative arrangement of their proxies. A line connects each highlighted *Landmarks* and *Detailed Views* to show their relationship (see Figure 7.2). To complete the study task, participants need to browse the visualisations in the *Detailed Views* area, which they must navigate by manipulating the *Landmarks*.

We created four prototype systems for evaluation. Each system combines two of the five surface categories, using one for hosting the *Detailed Views* and the other for the interactive *Landmarks*:

1. **Wall Display for the *Detailed Views* + Tabletop Display for the *Landmarks*:** This prototype consists of a table arrangement to hold the *Landmarks*, and a wall arrangement to display the *Detailed Views* (see Figure 7.1-a). Participants need to use hand-held controllers to rearrange and select visualisation views on the Tabletop Display to activate the correct *Detailed Views* on the Wall Display and find the answer to the task.

2. **Wall Display for the *Detailed Views* + Cockpit Display for the *Landmarks*:** This prototype consists of a body-synchronised arm-reachable space for the *Landmarks* and a wall display for the *Detailed Views* (see Figure 7.1-b). Participants need to use hand-held controllers to rearrange and select visualisation views on the Cockpit Display to activate the correct *Detailed Views* on the Wall Display and find the answer to the task.

3. **Wall Display for the *Detailed Views* + Floor Display for the *Landmarks*:** This prototype consists of a room-sized floor space for the *Landmarks* and a Wall Display for the *Detailed Views* (see Figure 7.1-c). Participants need to use tracked foot interaction to rearrange and select visualisation views on the Floor Display to activate the correct *Detailed Views* on the Wall Display and find the answer to the task.

4. **Body-fixed Display for the *Detailed Views* + Floor Display for the *Landmarks*:** This prototype consists of a room-sized floor space for the *Landmarks* and a large body-synchronised space for the *Detailed Views* (see Figure 7.1-d). Participants need to use tracked foot interaction to rearrange and select visualisation views on the Floor Display to activate the correct *Detailed Views* on the Body-fixed Display and find the answer to the task.

We discard the other combinations of surfaces such as using the Floor Display for *Detailed Views* because the *Detailed Views* requires a large proportion of attention during the task and using the Floor Display would introduce too much fatigue. We also discard a combination that uses a Body-fixed Display for *Detailed Views* and a Cockpit Display for *Landmarks*, because locomotion is not compulsory in the task design, the user behaviour will be the same as the combination of Tabletop Display and Wall Display.

All views in the *Landmarks* area can be selected implicitly using proxemics. The closest relevant views to the middle point of participants' hands or feet will become highlighted with a green border (see Figure 7.2). All views in the *Landmarks* area can also be selected explicitly and individually using direct input with the hands and feet. Views selected by participants will become highlighted with a blue border (see

Figure 7.2). Participants can also grab and rearrange the views using their hands or feet. While rearranging, the views will have a yellow border (see Figure 7.2).

Foot interactions are implemented via two external devices (see Figure 7.1-h) with pressure sensors. While giving pressure to each device using feet, participants can see a colour indicator in a circular shape showing the current pressure given by the specific foot. Specifically, a red circle means the pressure is under the threshold and nothing happens (see Figure 7.1-e); a yellow circle means the pressure meets the threshold of being able to move the touched visualisation view (see Figure 7.1-f); and a blue circle means the pressure meets the threshold of being able to select the touched visualisation view (see Figure 7.1-g). The threshold for selection is bigger than that the pressure applied when walking, which is to say that moving is easier with lighter strength than selection. This design allows participants to easily select views and reduce the chance of an accidental tap caused by normal locomotion.

After a pilot study, we choose to have 6 views in the *Landmarks* area and 3 views in the *Detailed Views* area. The total number of views that could be selected implicitly or explicitly is three, which is the exact number of views that are allowed to show on the *Detailed Views* area. This restriction ensures that participants have enough space to manipulate the views in the *Landmarks* area and also have a proper scale of the views in the *Detailed Views* area. The small number of *Detailed Views* compared with that of *Landmarks* also forces participants to interact with the *Landmarks* views in order to switch to the *Detailed Views*.

7.1.2 Task

We use a housing auction dataset collected from the Melbourne region. The dataset is chosen because it contains temporal, spatial, categorical, and numerical dimensions. We selected the four largest districts of the city to create four different subsets. Each subset will be assigned to one of the four experimental prototypes as its dataset.

Participants are given specific questions to answer. Each task requires an initial search through the available data before conducting an analysis. This is both for observing how participants achieve a specified goal and for giving some guidance to get familiar with the prototype and the dataset. We design four visual exploration tasks:

1 – Find the maximum and minimum values from multiple views. *Q1: Which real estate agent sold the most expensive houses? How about the least expensive?* In this task, participants are given bar charts aggregated by the maximum or minimum value.

Participants need to select the correct aggregated views, and look for the extremes in the selected views. This task allows us to examine the various interactions used for selection.

2 – Find the maximum value from multiple views, remember it, and then look for the coordinated attribute. *Q2: In which suburb is the most expensive house located? What was this year built of the most expensive house?* In this task, participants are provided with a group of bar charts aggregated by the maximum value, along with a group of scatter plots faceted by different year range on the x-axes and maximum value on the y-axes. First, participants need to select the correct aggregated views to find the maximum. They need to remember this maximum value, and then find the corresponding point in the correct scatter plot. Participants need to answer by giving the year value from the x-axis. This task allows us to examine the selection interactions and how the designs affect short term memory when switching views.

3 – Find trends over time. *Q3: What is the trend for land size over time? What is the trend for the number of bedrooms over time?* In this task, participants are provided with scatter plots faceted by different year ranges on the x-axis and numerical values (land size or the number of bedrooms) on the y-axis. Participants need to select the correct views (either land size or number of bedrooms) first, then they need to rearrange the view position to sort the year ranges. After sorting, participants are able to observe the temporal trend from the *Detailed Views*. This task allows us to examine the selection and rearranging interactions.

4 – Find trends over time in geographical maps. *Q4: How are the locations of new building sites changing over time?* In this task, participants are provided with dot maps showing the distribution of built houses in different geographical regions faceted by the year range. Participants need to rearrange the view position to sort the year ranges. After sorting, participants are able to observe the temporal trend from the *Detailed Views*. This task examines the rearranging interactions and effects on short-term memory when switching views.

7.1.3 Participants and Apparatus

We recruited twelve participants (six female and six male) aged between 18 and 39, all students from our university. All but one participant had already experienced VR, and three of these rated themselves as VR experts. Seven participants had experience with different data visualisation tools, and only four participants had experience with full-body tracking techniques. All but one participant listed the right hand as their dominant hand, while only half participants listed the right foot as their dominant foot. The remaining participants claimed that they don't have a dominant hand or foot. Participants signed up voluntarily and were rewarded a gift card (A$20) and small gifts (candies and chocolates) as a sign of appreciation.

We used an HP Reverb G2 room-scale VR device and the Unity development environment (2019.4.26f1). We also use the VICON system[1] to track the position and rotation of different body parts, such as the participant's waist and feet. Specifically, we use a belt with reflective markers to track the human waist (see Figure 7.1-i).

A pair of custom devices were fabricated in order to sense foot pressure, and track the position of the feet (see Figure 7.1-h). These consisted of 3d printed frames on which reflective markers were mounted, a battery-powered esp32 micro-controller board on each, communicating via UDP broadcast, and a force sensing resistor that curved around the front of each toe and mounted with elastic.

The prototype ran on a Windows 10 PC with an Intel I7 7800X (3.5GHz) processor and an NVIDIA GeForce RTX 2070 Super graphics card. We leverage VRTK [Bod18] for interactive components. The source code is publicly available and may be downloaded via GitHub: [Liu22a].

The experiment takes place inside a virtual room 4×4 m in size. Teleportation is disabled, so participants need to physically walk to navigate, and are able to reach any point within the virtual room. The size of Tabletop Display is 1×2 m. The Cockpit Display has a radius of 0.5 m and is vertically centred at the middle of the participant's shoulders. The size of the interactive Floor Display area is 1.5×2 m, which is the centre of the room. *Detailed Views* have a size of 0.8×0.8 m. *Landmarks* are smaller and vary with each design, with sizes proportional to the distance of the views from the participant's eyes. For instance, Landmark views on the Tabletop Display and Cockpit Display have a size of 0.2×0.2 m, whereas Landmark views on the Floor Display have a slightly larger size of 0.3×0.3 m, to ensure they are easily visible.

7.1.4 Procedure and Data Collection

After completing a consent form and demographic questionnaire, participants are given a verbal explanation of the trial workflow. Next, participants put on a VR headset and perform a series of training scenes to gain familiarity with the four

[1] A sub-millimetre motion capture system with high-resolution cameras (https://www.vicon.com/)

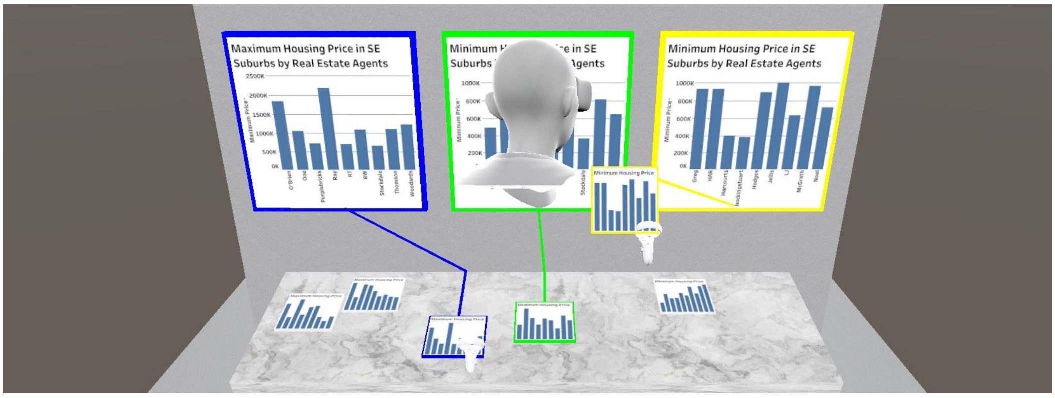

Fig. 7.2.: A participant is working on the question to find the extreme values from multiple views. The blue-border view means the view is pinned, the green-border view means the view is highlighted by proxemics, and the yellow-border view means the view is being moved by the participants.

experimental prototypes. After that, participants complete four blocks of trials with each block containing four questions. The sequence of blocks is counterbalanced between participants. Participants are asked to remove the VR headset to take a short break between blocks. During the break, participants are asked to complete a questionnaire with (1) the general strategy they use to complete the tasks, (2) six questions adapted from the NASA-TLX [Har06] in a 7-point Likert scale, (3) ten questions adapted from the System Usability Scale [Bro95] in a 5 point Likert scale, and (4) general comments about the interaction and the prototype. After the last block, participants complete (5) a short questionnaire with rankings on prototype and interaction preference, and (6) any comments on the current implementation. The total study duration is about 60 minutes, including roughly 20 minutes using VR.

Video and audio recordings are taken during the whole study, during which participants are asked to use a think-aloud protocol. Subjective rankings for the four prototypes and feedback are collected via online forms. In total, we collect data from 192 completed trials (12 participants $\times$ 4 prototypes $\times$ 4 questions). We treat the presented prototypes as an independent variable. Dependent variables include completion time, answer accuracy, NASA-TLX score, SUS score, and subjective ranking. All participants complete the full set of trials successfully.

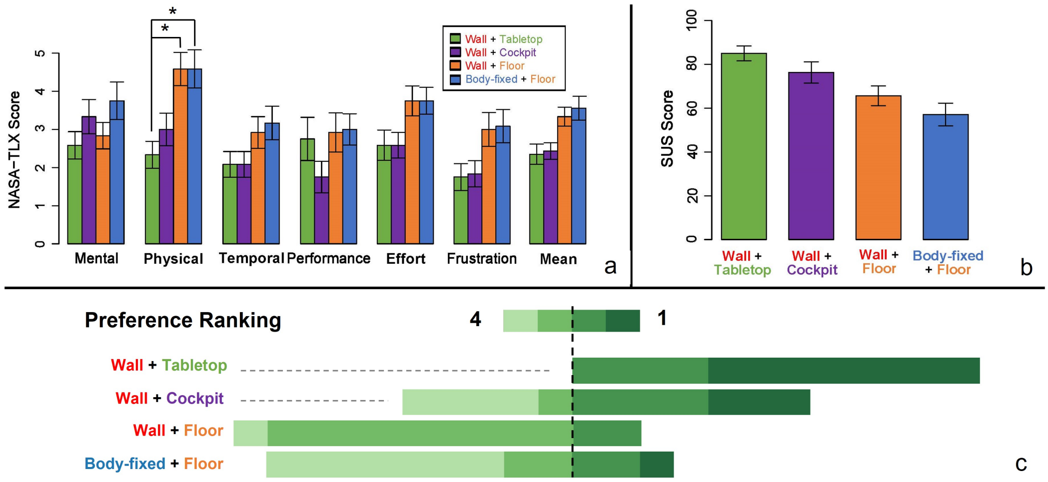

Fig. 7.3.: Each participant responds to the (a) NASA-TLX evaluation and (b) SUS evaluation on each prototype, and (c) preference for each prototype. In the NASA-TLX, performance was rated in reverse order (lower is better). Error bars denote standard error. Asterisks in this figure represent the level of significance: * means $p < 0.05$.

7.1.5 Results

Quantitative Results – We did not find a significant different among the four conditions regarding the completion time ($F(3, 44) = 1.79$, $p = .16$) and accuracy ($F(3, 44) = 1.14$, $p = .34$).

Subjective Rating – Figure 7.3-a shows the NASA-TLX score assessed by all participants for each prototype condition. A Friedman test reveals significant effects for physical ($\chi^2(3) = 17.3$, $p < .001$), effort ($\chi^2(3) = 12.61$, $p = .006$), frustration ($\chi^2(3) = 8.14$, $p = .043$), and overall mean ($\chi^2(3) = 10.27$, $p = .016$). A post-hoc test using Mann-Whitney tests with Bonferroni correction only shows the significant differences between prototype Wall Display + Tabletop Display and Floor Display + Wall Display ($p = .013$, $r = .63$) and between prototype Wall Display + Tabletop Display and Floor Display + Body-fixed Display ($p = .026$, $r = .59$) for the physical demand.

Figure 7.3-b shows the raw SUS score assessed by all participants for each prototype condition. According to Lewis and Sauro [LS09], we report our SUS result below by converting the raw score into percentile ranks and grades. The Wall Display + Tabletop Display prototype ($M = 85$, $SD = 11.68$) is ranked a $A+$ grade in a percentile range of $96 - 100$. The Wall Display + Cockpit Display prototype ($M = 76.25$, $SD = 16.8$) is ranked a $B+$ grade in a percentile range of $80 - 84$. The Wall Display + Floor Display prototype ($M = 65.63$, $SD = 15.74$) is ranked a

C grade in a percentile range of $41 - 59$. The Body-fixed Display + Floor Display prototype ($M = 57.08$, $SD = 17.99$) is ranked a D grade in a percentile range of $15 - 34$.

Participant's preference ranking can be found in Figure 7.3-c. Overall, the Wall Display + Tabletop Display prototype was ranked highest ($Mdn = 1$) among the four prototypes with 8 out of 12 participants ranked as the best while all other participants ranked it as second best. The Body-fixed Display + Floor Display prototype was ranked fourth most often among the four prototypes, with 7 out of 12 participants ranking it as the worst prototype. Both prototypes using foot interaction have a similar ranking which is lower than the other two prototypes using hand interaction.

7.1.6 Discussion and Design Implications

Space Perception: Exocentric and Egocentric Reference Frames

Overall, from the results of the subjective ratings, we can see that participants mostly preferred **exocentric** and **fixed** surfaces such as Wall Display and Tabletop Display. Regarding the `Spatial Perspective` design dimension, a possible reason to choose the exocentric surface might be that it requires less mental effort (see Figure 7.3-a). One participant also stated that "*since table and wall are fitted in their place, I could concentrate on the task better, instead of finding the charts and having a problem with them*" (P7). The mental model created in these surfaces is consistent with the real-world objects, and "*is something I can relate to in real world*" (P12). One participant also mentioned that public presentations would benefit from these surfaces because "*I can easily select and show the charts that I want my audience to see*" (P5). However, some participants prefer egocentric surfaces because these make repositioning and reorientation "*irrelevant in the process of problem-solving*" (P12), where users don't need to "*constantly reorient themselves towards a fixed direction*" (P4). Considering a possible combination of both exocentric and egocentric surfaces, one participant (P5) proposed that exocentric surfaces would be more suitable when a presentation to other people is needed, while egocentric surfaces would be better if the surface is used for the user's own sake such as reading and making notes. Thus, we adopt this idea in our hybrid prototypes in Section 7.2 and propose a concept of using different `Spatial Perspective` for different purposes: exocentric surfaces for public space while egocentric surfaces are for private space, which is similar to the territories proposed by Lee et al. [Lee+21b] in their collaborative user study.

Regarding the `View Movability` design dimensions, overall prototypes with fixed surfaces, such as Wall Display + Tabletop Display and Wall Display + Floor Display, have less mental demands than the other prototypes with movable surfaces, as we can see from Figure 7.3. Moreover, the fixed Wall Display + Tabletop Display prototype is the most preferred prototype. However, the qualitative feedback from the study about movable *Landmarks* and *Detailed Views* gives contradictory reasons. On the one hand, one participant (P6) reported that movable surfaces provide "*freedom to move around more and were still interactive*". Also, some participants (P5 and P7) claimed that the **movable** surfaces could reduce the physical movement needed. On the other hand, one participant (P3) mentioned that in the fixed surfaces, since objects are not moving around, the space provides freedom and comfort to move around more often. Also, another participant (P4) disliked the movable surfaces because they were too sensitive. Most participants (P1, P3, P5, and P9) also reported that when using both fixed and movable surfaces together, they may have occlusion issues. Thus, the future design of movable display surfaces should take these points into consideration, such as the sensitivity and potential occlusion.

Reference Frame Geometry: Curved and Flat Surfaces

We design both flat (Wall Display, Floor Display, and Tabletop Display) and curved surfaces (Cockpit Display and Body-fixed Display) in this study. Most participants like the curved surfaces and reported in the post-study feedback that curved surfaces have everything around them and make them feel like they are much closer to the data visualisations (P6). Moreover, one participant (P7) mentioned that the Cockpit Display helped them to select visualisation views easily and quickly, having all the views in their field of view. This argument is aligned with the findings of Liu et al. [Liu+20] in their study, which showed that semicircular layouts have a similar performance as flat layouts but are more preferred.

User Interaction: Novel Interactions

The completion time and accuracy results don't show a significant difference. However, we observed that participants spent relatively more time on the prototype conditions with foot interactions (Floor Display) than those with hand interactions during the experiment (confirmed by reviewing the recordings). The observed back-and-forth foot movement indicated that participants might be unfamiliar or unconfident with this novel interaction technique. Evidence can be found in responses to the post-experiment System Usability Scale [Bro95] questions: "Q7: I would imagine that most people would learn to use this System very quickly" and "Q9: I felt very confident using this System". For Q7 (easy to learn), participants rated prototypes with hands ($M = 4.63$, $SD = 0.58$) higher than with feet ($M = 3.83$, $SD = 1.05$).

For Q9 (confidence), participants rated prototypes with hands ($M = 4.2$, $SD = 0.83$) higher than with feet ($M = 3.2$, $SD = 1.02$). Participants also reported in the post-experiment comments that sometimes they could accidentally step on landmarks while walking to navigate (P1, P3, P6, P12), "*I have to make sure that I did not accidentally walk over landmarks*" (P8) and if "*accidentally stepped on one it might mess up the entire layout*" (P4). The conflict between the tap gesture and physical navigation affects participants' confidence; as a result, they felt the foot interaction is not flexible (P2) and tends to move uncontrollably (P1).

Moreover, participants reported other challenges while using their feet on the Floor Display. On the one hand, they felt neck strain because they kept looking down at the ground (P3, P4, P8). On the other hand, the sliding gesture to move visualisation views using one foot causes the other foot to stick on the floor (P10), influencing their balance, limiting their moving distance, and disabling the bipedal interactions.

However, participants also shared positive comments after raising the above issues. For example, half of the participants reported that the foot interaction is intuitive and easier than expected (P1, P3, P4, P5, P8, P12). The trade-off for feeling neck strain is to free their hands (P12), and then they have less fatigue on their hands (P3). Other advantages of displaying visualisation views on the floor include having an overview of all the views (P7) and having a clear working environment at eye level (P10).

Overall, despite these challenges and limitations, participants showed a positive feeling for the novel foot interaction for view management tasks. These limitations could be solved by a more robust foot gesture design or other techniques. For example, P4 argues that it is uncomfortable to rotate views using feet, so an auto-rotate to face the user would help. Regarding the neck fatigue issue, P4 suggested having a mirror view at eye level that shows the ground without needing to look directly at the floor. P9 proposed a novel foot interaction technique to have the left and right foot as the left and right click on the mouse.

Our quantitative results do not show significantly reduced performance compared to hand interaction, as might be expected based on past studies of foot interaction, e.g., [PR04]. However, our qualitative results lead us to agree with the investigation by Klamka et al. [Kla+15] that users can perform high-precision interaction tasks with their hands, whereas foot interaction can support secondary navigation tasks such as panning and zooming. On top of that, we argue that the main purpose of introducing foot interaction is to free users' hands and may also create an eyes-free interaction. The foot interaction technique increases the accessibility of the system and may assist other modalities in complex tasks [Kla+15; HH18].

Proxemic interaction has also been explored in this study as an optional implicit input for view selection. Although participants mainly used the explicit selection by tapping to lock the selection, some participants still find this interaction style useful, claiming that "*for reading the chart, they only need to stand nearby the closest views*" (P9) and that "*I can confidently navigate myself to selecting and deselecting data graphs to show*". However, when participants finished the selection task on the *Landmarks* and started working on the *Detailed Views*, the following physical navigation may accidentally override the selection via proxemic interactions, as reported by P7 "*when I'm looking at the wall but because of my foot position, charts were changing*".

7.2 Hybrid Prototypes

Learning from the user study, we improve the interaction techniques and propose two hybrid prototype interfaces that demonstrate the interaction possibilities of our design space. We first describe a multi-modal interaction using hands and feet to interact with visualisation views for view management tasks. Then we introduce a prototype using proxemic interaction. Both prototypes consider interactions with individual views as well as the whole reference frame.

7.2.1 Multi-modal Interaction with hands and feet

From the results of the study, we learn that the exocentric world-fixed surfaces could serve better as public displays while the egocentric body-fixed surfaces are suitable as private workspaces. In this prototype, we design a Wall Display for collaborative public use and a Cockpit Display for each user as personal space. The Wall Display is visible and can be interacted with by all users, while the Cockpit Display can only be viewed and interacted with by the owner. We use transparent views for any other users' Cockpit Display for privacy considerations (see Figure 7.4-c). The Cockpit Display has up to three rows. The curvature and radius of each row can be adjusted by users to switch between a horizontal body-fixed circular surface and a spherical body-fixed surface.

As for the interactions with these surfaces, we learn from the results of the study that foot interaction is natural and easy to learn but is less effective than hand interaction for primary tasks. Kalama et al. [Kla+15] also suggested that foot input is better for supporting secondary navigation tasks, such as zooming and

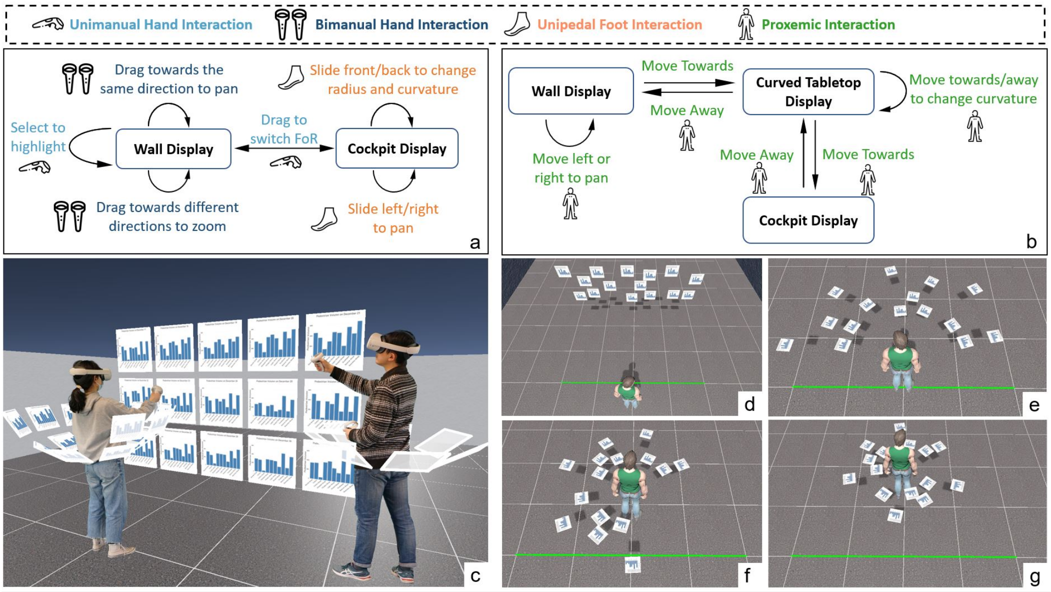

Fig. 7.4.: The top two figures show the state model of the hybrid interfaces: (a) multi-modal interaction and (b) proxemic interaction. The bottom figures illustrate example scenarios for each of the hybrid interfaces: (c) a collaboration scenario with a public wall display and a private cockpit display for each user; (d)-(g) using proxemics to interact with visualisation views by changing their reference frames and the geometry.

panning. Moreover, considering the deficient visibility of the foot interactions in a collaborative environment, we only design foot interactions for private workspaces. As for the public workspace, we adapt some common hand interactions and gestures from related work [Liu+20; Lee+21b]. Specifically, for the public Wall Display, we design unimanual hand interaction to select and highlight individual views by direct tapping on the views. Direct dragging a view from the Wall Display to anywhere close to the user will move the view from the Wall Display to a Cockpit Display, where users can work privately. We also design indirect bimanual hand gestures for panning and zooming the public space. For instance, holding a button and moving one's hands in the same direction triggers panning while moving them in different directions triggers zooming. This interaction design is adapted from the design by us [Liu+20] for small multiples.

We design unipedal foot interactions for the private space, such as sliding forward or backward to change the geometry of the Cockpit Display and sliding left or right to pan the Cockpit Display. We consider all the gestures explored by Velloso et al. [Vel+15] and use sliding only, which was also the most natural interaction observed in our study. Sliding also doesn't require a lot of attention from the user, allowing for eyes-free interaction. The state model of this prototype can be found in Figure 7.4-a.

7.2.2 Proxemic Interaction

We further explore proxemic interaction to interact with views and switch between different surfaces. Inspired by the related work [RFD21; Gre+11; VB04], we focus on the distance and orientation proximity of users relative to a world-fixed exocentric display surface.

For example, when users are far from the display area (see Figure 7.4-d), they will see a world-fixed exocentric Wall Display. Users can move to their left or right to implicitly trigger the panning of the whole surface. When users move close to the display area (see Figure 7.4-e and f), the Wall Display display will be transformed into a curved world-fixed Tabletop Display. The curvature of the surface can be changed when users move forward or backward. Finally, when users keep moving forward beyond the original display area, the surface becomes a body-fixed Cockpit Display. The state model of this prototype can be found in Figure 7.4-b.

7.3 Conclusion and Future Work

In this chapter, we present a user study that explores and evaluates the usability of four of these designed techniques. Informed by lessons learnt from our study, we propose design implications and a discussion on visualisation view management for 3D surfaces and spaces. Lastly, we implement two hybrid prototypes concerning the design implications, which demonstrate the use of our design space that focuses on novel foot interaction and proxemic interaction.

Our prototype systems and the user study is the first to test the effect of foot interactions on floor displays for visualisation tasks in a room-sized immersive environment. Our study also confirms previous results from general foot interaction studies in non-immersive environments, that foot modality enables eyes-free interaction and is helpful when hands are occupied. Although from the results, prototypes that require foot interactions have a higher physical demand than those with hand interactions, participants still like this interaction modality and report that it was intuitive and easy to learn. Together with the favoured proxemic interactions, these novel interaction styles and modalities are promising and can free users' hands and mental concentration.

From our study, we observe novel behaviours and collect feedback from participants with a set of interface designs unique to visualisation view management. Participants suggested having world-fixed exocentric display surfaces for collaboration purposes, and body-fixed egocentric display surfaces for private use. However, they noted that context switching between Floor Display and wall displays come with a cognitive cost, so combining these surfaces should be done with care. We also noticed some interesting side-effects of our virtual environment; for instance, participants were conscious of the visualisation views on the floor and tried not to stand on them. Though body-fixed surfaces can be moved along with participants, they were still unwilling to walk more than a few steps in the virtual environment. This may due to a tether or unfamiliarity with physical navigation in VR and may be less of an issue as untethered devices become more commonplace.

Future work involving the use of the full 3D space may consider the floor display and the foot interaction as an additional input channel for assisting other modalities. For example, gaze input can be augmented with foot interaction to trigger the selection with a foot tap, leaving hands free for other activities. Foot interactions also support secondary navigation tasks [Kla+15] while hands are busy with the primary interaction tasks. There is also a future opportunity to thoroughly explore the foot interactions such as effective foot gestures for view management tasks. For instance, we only explore the foot sliding and tapping in our study, while the other various foot gestures [Vel+15] could be mapped to other visualisation tasks. Also, foot interactions for collaboration in immersive data visualisation have not been sufficiently explored. Finally, the scalability of this design space can be tested with a large number of visualisation views.

8 Discussion, Future Work and Conclusion

> *The idea of a "virtual reality" such as the Metaverse is by now widespread in the computer-graphics community and is being implemented in a number of different ways.*
>
> — **Neal Stephenson**
> (American Writer, Inventor of the word "Metaverse")

In this final chapter, we first summarise the primary research contributions described in the previous chapters (Section 8.1). We then reflect on visualisation view management with regard to some important aspects and practical examples explored in this thesis (Section 8.2) and consider other possibilities for future work (Section 8.4).

8.1 Contributions

This thesis overall contributes to a comprehensive investigation of visualisation view management in immersive environments. Specifically, we contribute a design space for presenting and interacting with small-multiples visualisations. We also evaluate the effects of layout curvature of display views in 3D environments with a series of user studies. Furthermore, we derive design implications from the user studies and propose a thorough design space for visualisation view management exploring novel interactions, including proxemic and full-body interaction. Finally, we test a few design applications using our design space and demonstrate interaction possibilities via hybrid prototypes.

In Chapters 3 and 4, we contribute:

- a design space for the layout of and interaction with small multiples in an immersive environment;

- a prototype system that allows us to explore layout and interaction designs;
- two user studies that evaluate the effect of introducing curvature into the shelves such that they wrap around the user;
- and finally, findings from these user studies: a flat layout is more efficient than a curved one with a small number of multiples, although it requires more walking; with many multiples, walking hinders the flat layout performance and user preference; fully enclosing circular shelves are particularly disorienting, but a half circle layout is a popular compromise.

In Chapter 5, we present:

- two user studies to test the effect of different display layouts (*Flat* vs *Full-Circle*, *Flat* vs *Semicircle*) by investigating the users' ability to recall locations of items within the layout for a straight-forward visuo-spatial memory task;
- overall, the findings from our two studies suggest that when the tasks depend on the user's spatial memory of the layout, layouts of the information displayed in immersive environments that fully surround the user should be avoided.

In Chapters 6 and 7, we contribute:

- a design space for presenting and interacting with visualisation views for visualisation view management for 3D surfaces and spaces;
- a qualitative evaluation based on four prototype implementations of view management interaction designs drawn from our design space;
- design guidelines for future view management systems;
- and finally, two hybrid prototypes following our design guidelines and demonstrating interaction possibilities of the design space.

8.2 Discussion

In the preceding chapters, we have reviewed, explored, and evaluated various visualisation view management design spaces and techniques, as well as related user studies. In this section, we discuss what we have learned regarding the potential benefits and challenges that immersive 3D display environments bring to visualisation view management, with a comparison to traditional 2D desktop displays.

In the following discussion, we consider all three HCI perspectives. That is, from the human perspective, the computer perspective and the interaction perspective.

8.2.1 Human Perspective — Spatial Skills and Spatial Memory

Compared to traditional desktop environments, immersive 3D space allows users to bring their spatial skills and abilities learned from the physical world to support sense-making tasks. One of the important components involved in such spatial skills is the perception of depth. Depth perception refers to the ability to perceive the distance to objects in the space using our visual system [How12]. The study of this visual mechanism has a long history back to ancient Greece and was formalised by Gibson in 1950 [Gib50]. Such ability allows users to build an accurate mental representation of the 3D objects in either real or virtual environments. For example, in the motivation scenario illustrated in Chapter 3, users need to explore small-multiples views of building models. Compared with complex interactions with these views on the desktop displays, immersive spaces allow users to move naturally to navigate. Such physical movement provides monocular cues called motion parallax [Fer72], which provide depth information to help users build an accurate mental representation of building models efficiently. Unlike the limited size of the desktop display, immersive spaces also provide users with abundant space to display and arrange visualisation views without scaling them. Thus, objects can be rendered in the environment at a 1:1 scale and the user can move within them, nearby them, or view them from far away to gain an overview. The perception of such accurately scaled information also creates depth cues called "familiar size" to assist in understanding the spatial information of the views and creating a visceral feeling of being there. For instance, Lee et al. [Lee+21a] explore the basic understanding of units and measures normally abstracted in data visualisation. They build VR prototypes to test the quantitative understanding grained from data visualisation, such as using the Eiffel Tower (see Figure 8.1) in its real-life form for users to navigate freely.

Spatial memory, as explained and discussed in Chapter 5, is one of the spatial abilities of human beings. It reflects effective navigation, especially for data visualisation comparison tasks. Specifically, when working with multiple views in the same display space, such as comparing different views, it is crucial to remember the spatial position of visualisation views, as users may switch their focus between them. The spatial memory of the user influences this ability, but how the spatial memory is affected by the spatial arrangement is still being determined. In Chapter 5, we use an abstract task to measure the spatial memory on recalling spatial patterns in a grid

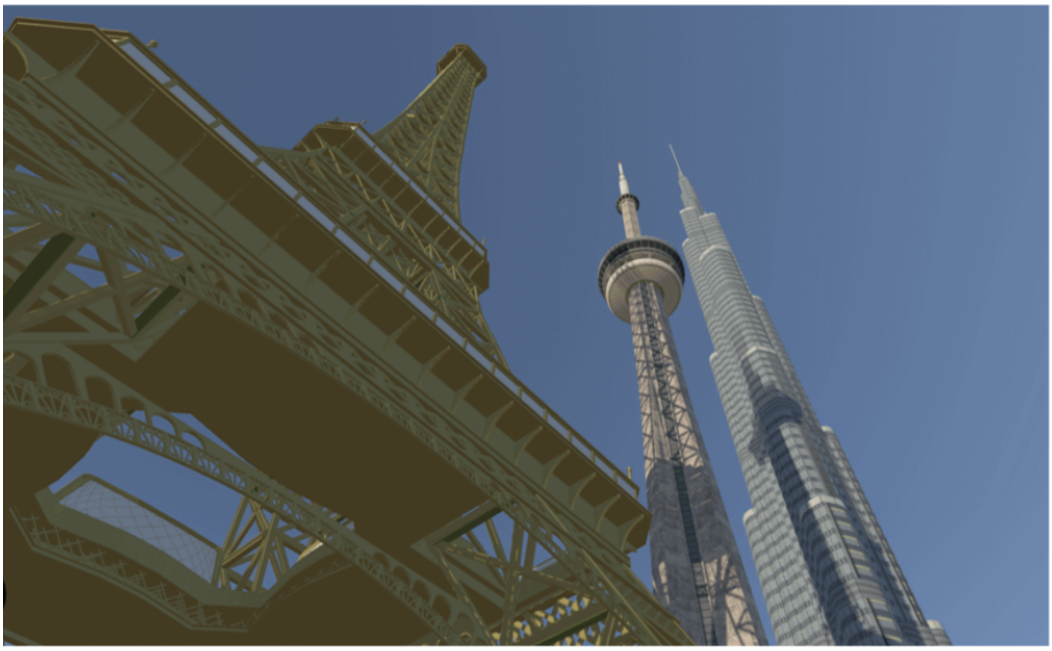

Fig. 8.1.: Looking at the Eiffel Tower, CN Tower, and Burj Khalifa at real-life scale from below [Lee+21a].

arrangement among three layouts (flat, semicircle, and full-circle). From the related work, we hypothesise that the flat layout would have the best performance due to the ability to (1) have an overview of the whole grid and (2) afford the natural landmarks on the corner. However, the study results didn't show a significant effect of these two confounding factors on spatial memory. On the other hand, we found that participants using the full-circle layout had the worst performance in recalling room-scaled patterns among the three layouts. Furthermore, from the qualitative feedback after the study, participants reported that too much rotation was needed in the full-circle layout, which disoriented them during the task. Thus, in our later exploration and design for visualisation view management systems in Chapter 7 (where we developed the DataDancing design space), we propose the ability to switch between flat layouts and curved layouts for different visual analysis tasks.

We attribute the effect we observed of different layouts on spatial memory in our user studies in Chapter 5 to spatial navigation in immersive 3D space. As discussed above, the rotational navigation involved in the full-circle wraparound displays is disorienting compared with the translational navigation in the flat displays. It suggests that when performing visual analysis tasks that require spatial memory to remember the position of views, all views should be placed in a flat layout. However, in most related work where visualisation systems are deployed in a room-scaled environment, users often exploit the full display capability by using space around them, such as walls in all directions, to position visualisation views [Lee+21b]. Though the size of the circular layout in our study is at arms reach, which may not prove to apply to such room-scale environments, future studies to test a larger circular layout would give more evidence of such spatial navigation on spatial memory. Similarly, future research can also compare the physical navigation used in our study with virtual navigation, such as panning the views in a circular arrangement, where users don't need to rotate or move.

8.2.2 Computer Perspective — Arranging Multiple Views in 3D Space

The discussion above summarises our findings related to human perception and cognition in immersive environments. In this section, we focus on the limitations of computer hardware. Specifically, the display capability. Display technology is a fast-moving target. The cost of screens has decreased massively over the decades while the resolution has increased. Immersive technologies have also improved in both cost and resolution but also in responsiveness and field of view. However, there are certain fundamental differences between screens and immersive environments. In particular, this thesis is motivated by the limitations of displaying multi-dimensional visualisation or 3D data, such as geographical and spatial-temporal data, on traditional desktop screens. Multi-dimensional data exploration often requires data analysts to arrange multiple views of data for rich details to be analysed simultaneously. Traditional desktop displays are good at displaying 2D visualisations, while 3D visualisation views may suffer from occlusion, distortion, and a loss of information [Mun14]. However, 3D immersive spaces preserve the original form of the view and can be navigated by users both egocentrically (users move 3D views) and exocentrically (users move themselves). Moreover, such a combination of 2D and 3D views enables a flexible focus + context view approach [Mun14], where the immersive 3D views allow rich detailed exploration and on-the-spot decision-making and 2D views can provide simplified abstract representations.

An important aspect that a 3D space would bring to visual analytics is that users can arrange visualisation views in the space around them. This thesis mainly explores the effect of display layouts on comparison tasks (Chapter 4) and on spatial memory (Chapter 5) via prototypes that have visualisation views positioned wraparound the user in a circular layout. The abundant display space in 3D immersive environments enables various design opportunities (explored in Chapter 6). For example, in an office environment with AR displays, one can place visualisation views on the surfaces of furniture or other objects in the space [Luo+22], leveraging spatial cues to enhance the spatial memory [Per+15]. However, as investigated by Yang et al. [Yan+21b], the benefits of displaying visualisations in a room-scale 3D environment depend on the visualisation tasks and users' ability.

Another possible advantage of 3D space is that it supports non-rectangular, arbitrarily shaped irregular displays within the space (e.g., a round table or irregular projection surfaces along adjacent walls). Recent studies have explored general view management for such surfaces [Wal+11; Niy+21; Jon+14; Jon+13; Nac+07]. During the exploration of our DataDancing design space, we also investigate the possibility of switching the reference frames of the visualisation views, such as translating views from vertical wall surfaces to horizontal floor surfaces. The transition is continuous, and the middle stage, while views are on both surfaces, can be treated as a bent surface for visualisation views. Such surfaces are similar to the Perspective Wall [MRC91], where users have multiple semantic levels of views (i.e., focus + context). However, whether and how non-rectangular displays may benefit visualisation view management has not been thoroughly explored.

8.2.3 Interaction Perspective — A Visceral Experience

Interaction is an essential part of visual analytics. The immersion offered by immersive display techniques may improve such interaction. As described by Slater and Wilber [SW97], immersion is the technological affordances of the system that determine the degree of presence experienced by the user, which allow users to engage in a visceral experience of interaction [Ens+21a]. On the other hand, the embodiment is also enabled by immersive displays, where users engage and act effectively in a physical world [Büs+18] (either the real physical world, such as large wall displays or the virtual physical world, such as in VR environments). In this thesis, we explored several approaches to interact with visualisation views to leverage the benefits of immersion and embodiment. For example, in all user studies discussed in this thesis, physical locomotion is designed to navigate the visualisation views. Moreover, we design direct manipulation such as grabbing, dragging, rotating, and throwing using different body parts. Unlike traditional mouse and keyboard interactions, interacting with our body parts, such as hands or feet, is more natural. However, physical navigation and manipulation require spatial skills (e.g., proprioception and spatial memory), which are learned skills and may not be suitable for general users. We need to be cautious about this fundamental issue when designing embodied interactions for visualisation view management in immersive environments.

In the past, immersive technologies are characterised by large and heavy lab equipment. However, with the rapid development of tracking devices and computational speed, recent immersive displays are lightweight and untethered, which boosts the mobility of such display techniques. For example, users can wear AR headsets like the HoloLens anywhere without physical constraints. Users can, but are not limited to, interact with visualisation views in their office, directly interact with an overlaid X-ray view of a CAD model over the machine they are repairing onsite [Moh+15; Pro+20], and explore situated visualisation when walking on the street [Nia20] or watching a soccer game [HZR21]. However, such techniques require high-precision tracking capability and stability because we need to know not only the user but also the spatial properties of the referents [Ens+21a].

Another advantage that immersive technology brings is the possibility of creating a hands-free environment. Traditional desktop displays heavily rely on the hand interactions such as using a mouse and keyboard. However, immersive 3D space allows users to interact with visualisation views using any part of their body, such as the head, eye, torso, and foot. In our user study to explore such novel interaction modalities in Chapter 7, participants prefer freeing their hands by using their feet to interact with views on the floor. Although such interaction depends on the tasks and the position of views, novel interactions using foot or gaze look promising. However, one issue that we identified with using foot interaction is increased neck fatigue because users need to look down at the ground more often.

Similar to hands-free interaction, recent research explores the possibilities of designing eyes-free interactions. The human visual system can only focus on a single object or plane at any one time, which means that users in a visualisation system need to switch their focus between views. Thus, in the design space exploration discussed in Chapter 7, we think that foot gestures such as tapping and sliding for secondary navigational tasks are eyes-free, allowing users to remain focused on the visualisation views at eye level.

Another known issue for interaction in immersive spaces is the "gorilla-arm" syndrome, i.e., extensively holding one's arm in the air leads to fatigue and other side-effects [Hin+14; Jan+17]. In our design space exploration, we seek solutions such as using multi-modal interactions (e.g., gaze + hands, gaze + foot) to reduce this effect.

Fig. 8.2.: The first commercial GUI was introduced by the Xerox Star 8010 workstation [Tha+81] (thanks Dave Curbow for the photo).

8.3 Potential Research Impact

The work presented in this thesis explores immersive display and interaction technologies that are not yet widely used in visual data analytics. Though immersive technologies represent a potential step-change in HCI, such revolutionary changes in how people use computers have precedents.

Traditional visual analytics on desktop displays trace back to the 1970s when a windowed Graphic User Interface (GUI) was originally explored at Xerox PARC [Tha+81] (see Figure 8.2), where the term WIMP (i.e., windows, icons, menus, and pointing device) was coined. Such WIMP-based GUIs became commercialised in Windows and Mac products in the 1980s and became standard in homes and workplaces in the 1990s. Recently, as new interaction techniques have been invented, the post-WIMP interface design (e.g., multi-touch screens, gesture-based interface, zooming interface, tangible interface, and VR systems) attempts to go beyond the paradigm of the traditional user interface. With heavy investment in immersive technologies from big companies (e.g., Facebook, Microsoft, Apple, etc.) in these new interfaces and interactions, we are sure that the future of Human-Computer Interaction and data visualisation will not look like the past. This thesis contributes to the post-WIMP interface design focusing on immersive systems for data visualisation view management. Our contribution helps to lay the groundwork for future data visualisation systems in immersive spaces.

While immersive technologies have only become ubiquitous in recent years (particularly since the advent of low-cost VR devices such as the first Oculus Rift), immersive technologies have a long history. For example, the concept of immersive information displays was considered in the 1950s with the "Sensorama" multi-sensory theatre [Hei62]. Until the 1990s VR technology remained an experimental technology, exclusive to computer science or engineering labs or special exhibitions. The early projection-based systems and early headsets were still not affordable to the general public and there were only limited applications considered. However, in the 21st century, big companies have started investing money in this field, and various devices are available, allowing more and more people to try and use them, such as the Oculus Rift[1] in 2014 and HTC Vive[2] in 2017.

Nowadays, immersive technologies make reality and virtuality collide. For instance, Magic Leap 2[3] can render completely opaque virtual imagery over the real world. Varjo[4] and Oculus Quest Pro[5] headsets are improving the quality of video pass-through AR. There are other novel 3D displays (e.g., Light Field's holographic display[6] and Voxon's 3D volumetric display[7]). Promoted by Mark Zuckerberg and his "Meta", the emerging word "Metaverse" is now well known by the general public. The term "Metaverse" originated in a 1992 science fiction novel "Snow Crash" [Ste03] as a portmanteau of "meta" and "universe". In the "Metaverse", novel interactions become available, such as tangible input, gaze selection, mid-air gestures using hands or feet, and proxemics. Sooner or later, there will be a radical shift in how humans interact with and work with computers. The work in this thesis is helping to lay the groundwork for future data visualisation systems where immersive interaction is much more commonplace.

Last but not least, our contribution to knowledge about spatial memory establishes a connection between spatial memory and analytic tasks in information visualisation and could be used as a foundation for future work expanding this fundamental topic. This research also covers broad HCI concepts including, but not limited to, embodied interactions, interaction styles (i.e., implicit or explicit interactions), input modalities (e.g., whole body or foot interactions), and workspace arrangement.

[1]Oculus Rift: https://www.oculus.com/rift-s/
[2]HTC VIVE: https://www.vive.com/
[3]Magic Leap 2 AR: https://www.magicleap.com/
[4]Varjo VR/XR: https://varjo.com/
[5]Oculus Quest Pro: https://www.meta.com/au/quest/quest-pro/
[6]Light Field's holographic display: https://venturebeat.com/pc-gaming/light-field-lab-shows-off-solidlight-high-res-holographic-display/
[7]Voxon's 3D volumetric display: https://voxon.co/products/

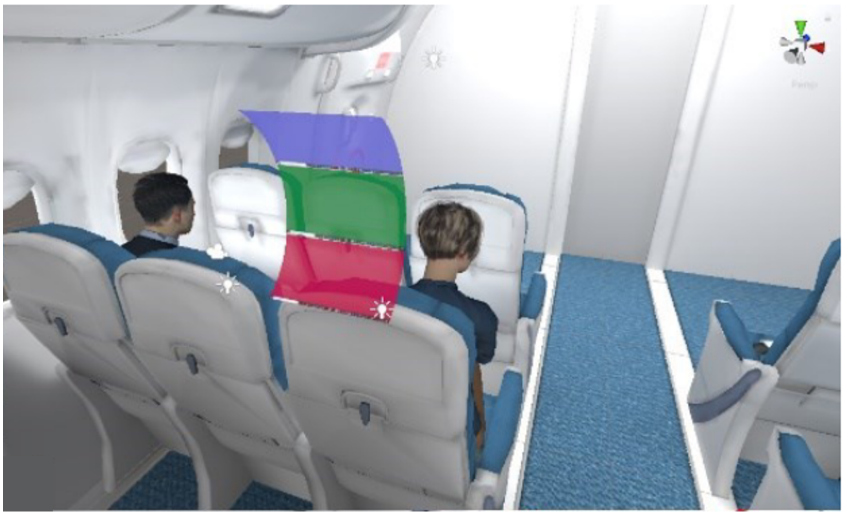

Fig. 8.3.: A vertical curved display in a simulated VR passenger airplane environment [Ng+21].

In summary, our research may inform design of future data visualisation systems involving sophisticated view management, which may become popular as immersive technologies further improve in terms of cost, resolution, field of view, comfort and other issues that currently limit their accessibility. We hope the work in this thesis can lay the foundation of immersive view management design and can be used by future researchers and data analysts.

8.4 Future Work

8.4.1 Other Layout Options

There is a future opportunity to explore the curvature design space more thoroughly. Besides the horizontally curved displays explored in this thesis, vertical curvature has also been investigated in a simulated VR passenger airplane environment [Ng+21] (see Figure 8.3). The authors show that participants preferred the vertical layout for productivity and were suitable for a shared environment like an airplane. However, whether this vertical curvature could be used for a large-scale data display still needs to be discovered.

Moreover, users may stand outside a circular layout from an exocentric perspective [MRC91]. This layout allows users to have a focused view in the centre and a collapsed view on the side to adjust the ratio of detail and context smoothly in a

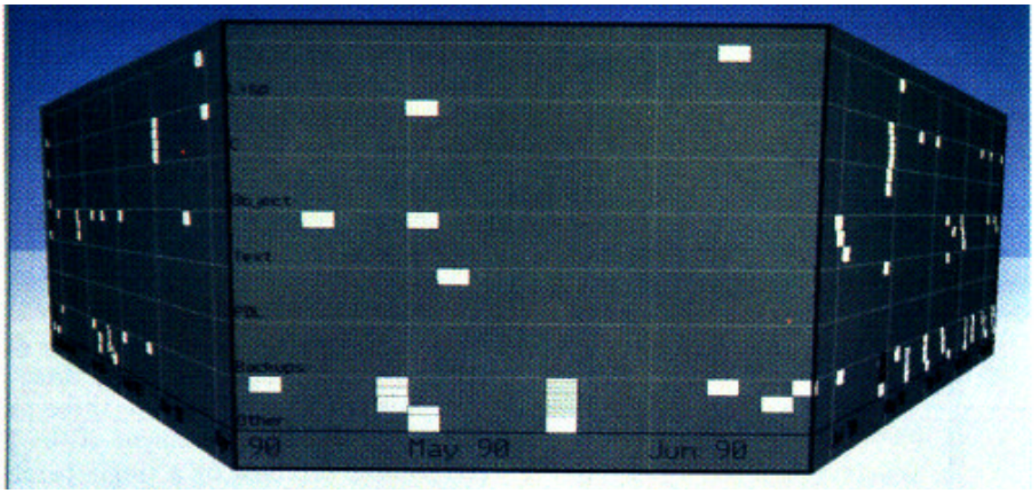

Fig. 8.4.: A linear visualisation technique by smoothly integrating detailed and contextual views [MRC91].

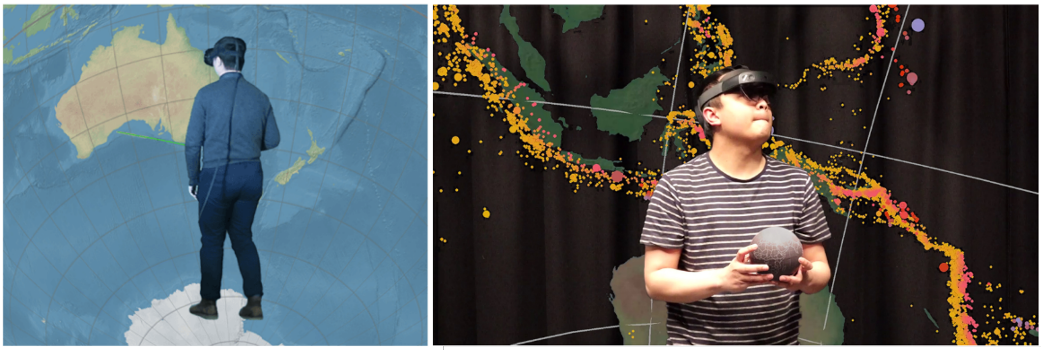

Fig. 8.5.: Two visualisation techniques to display virtual globes in both VR [Yan+18] and AR [Sat+22]. In these techniques, users are enclosed by a 3D spherical globe.

3D metaphor. Compared to a flat layout, this curved display would save horizontal space without losing much information (see an example in Figure 8.4).

Besides these 2D curved layouts, 3D layouts could support more visualisation views to be displayed. For instance, a spherical layout could be interesting to investigate. In recent studies for both body-scale [Lub+16] and room-scale [Sat+20] displays, this enclosure of data may provide users with a better immersive feeling by utilising their spatial skills (see an example in Figure 8.5). Other 3D layouts are also possible, such as displaying views in a volume [Yan+21b]. Although the third dimension introduces occlusion, interactions such as panning and zooming might be helpful to navigate within these layouts.

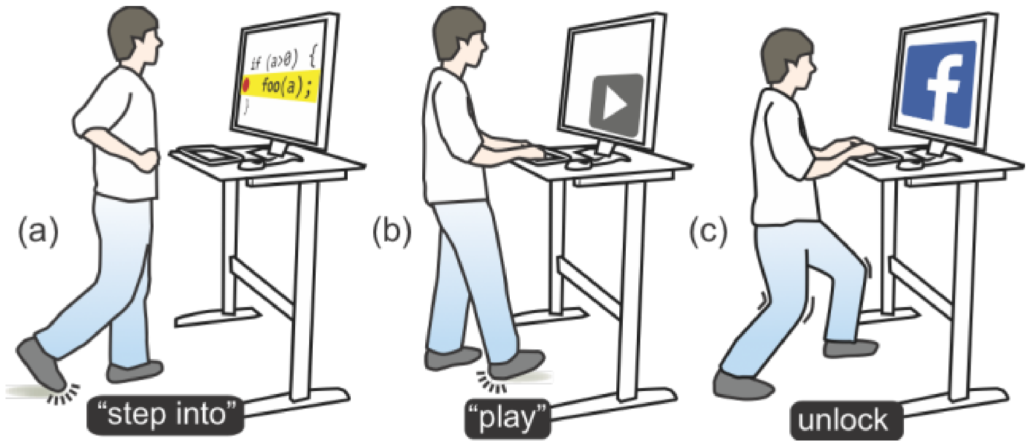

Fig. 8.6.: An interaction technique that allows users to use their feet to perform different actions such as typing and clicking [SV16].

8.4.2 Other Interaction Possibilities

This thesis explores natural interaction modalities such as hand and foot interactions. We also introduce the proxemic interaction using the whole-body positions. Our literature review shows that foot interactions for visualisation view management have yet to be investigated thoroughly, such as the four types of floor-based interaction: (1) projection-based system such as Kickables [Sch+14], drone.io [Cau+19], and HMD Light [Wan+20]; (2) sensor only, foot-centric systems such as smart floor [OA00], Z-tiles [Ric+04], StandingDesk [SV16] (see Figure 8.6), and SmartCarpet [Gla+07]; (3) underfoot displays or projections such as Multitoe [Aug+10]; and (4) floor-based signage using a glass surface with a capacitance system such as TapTiles [Dal13].

Moreover, in Chapters 6 and 7, we propose using multi-modal interactions such as a mix of hands, feet, the whole body, and gaze. These proposed interaction techniques could eliminate the drawbacks of a uni-modal interaction type and, thus, increase performance.

Our user studies mainly investigate a room-scale multi-view visualisation environment. However, our design space could also be applied to an expansion of the display space to handle multiple views of various sizes. For example, users can change the aspect ratio of a large-scale panel of views (e.g., 10 m x 10 m) and use the panning interactions to work with visualisations. Another solution for this would be using a context + detail approach where users can interact with the context view as explored by Yang et al. [Yan+21b] (see Figure 8.7). Inspired by the explored

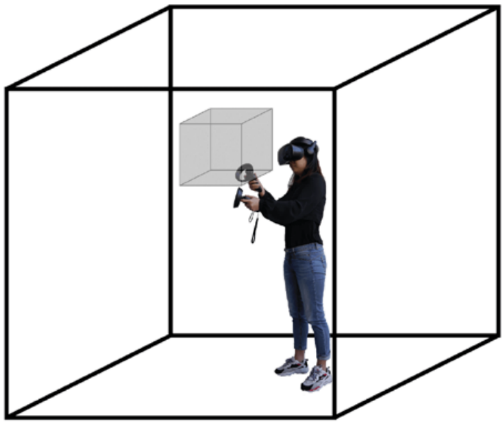

Fig. 8.7.: An example of using World-in-Miniature for a large-scale data visualisation [Yan+21b].

approach to deal with large-scale multi-view visualisations, future work would be needed to explore and evaluate other design possibilities.

8.5 Conclusion

We begin this thesis by reviewing the related research on Immersive Analytics (IA), visualisation view management, and small multiples visualisation (Chapter 2). Afterwards, we present a design space exploration for 3D small multiples visualisations (Chapter 3). We then investigate the effects of display layout for data comparison tasks using small multiples visualisations (Chapter 4) and the effects of display layout on spatial memory (Chapter 5), followed by an exploration and evaluation of design space for visualisation view management (Chapters 6 and 7). Lastly, we give a speculative exploration of how the work in this thesis may have an impact on future Immersive Analytics systems and begin to explore some additional questions of visualisation view management that remain open for future research directions (Chapter 8).

Finally, we conclude this thesis with a contribution and a clear take-away message: Immersive Analytics proposes novel and interesting design alternatives for visualisation view management to support sense-making tasks (e.g., data exploration and comparison); ultimately, we hope our thesis lays a foundation for designing future view management systems.

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Appendix A

The appendix lists all the qualitative feedback from the five user studies.

ID	Please briefly explain what did you like/dislike about the Flat Layout? (BIM dataset)	Please briefly explain what did you like/dislike about the Flat Layout? (Bar charts)
1	The main issue that I encountered was inspecting the ground floor and all visualisations at the bottom (last line). It would be helpful to be able to lift and rescale the entire visualisation interactively.	It has the same problem as the other flat layout
2	Even though the layout wasn't circular, it didn't feel like it mattered as much as there was no important information that was hidden/occluded as a result of rotation.	Interpreting information before I get started (i.e. standing far back) felt really confusing because of all the information in front of me, but as soon as I dived into a specific SM it became much manageable. I liked how the relevant dimensions were labelled in red, although at the same time this could probably be simplified by just hiding irrelevant SMs.
3	walk from left to right is time consuming, I don't like to crouch down	need to remember the value, need to walk a long distance
4	The lowest row was too low.	The lowest small multiples row was too low. It's hard to bend down and do the comparison.
5	Again the same, if the multiples were not close to each other comparing them was tough. As I had to remember the results.	Same.

6	it is stright forward to aim for the graph, but the distance between models is too large	Same.
7	need to move around more	hard to compare values across charts
8	information is arranged in order and easy to compare	information is arranged for ease of overviewing
9	It is better than the half circle, doesn't need to move my head a lot, the vertical height difference is not much	It's easy to find different dimensions
10	feels I can step on the color legend	near to me, easy to find, rotation of all the SMs has better cognition, doesn't need to move body
11	Advantage of flat layout is that it didn't require user to rotate. Disadvantage of flat layout is that it requires a lot of movement to go from one side to another side to see the data	Out of the three methods, the flat one suits bar chart the most as it didn't require as much rotation
12	For this task because I didn't need to rotate the graphs it was easy to find the information in the flat layout.	I needed to walk a lot through different charts to find the information.

Tab. A.1.: Qualitative results from the user study described in Section 4.1. This results show participants comments on the flat layout.

ID	**Please briefly explain what did you like/dislike about the Quarter-Circle Layout? (BIM dataset)**	**Please briefly explain what did you like/dislike about the Quarter-Circle Layout? (Bar charts)**
1	This layout require less body movement because all visualisations can be covered by head rotation. It is easier to compare distance visualisations (e.g. April vs January). However, it does not solve the problem of inspecting visualisations at the bottom.	Similar to the previous comment on the same layout.

2	Felt same as before.	It felt there was more space between each column which made it easier to rotate the SMs. Still didn't like how low they were and me needing to crouch. Also the labels were facing at odd angles away from me if I was at one side of the SMs, therefore even though I could definitely see the labels from the position I was at, they weren't rotated properly towards me, meaning I had to move to read them anyway. (I think this problem was also in the flat layout, but I didn't bother looking at the labels anyway because they weren't even visible due to the layout).
3	The views are more closer than others.	same as before
4	The curve and the distance between columns were good. The lowest column was too low.	The curved structure and also the columns are not too far away.
5	If the months were not close to each other, I had difficulty comparing them.	Same as before.
6	the curvature is good, the models have short distance, I don't need to rotate much to find models	best visual design
7	easier than flat, worse than half circle	easier to walk
8	with the color panel information is easy to compare in quarter circle layout	i can have an overview of whole information easier w/o turning around my body
9	Better view angle	same as before
10	comfortable, not like flat shape, needs to walk left and right	same as before
11	Quarter-circle is my personal favorite as it doesn't require as much rotation to find data, and looking data doesn't require as much movement.	The need to rotate similar to the half circle is challenging for bar chart

12	I needed to move my head for different tasks but was easy to use this layout.	I didn't need to move or rotate a lot, and it was very easy to find all the information.

Tab. A.2.: Qualitative results from the user study described in Section 4.1. This results show participants comments on the quarter-circle layout.

ID	Please briefly explain what did you like/dislike about the Semi-Circle Layout? (BIM dataset)	Please briefly explain what did you like/dislike about the Semi-Circle Layout? (Bar charts)
1	The circular layout is less body-movement demanding. I did not feel much difference in term of usability with the other circular layout. Since this layout has a higher distance of visualisation columns, it requires more extensive head rotation than previous one and should be less effective. Interestingly, I did not find that disadvantage significantly affected my performance.	The same comment as previous half-circle layout
2	Same as before.	Easier because I could just turn around and rotate rather than having to walk as much. It was still annoying having to crouch all the time, especially to read the lower SMs on an equal level.
3	Have to turn around body.	Hard to find SM to compare
4	The distance was a bit too much between columns.	The distance between columns is too far.
5	In one task I had to compare two months on the same column, it was difficult not able to move the small multiples.	Again due to curved the multiples were closer to compare.
6	It's uncomfortable to rotate myself when I wear the headset, it's anoyying to rotate myself	Model has short distance, but this curvature is big, so it's time consuming to find small mutliples
7	best layout	just rotate no walking

8	it's more difficult to read all information	it's more difficult to have an overview of the whole information
9	I don't like it	dizzy
10	similar to quarter circle, overall, it's low for position	I feel dizzy to rotate my head, and isolation feeling
11	Circle layout is appealing, but it's difficult to read and find data as it requires a lot of rotation	Difficulty to find data needed between chart that are far
12	Needed to rotate my head too much, not very convenient.	It is a bit hard first to find the information on the charts, I needed to rotate my head many times to go through the charts.

Tab. A.3.: Qualitative results from the user study described in Section 4.1. This results show participants comments on the semi-circle layout.

ID	Please briefly explain what did you like/dislike about the Flat Layout? (Trending Task)	Please briefly explain what did you like/dislike about the Flat Layout? (Comparison Task)
1	Because there are three rows of small multiples, it is easy to underestimate the value of the bars in the top row and overestimate the values in the bottom row. Thus, users have to do multiple checking with all candidate bars.	It is really tiring to stand all the way throughout this section. The difficulty of using flat layout depends on the distance between two test small multiples. It is really bad if two small multiples are at two ends. If I could teleport, it would be great!
2	It is still quite difficult to compare bars because of the perspective foreshortening. But I would not say I dislike this layout because I could step back to get a better view.	I wish I could perform less physical walking. Panning the vis would be great in this case.
3	needs walking, but more related to life	Although needs movement, but I'm used to it, sometimes the number will be occluded when using ruler to see the year tag, it is easy to find specific small multiples
4		easy to find target

5	Also quite physical demanding.	better than last one, I prefer to walk rather than rotate
6	The charts are all far enough and in front of you which enables to have an overview of all data, however they may be a little too far on the sides, which makes that you can't see very well the charts from the center of the area, and walking from one side to the other is making losing some time	You can see the chart you are looking for quickly as they are all in front of you, you just have to turn your head a bit. However, the entire graph is really large and you lose some time walking from one side to the other when charts are far one from the other
7	some data are further to the user and not straightforward to look for answer	data is arranged in a plane and it's easy to explore the answer
8	it's easy to compare in the same surface, the result can be seen directly	it takes time to find small multiples
9	needs walking, too far, cannot compare directly	Fuzzy, All the SMs have little difference, so it's hard to find data
10	Can be seen all the data, can select a large range of possible answer, it is good to filter the best result	target is easy to find, the flat is straight forward
11	the label will hide the vision when you stand far	to much walking
12	dislike: it is quite long way to move instead of turning around for comparison.Like: quite easier to relocate the one I forgot since all the graphs are clearly ordered.	pro: It is easy to see the whole overview for the bar chart. cons: BUT I have to move to select the details.

Tab. A.4.: Qualitative results from the user study described in Section 4.2. This results show participants comments on the flat layout.

ID	**Please briefly explain what did you like/dislike about the Semi-Circle Layout? (Trending Task)**	**Please briefly explain what did you like/dislike about the Semi-Circle Layout? (Comparison Task)**

1	Half-circle is probably my favourite because it is easy to locate the candidate bars while standing at the spawn point. It is better than flat layout because the distance between the user and bars are relatively equal. I don't need to move around to have a close inspection of the bars.	At this point, I was used to the system. Thus, I felt easier to play around. As I don't like walking around, half-circle layout is not my favourite.
2	In general, scanning all visualisations is easy to do. However, estimating value of the visualisation at the bottom is difficult.	It require less walking than Flat one. Searching the target visualisation is easier as well because the distance between my eyes and each visualisation is the same.
3	Doesn't need to move, similar distance to data	The last question A and B is too close, cannot distinguish, ruler is also hard to show it, the previous three cannot see clearly
4	easy to find trend	in the VR headset, the resolution is not good, I cannot highlight multiple cube
5	relatively low physical demanding compared with the other two	The order of data leaves me best feeling, I don't need to rotate much and I don't need to walk frequently
6	Charts are far enough to provide an overview of all charts and there are all in front of view so you don't have to turn a lot to be able to analyse all the charts	Charts are further than with Circle Layout, which allow a better view of all the data, however the half-circle is quite large, so can't see all the charts in your field of view and you may take some time finding the data and walking from one chart to another.
7	it's easy because when comparing budgets all the data is presented in front	not difficult to identify the data
8	I compare the length using my eyes, it is hard to look in the curved layout	Need to rotate to find year section, not like flat, all the SM is in your vision
9	cannot use my eyes to compare, need to use tools	Ruler will be occluted and transparency differ less

10	blue and transparent color is similar, and feel I have walked a far distance	Good, convenient, too low, fuzzy when I rotate, the ruler helps me on number memory
11	easy to compare	too much walking
12	some coordinations related to country and sector has visual occulsion	still need to turn around. But better view for me to filter.

Tab. A.5.: Qualitative results from the user study described in Section 4.2. This results show participants comments on the semi-circle layout.

ID	Please briefly explain what did you like/dislike about the Full-Circle Layout? (Trending Task)	Please briefly explain what did you like/dislike about the Full-Circle Layout? (Comparison Task)
1	It is less straightforward than the flat layout because the bar charts are too close. I prefer to view from a certain distance. It is easier to gain a rough overview. However, in the circle layout, I have to look around a few times.	It is still tricky to locate the sample small multiples. But it's more user-friendly because users don't need to walk around.
2	Again, surprisingly I failed to recognise benefit of this layout when I compare it with flat one. I guess it has something to do with the distance of my position to the visualisation. In flat layout, I can move back to see more visualisation. But with this one, I did not have much of that option. Hmm... interesting.	I really like this one. I think it's mainly because it requires less walking. I am wondering how the half circle will look if the radius is the same as this one.
3	Too dizzy, Because every question i have to see all the data, it requires rotation, maybe the different layer cause difference of bars	dizzy, maybe I move too fast, If I crouch down, the data will be fuzzy for the lowest row, constriction when I move closer
4	When the difference is not too much, hard to compare different cubes	I cannot find the selected year quickly
5	not too many useful toolkit to solve the issue, only eyes can be uses which makes more pressure	Sometimes are quite physical demanding as I need to look around to find the data instead of just looking at a direction

6	Like : just have to turn around on yourself to see all charts, it's quick to have a look on all charts	Like : the "last" data of a row is close to the following year, which is the first of the following row. Dislike : you have to turn around completely to see all data, so you may lose some time finding the year you are looking for
7	i can compare the budget easily among all the years	data is closest to the user and it's easy to find the answer though i spent some time looking around to find where the data is situlated
8	not in the same layer, need to go back and forth to see if I missed any information	I'm confused to look for year, it seems the order is messy, but I don't need to move a lot, so it's overall fine
9	too tired, hard to find when rotation, too close, too intensive, cannot find easily, especially the lowest layer, the view angle when looking down is smaller	I don't like to rotate, the view angle is little, ruler cannot provide confidence, ruler in bar is not clear
10	better than last experiment, I feel good to stay closer, but I will forget when will the circle starts	Not easy to find, if stay near, the rotation will be more, number is hidden (bug), green label is hard to find, device view angle is small, maybe I'm used to the human view angle
11	different angle when looking three different rows, need to crouch down to compare	hard to find the exact year
12	It is good to use the brush to locate the bar and quite intuitive to compare. But I think it is better to label the number when the bar is highlighted. And sometimes it is confused to encode one of variable using both axis and color.	it is difficult to filter the year and I am not comfortable for the sitting-down to look at.

Tab. A.6.: Qualitative results from the user study described in Section 4.2. This results show participants comments on the full-circle layout.

ID	What are your comments on two different layouts (Flat vs Full-circle)?

1	Memorising the exact location is very difficult to do without creating some sort of spatial cues/references. Thus, what I did is basically finding/defining these cues/references. For example, most of the time, I first find and memorise an anchor target card then memorise the positions of other target cards relative to it. Sometimes, the anchor can be a group of non-target cards. For example, target cards can be located around a 2 x 2 grid of non-target cards.
2	the circulsr layout was a bit confusing, I need to turn to view pattern so a little hard to follow patterns. The flat was easier to remeber the pattern but it was very wide that I need to just move or turn my head to see the pattern. so, I could not just remember the pattern in one glance.
3	Flat layout: to be fair this layout works well with memorising from left to right by order as well as reversed memory. For example, the total 12 columns can be numbered as 123456654321. However, reversed memory isn't applied well to circle layout in my case. It is very easy to forget the exact position of the last white card when I rotate. During the experiment, there are three key information factors I would try to obtain: the position of the first white card (top level, middle level or botton level), the number of the column the white card is in, relative position of the current white card to the previous one. Rotation in circle layout makes it harder to track the relative position because I have to memorise both the difference of column numbers as well as the angles I have rotated.
4	The flat layout is easier for me to figure patterns and remember them. I can use the coordinates to help me rememeber. For the circular layout, it's hard for me to find a starting point and I kinda lost track after rotating several times.
5	circular layout needs too much turn around, hard to learn and remember
6	Flat is better for logic. Circular layout has no clue for start and end point.
7	circular pattern was very confusing, loose of orientation
8	Circular layout was hard because it is easy to get disorientated, making it easy to get two squares side by side mixed up. Flat layout was easier because it had a solid reference point (the wall). I wanted to use bimanual interaction for the circular layout, as I would then be able to use both arms to try to remember locations of squares. Because there was only one controller, I had to twist my body a lot to reach the squares, making me disorientated.

9	While circular layout is closer to user, flat layout is easier to remember the relative positions than circular. This is related to the way i memorised the pattern. And I would wonder how the performance would be if I can see coordinate system in a circular layout.
10	The flat layout is better as I can find the starting point easier with it than with circular layout. Sometimes I lost where should I start in the circular layout.
11	sometimes i forget where I start from in the circular layout
12	Flat: Easier as I have more reference points. I know the edges of the layout. In circular layout, I'm unsure which one is the first column after turning back to examine the boxes behind my back.

Tab. A.7.: Qualitative results from the user study described in Section 5.2. This results show participants comments on two different layouts (Flat and Full-circle) without any visual modifier.

ID	What are your comments on two different layouts (Flat vs Full-Circle) [Limited Field of View]?
1	It takes long time to go through flat layouts, while circular ones make me have more time to memorize the patterns.
2	Flat enabled easier recognition of patterns based on relationships between cards. For the circular layout a greater emphasis was placed on remembering spatial, physical information as it was less intuitive to find patterns without concrete start/end (landmarks) and the patterns felt less recognisable
3	It's easier to recall the flat layout as you can rely on the column position from the left/right. Circular layout requires the user to rotate and it's difficult to recall the exact column position. I think an indicator with column number will make recalling of circular layout much easier.
4	I prefer looking at the flat layout especially when I have got a correspondingly efficient memorising method. However, for the Circle layout, most of time I forgot which column I began with.
5	Circular did not have corners so it was harder to understand the position, however circular layout actually provided me with the view of the sun which helped me to remember the scene (like I have the image of it in my memory).
6	flat layout is easy to recall if you use some memory tricks
7	- equally supported learning and recall. - progress can be seen in both, as more rounds are done

8	When I have to turn my body around in the circular layout, my memory shifts
9	I feel the flat layout is more easy to recall. Circular layout is had to distinguish where did I start learning.
10	I think for circular layout, I might miss the correct block due to wrong rotation, but for flat layout I am able to locate the blocks because I have a rough idea of the position of the column
11	I was initially very interested in the novelty of the circular layout and felt that it may be easier to recall the squares because I was surrounded by them. This proved not to be the case as I struggled to find points of reference for the 'starting' point for my recall. The field of view also feels a lot more cluttered in the circular layout and I couldn't as easily separate the quarters of the tiles. The flat layout was more easily split into quarters and made it easier to remember where the tiles were in a 3 by 3 configuration.
12	Circular was easier to navigate, but harder to remember locations, whereas flat was easier to remember locations as you could count how many columns across or how many columns from the starting point.

Tab. A.8.: Qualitative results from the user study described in Section 5.2. This results show participants comments on two different layouts (Flat and Full-circle) with limited field-of-view as the visual modifier.

ID	What are your comments on two different layouts (Flat vs Full-Circle) [Landmarks]?
1	Flat layout gave me more clue on the position of filled cards and also my starting point. The circular layout was also too close to me so I needed more head movement to have a better overview. Also, the small yellowish spheres were very helpful, however, in some cases It's confusing which side of the sphere the filled card was.
2	The flat layout is easier to remember when the white squares appear in or near the corners. But because the layout stretches quite long, it is hard to locate targets when they appear in the middle. The circular layout was quite terrifying at first, but gradually i found this layout to be easier to navigate. I believe with more practice, I could perform better in a circular layout.
3	The flat layout was easier to memorize whereas the circular one sometimes confused my thought process, causing me to choose the incorrect options.
4	with the circular it was harder to have a point of reference compared to the more simpler flat layout

5	Flat layout makes it easier to create a so called data structure in mind as I find it easy to find the anchor point. Circular layout makes it a lot harder to do so which I have to use the square foot icon to make a start. Flat layout also provides me convenient to view it from a further point which is infeasible in circular layout
6	flat one is better for memory
7	Overall, I found flat layout is much easier for me to recall compared to circular layout. For flat layout, it requires me more body movement such as walking. While in circular layout, it requires me more rotation, sometimes made me lost.
8	flat layout allows you to look into the entire pattern but circular layout needs to move your body where your memory may not remember exactly where the white boxes are
9	it's easier to memorise the locations of selected cells with the flat layouts
10	Circular layout is easier to recall as long as I remembered the flow of my body but sometimes I got a little dizzy and missed one when turning around. But it's easier to get all right for flat layout if I can remember the first few.
11	Flat layout is much more easier to remember for me
12	For the flat layout, it is a bit easy to remember the white board if I am familiar with the location of yellow ball and white board. However, for the final test of flat layout, it is different from previous location of white board in the flat layout since it is not a lot of yellow boxes as marks, so I got 0/5. For the circular layout, it is quite hard for me since after I turned around to touch all of the white boards, I always forgot the location of them in the beginning. However, after several testing, I changed my way to remember them so I might get a better result than previous circular layout tests.

Tab. A.9.: Qualitative results from the user study described in Section 5.2. This results show participants comments on two different layouts (Flat and Full-circle) with landmarks as visual modifiers.

ID	What are your comments on two different layouts (Flat vs Semi-Circle)?
1	For the Flat Layout I feel hard to touch all the five white board in 15 seconds and I have to run sometimes. For the Semi-Circle Layout, I feel it‘s less distracting cause I don‘t have to worry that I may not able to touch all the 5 white boards but I have to turn my head slowly because I may feel dizzy when I turn my head fast when putting on vr .

2	Personally, I feel that most of the 15 seconds is spent on going to the graphics, but I have some single threads, which makes it difficult for me to remember during the exercise. After the third round of experiments, I can start to memorize while walking, and there will be some movement distance. Helps memory (for example, I should have taken 3 steps to reach the first one). Personally, I feel that the semi-circle is more convenient to click on the graphics, so that I have more time to memorize, and I can see more graphics at a glance and use the image memory. If it is flat, the whole figure is elongated, and it is difficult to remember it with image memory.
3	Compare with flat layout, semi-circle is simpler to remember because it can easy decomposition into 3*3 box
4	For the flat layout, it's will be better for learning since people can go through quickly and have the overall view. The layout relatively easier but not actually in help with the long-term memorization. Furthermore, if VR is going to be implemented, flat layout will be boring since it's not much different to a white board. For the semi-circle layout, it will be more interactive. Students have to actually move around to read over the content. This will actually help with the memorization. The unique stuff or layout will usually has more impact to the people.
5	Flat layout is better for learning but quite hard to recall, especially for the target near the central axis. It's much more easy to find the central axis of the semi-circle layout when you face to the wall, which gives 3 landmarks (1 central axis and 2 sides) or references for participants to memorize the targets.
6	Semicircle: The interface will take less time to click on the square, and the corresponding memory will take more time. Flat: Clicking on squares takes longer to provide better global fuzzy memory.
7	Flat layout gives a more complete image of the whole pattern whereas semi-circle layout breaks the pattern according to the limit of perception of human visualisation. It's easier to recall flat layouts because it forms a complete picture in the mind. However, there are more physical efforts required for flat layouts compared to semi-circle layouts.
8	If the flat view is too far away, you need to walk back and forth to observe the whole picture. If the surface view is relatively close, you only need to turn your head. Surface plot wrapping is easier to navigate than.

9	Semi-Circle is interesting, I has distance with the wall so I can use the distance and the view to remember the white part. The distance from the head to the end of the Flat made a bit difficult for me to finish the selection in the beginning
10	Flat - I find it harder to remember, I try to remember the location but not very impressed. Semicircle - I prefer to see the topic of semicircle from a sensory point of view, my brain is more active and impressed by the semicircle figure Psychologically, I prefer the semicircle to these two layouts. I am more confident in the semicircle that I can choose the right one, which gives me a sense of accomplishment.
11	semi-circle is easier to see and member than flat layout.
12	The semi-circle layout is more close to me and needs less steps, therefore save time to memory the patterns

Tab. A.10.: Qualitative results from the user study described in Section 5.3. This results show participants comments on two different layouts (Flat and Semi-Circle).

ID	What did you like or dislike about the interaction with the landmarks?
1	Dislike -1. hard to select with my feet 2. when a new question starts, the question might be covered by landmarks and I had to move the question each time
2	Compared with using the controller, the foot control is harder since my feet movement is not that flexible than hand movement.
3	I liked interacting with foots, less fatigue I would say in comparison with holding a controller in my hand. but sometimes I stepped on a wrong card. but with controller, I made less mistake.
4	My thoughts on the interaction with the landmarks are mostly the same as before. It is too easy to accidentally pin a landmark accidentally. Because of this, I cannot walk over any landmarks that I have placed, making them a "no go zone" that artificially restricts the space that I have to move.
5	if the equipment has some issues with selecting the landmarks, it's gonna be a bit embarrassed to hardly step on them in front of people
6	I couldn't move around freely and kept selecting the wrong landmarks by mistake as it came in the way. I liked how I could move them around by dragging my feet.
7	Most of the time we use hands to interact with a system, but this system helped me to have almost four hands to do the tasks

8	It was scattered over the place. I had to hunt for landmarks. It was like playing some puzzle game, which drastically reduced productiveness.
9	Similar as pervious floor+ wall combination.
10	The foot interaction is not that flexible than hands, because we often use our hands rather than foots. so when I use my foot to move the figures, it is a little bit harder than hands. Besides, when I want to move the figure, one of my foot has to stick on the floor and move it, so the body movement is not very comfortable in this way. The another thing is that I have to keep watching at the floor to search the correct figures, this action is also not very comfortable. However, the good thing is that it is clear around us, then when we can just focus on the target figure on the wall frame.
11	The console is ok, but using my feet requires control and too much walking, while also focusing on the display that moves with me.
12	Very intuitive. I like using foot to drag landmarks around.

Tab. A.11.: Qualitative results from the user study described in Section 7.1. This results show participants comments on interactions with the landmarks.

ID	What did you like or dislike about the combination of the floor and body frames of reference?
1	Both body and floor tend to move uncontrollably, so it was a bit hard to arrange charts in order. But was easy to answer the first three questions, and for the last one, it was hard to pin the charts in the order that I wanted.
2	Like, since in the real life, lots of activities like playing ball need to use our feet. It can help us to practice our agile.
3	Having foot interactions made it easier to select objects. But body frame limited the view.

4	There are two main things I liked about this compared to the wall frame of reference. First, the fact that I don't have to tilt my head up as high to look at the wall was nice. This made the system less painful to use. Second, I like how I was not required to constantly reorient myself towards a fixed direction. The fact that I could spin around and do the task facing whichever direction I found most comfortable made it both easier and faster, as I did not need to worry so much about carefully positioning the landmark. It also lowered the barrier between me and the system, as I could focus more on doing the task rather than needing to adjust the layout in order to be able to do the task in the first place. That said, this all no longer became possible when the ordering of the three detailed views began to matter. This was because the order of the detailed views was still determined based on the direction of the environment and not of my body. This made it so that I still needed to position the landmarks more or less how I had to do them for the wall condition, which more or less negated any advantage this one might have had. I also didn't like how sensitive the body view was to my waist movements. As I turned to move my head, my waist would naturally rotate with it as well. This would cause the detailed views to rotate away from my head, meaning I would have to turn my head even further. Maybe some sort of smoothing function to restrict how much the body view moves as a result of waist movements would help.
5	the detailed view is movable with my body movement so i can equally see every detailed chart (dont need to walk to the one I want to see more clearly)
6	I didn't notice that much of a difference. It felt like I was using the same references throughout the experiment.
7	Body frame looks a bit unnecessary, but floor reference can be useful in some cases since I could select the charts easily
8	The body frames were tracked at the waist. When you move your head, you usually have a slight turn of your waist. It felt like I was fighting with myself, trying to stop moving my waist to see what I was doing.
9	Floor+ Body combination provide more flexibility on landmark movement and selecting. By rotating the body the detailed chart can be easily shown in front of body.
10	The combination is good, if we exactly know where is our target figure, then it is very convenient to touch that and then display the details on the wall.
11	Not very used to using feet to select and drag.

12	This is very intuitive combination. Pining a frame is a bit cumbersome in this mode, but on the other hand I can very easily navigate my body to filter the projected graphs.

Tab. A.12.: Qualitative results from the user study described in Section 7.1. This results show participants comments on interacting with floor and body-fixed displays.

ID	Do you prefer the hand interaction or the foot interaction? Why?
1	Hand. I find it easier to control than feet (probably because I use hands more often in daily life to control) Even though the hand control still need to be targeted at the interface in order to select/move, and sometimes I needed a second try.
2	I prefer hand interaction, because in daily life and study, I use my hands more. For me, my feet may lack continuous exercise, so they are not as flexible as my hands
3	Hand interaction was less confusing (not sure I choose this one because I am used to it but it was easier to work with controller. Also, with foot, sometimes I stepped on a wrong card or I had to be careful not to put my foot on the cards so I could not move comfortably in the space.
4	Hand interaction was definitely easier to use, although not when the landmarks were moving around all the time in the cockpit view. It is generally more accurate and less tiresome to use. The foot interaction is pretty nice when used to make spatial regions of analysis, so to speak. Having different parts of the environment where I know to go to in order to do some specific task felt pretty good, although this is set back by the sensitivity of the pin action making movement feel restrictive.
5	hand interaction, imagine i need to to a presentation in front of hundred of people, and i have to hold one foot on the ground then walk with a wired movement...
6	Hand, as it was more natural to select. I didn't end up making so many mistakes.
7	Hand interaction, less distracting, and needs less movement
8	Hand interaction. It was faster and easier. I could organize landmarks faster. I could select them faster.
9	Hand version is easier to control with pressing the button comparing using foot to touch hardly or gently on the landmark which is hard to control.

10	I prefer the hand one, because I do not need to blow my neck to check the figures on the floor then look back to the wall to check the details on the wall.
11	hand interaction. Because the hands are more flexible, and the hands are easier to do some complicated work
12	I prefer foot interaction. Tapping foot and walk around feels more natural than button pushing and drag and drop.

Tab. A.13.: Qualitative results from the user study described in Section 7.1. This results show participants comments on foot interactions.

ID	Overall, please explain what did you like about this system?	Overall, please explain what did you dislike about this system?
1	Body view was hard to ok to use, but I think I prefer the wall because wall is a less curved view. I didn't really like the floor reference.	Probably the hardest system to control and use in the four systems. Feet were hard to select (than the third one?)
2	In general, I don't really like it, but I don't hate it	I need to use my feet to drag the chart to move rather than using my feet to select and then it can move. To be honest, it's a bit exhausting.
3	Only the foot interactions.	I did not like the body frame. It occlude my view, (I had a very limited view which made me feel uncomfortable). Moving frame made me feel sick and dizzy. I prefer the static wall rather than a moving frame. For foot interaction, I had to look down on the floor and then look up to see the changes, this head movement made me feel sick and feel more fatigue. At the beginning, selecting cards was a bit confusing, but later I got used to it.
4	The detailed view felt more properly integrated with the floor.	See above.
5	easy for me to see the detailed view as it will move with me	a lot of body movement

6	I liked how I had the freedom to move the landmarks around and it automatically pushed the other landmarks away when I was setting it up.	There were too many landmarks to choose from and it was physically straining to use my feet.
7	The best thing that I liked a lot to move a chart with my foot was really intuitive way of doing that. Also, I could have a overview of the all charts that I have on the floor and choose the most relevant ones to investigate more.	I could do wrong interaction a lot when I didn't mean to do that. Also needs lots of physical efforts that may reduce my attention to the question.
8	Just the simplicity of the system.	It was difficult to use. How it only showed 3 items in the detailed view. I wasn't able to see the overall trend across the entire era. I just picked the most recent years to see a trend. I was too tired to reselect landmarks to look further back in history. I felt dizzy because everytime I turned my head to look at the detailed view, the detailed view kept moving.
9	Selecting and viewing on the chart is easier than floor+wall combination. Comparing with the body and wall combination. The detailed view is not easily be covered by other things.	Same reason as the foot selecting functionality.
10	The thing I like is that it is clear around me, so I can clearly focus on the details figures on the wall frame.	The thing I dislike is that is a little bit inconvenient to find the target figures on the floor, I have to keep blow my neck and watch on the floor

11	Hand interaction can be reduced	Choosing with my feet is a relatively novel attempt, and for me, it's okay but not necessary. Especially when you use your feet to drag the block, you will feel some discomfort, and you will feel some pressure. I am worried that the force change of the foot in the middle will cause the drag to fail, and the other foot will not be able to move smoothly, and it will be easy to mistake. When I touch something else, because the system senses the position of my body at the same time, it will directly cause the three images on the screen to flicker and change during the dragging process, which will increase the pressure of my answering questions. In addition, if you only show the information to yourself, it will be fine, but if you show it to others at the same time, it will be a bit silly.... The hand basically only has button operations, and it will feel a bit awkward to hold the handle. And the screen of the follower, although it is convenient for me to see the information when I turn around, but when I drag the block with my foot, it will become a part of my distraction and hinder me.
12	I like that I can confidently navigate myself to selecting and deselecting data graphs to show. I like that the body following detailed view make my standing position irrelevant in the process of problem solving.	Sometimes I accidentally pin a graph by standing over it. Also if the detail view is too large and I have trouble read text on the two sides. They tend to follow my head movement instead of my body.

Tab. A.14.: Qualitative results from the user study described in Section 7.1. This results show participants comments on the prototype system.