DataDancing: An Exploration of the Design Space For Visualisation View Management for 3D Surfaces and Spaces

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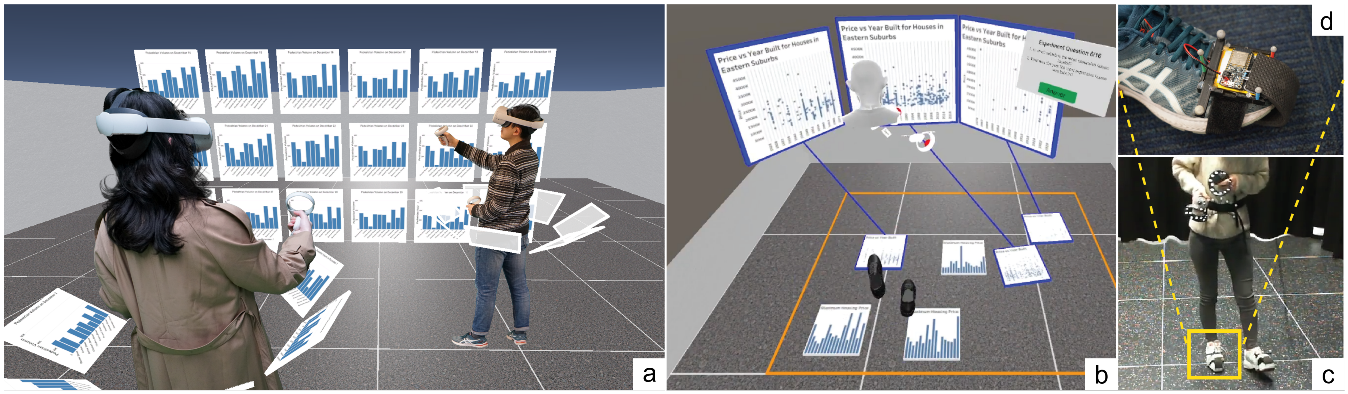

Figure 1: (a) A hybrid prototype demonstrating interaction possibilities of the DataDancing design space for visualisation view management. (b) One of four prototypes evaluated in a qualitative user study with a body-fixed large display and a floor display with novel foot interactions. (c) The third-person front view of one participant 'dancing' with views on the virtual floor in VR (synchronised with scene b). (d) A novel foot device used in the user study for each participant foot with reflective trackers and a pressure sensor system.

ABSTRACT

Recent studies have explored how users of immersive visualisation systems arrange data representations in the space around them. Generally, these have focused on placement centred at eye-level in absolute room coordinates. However, work in HCI exploring full-body interaction has identified zones relative to the user's body with different roles. We encapsulate the possibilities for visualisation view management into a design space (called "DataDancing"). From this design space we extrapolate a variety of view management prototypes, each demonstrating a different combination of interaction techniques and space use. The prototypes are enabled by a full-body tracking system including novel devices for torso and foot interaction. We explore four of these prototypes, encompassing standard wall and table-style interaction as well as novel foot interaction, in depth through a qualitative user study. Learning from the results, we improve the interaction techniques and propose two hybrid interfaces that demonstrate interaction possibilities of the design space.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Interaction design**; *Visualization systems and tools.*

KEYWORDS

visualisation view management, design space exploration, immersive analytics, virtual reality, 3D surfaces and spaces

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1 INTRODUCTION

In emerging immersive systems for data visualisation, it is becoming common practice to display multiple visualisation views on wall or tabletop arrangements [54, 58, 78, 95]. 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 [59] 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 [60] or a spherical layout [78]. 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 arms-reach, other body parts—such as feet—may provide alternatives to conventional hand interaction for accessible input [88]. Also, feet can provide additional input channels for assisting other modalities in complex tasks [13]. 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 [5, 32, 43, 62]. 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 paper 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. We then conduct a user study that explores and evaluates the usability of four 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 contributions include: (1) a design space for the presentation of and interaction with visualisation views for visualisation view management for 3D surfaces and spaces; (2) a qualitative evaluation based on four prototype implementations of view management interaction designs drawn from our design space; (3) design guidelines for future view management systems; and (4) two hybrid prototypes following our design guidelines and demonstrating interaction possibilities of the design space. With this work, we hope to lay the foundation for future research and systems on visualisation view management in 3D surfaces and space.

2 BACKGROUND ON VIEW MANAGEMENT

View management in conventional 2D user interfaces can be traced back to tiled window managers [12, 86] and non-tiled window managers [4]. These systems use non-overlapping methods and constraint-based algorithms to enhance the visibility of views. Recent work on view management has also investigated tabletop collaborative visual analytics [42, 87] and the large wall displays [47, 50, 51, 71]. Although these systems have looked into interactions to support complex visual analytics tasks, none of them address spatial relationships in 3D environments.

Recent off-the-shelf technologies can not only track users' different body parts but also model the physical environment, allowing surrounding surfaces to be transformed into ad-hoc view locations. View management in immersive 3D spaces has been explored since early work in AR [7]. By optimising the layout and its appearance, the visibility of different objects, as well as their spatial relationships, can be maintained [2, 28, 69, 70]. For instance, Grasset et al. [31] introduced a novel view management technique for placing labels in Augmented Reality systems using an image-based approach to define important image regions and geometric constraints. McNamara et al. [64] proposed a similar technique to place information labels based on user attention in virtual environments, which integrates eye tracking to indicate objects of interest. Prouzeau et al. [72] defined a technical framework for routing visual links in 3D space, optimising layouts for the viewpoints of one or more users.

Recent results from multiple studies that allow users of immersive visualisation systems to create visualisations freely have reported that people tend to position visuals in a circle at arm's length around them. For instance, Batch et al. [6] conducted a design study with field experts and found that without the constraints and organisation frameworks which have been used in conventional 2D GUI

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

tools, participants cannot use the available space of analysis environment to its full potential. Lee et al. [54] proposed and evaluated personal high-resolution views in a flexible shared visualisation space. They found that participants preferred pinning 2D views on walls while placing 3D views egocentrically in the space around them. Satriadi et al. [78] also found that participants tended to prefer and arrange multiview maps in a spherical cap layout around them and that they often rearranged the views during tasks. While the studies above all featured purely virtual environments, similar view management concepts apply in physical environments using AR. Luo et al. [61] and their follow-up study [60] investigated the effect of office environments and work styles during a document classification task using AR with regard to content placement. They found that participants tended to use vertical surfaces as well as physical furniture as reference frames to place virtual contents.

Moreover, most data visualisation systems in immersive 3D spaces have defaulted to static placement of visualisations centred at eye-level in absolute room coordinates, such as small multiples visualisation [58], geo-spatial globes and maps [66, 79], and space-time cubes [95]. Hayatpur et al. [39] designed a novel visualisation system that enables users to lay out their data analysis steps in a virtual environment. They found that a horizontal layout is useful among a small number of views, while the vertical layout is most useful when looking at views separately. However, immersive and tracking technologies have enabled more interactive spaces or zones, such as floor-referenced displays and body-referenced displays, which are underexplored.

Several design spaces or frameworks related to spatial view arrangement have previously been developed for immersive environments. For example, Liu et al. [58] proposed a design space for displaying and interacting with immersive small multiples visualisation views. Ens et al. [20] introduced Ethereal Planes, a design framework that facilitates the classification and comparison of designs that use 2D information spaces in 3D immersive environments. Regarding interaction with information visualisations, Lee et al. [55] discussed design considerations that encompass existing interaction techniques and capture newly available interfaces and techniques. Jakobsen et al. [43] presented a design space organised from key characteristics of proxemics and information visualisation. In contrast to these, our proposed design space specifically addresses visualisation view management for 3D surfaces and spaces by systematically reviewing and categorising existing design examples and proposing newly possible designs.

3 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 paper 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 3). The dimensional organisation also helps understand existing designs by grouping and categorising them (discussed in Section 4). By contrasting and comparing these, designers gain insights into general patterns and identify gaps in the framework where designs do not yet exist (evaluated in Section 5). 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 contexts or through experimentation, by altering one or more dimensions and then imagining the resulting implications (explored in Section 6).

3.1 Approach

We develop our design space using methodology formalised in Zwicky's General Morphological Analysis [75] and which has been applied to HMD interface design by Robinett [76], as well as immersive information space design by Ens [20]. 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 [20]:

- 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.

3.2 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., [20, 32, 40, 53, 58, 91]). 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 2. 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.

3.3 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 [60, 78, 79] (visualisation view is relative to users) or an exocentric perspective (visualisation view is relative to an external *Frame of Reference*). Ens et al. [20] also use this term to define the relative viewpoint between the observer and the environment.

Proximity – This describes the distance relationship between people and visualisation user interfaces. We adapt and borrow a set of proxemic regions defined by Hall [33] and neuropsychologists [19, 41], and used by Ens et al. [20]: far [39] (extrapersonal space far from users and outside their arm's reach), near (peripersonal space surrounding users within arm's reach), onbody [27, 34, 91] (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 [39, 58, 73], while free-movable views may increase the effectiveness of comparison tasks, since users could bring views close to each other [15, 54, 60, 66]. 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 [8, 22], 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.

3.4 View Presentation — Frame of Reference

In this paper, 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 paper 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 [8]), 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) [58, 66, 78] 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 [49, 95]. It can also be vertical, such as presenting visualisation views on the furniture and traditional wall displays [47, 58, 73]. The uncommon spherical orientation refers to the emerging findings from recent user studies [78], 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 [14, 79]. On the other hand, fixed *Frames of Reference* are the common default, i.e., views fixed relative to a world-fixed reference point.

3.5 User Interaction — Interaction Style

Degree of Intent – This denotes the intent of the interaction. We borrow the dimension from related work [3, 45, 55, 81], where the explicit interaction is defined as an action that is initiated by user [55] and aimed primarily at interacting with a computer system [3, 81]. On the contrary, implicit interaction is described as user actions that are not primarily aimed at interacting with a computer system [45, 81]. 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 [14, 66, 78]. 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 [5, 32].

Proxemics – In general, proxemics refer to the study of space and how we use it. In the HCI field, Greenberg et al. [32] defined five categories of proxemics for ubiquitous interaction: distance, orientation, movement, identity, and location. We adapt these five

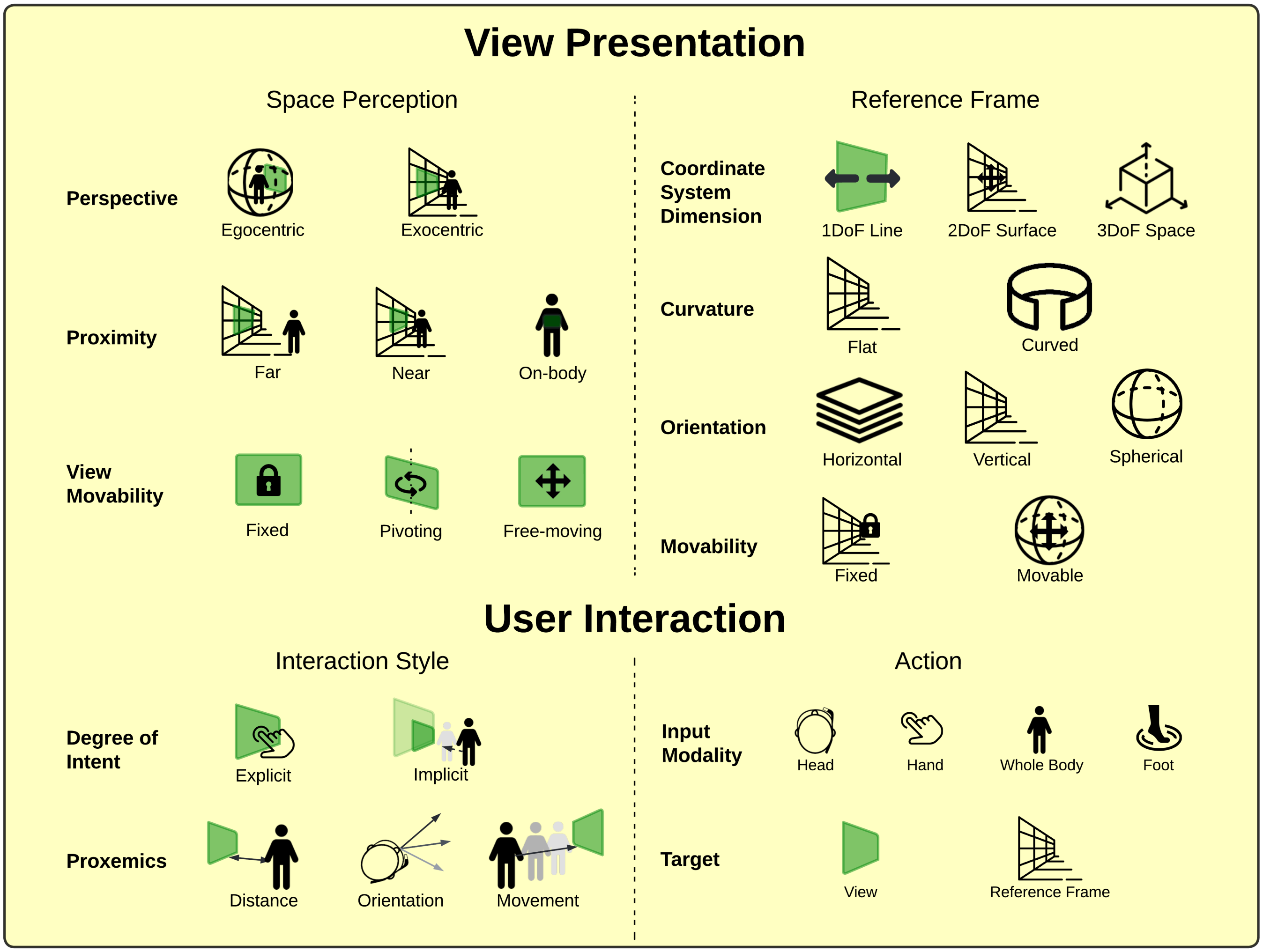


Figure 2: A design space illustration for visualisation view management for 3D surfaces and spaces. In this design space, we propose seven design dimensions in two categories for visualisation view presentation (top) and four design dimensions in two categories for user interactions with views (bottom).

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. [3], view scaling is controlled by the distance of the user from the display. Jakobsen et al. [43] also illustrate a distance-based semantic zoom technique. Ghaemi et al. [29] 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. [3] mapped the orientation of the user's head with the panning tasks. Jakobsen et al. [43] 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. [3] proposed to use the movement of multiple users to merge or split views, while Jakobsen et al. [43] showed an example of changing a dynamic query slider by moving.

3.6 User Interaction — Action

Input Modality – The input modality dimension covers a wide range of interaction modalities available. These include the head, hand, whole body, and foot. 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 [85]. 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 [25, 88], command selection using foot gestures or direct selection [11, 80], and locomotion interfaces [38, 83, 90]. However, Pakkanen and Raisamo [68] 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.

Other input modalities, such as the eye (gaze) and mouth (voice), are also commonly used in AR applications. Eye or gaze interaction exploits gaze input or eye tracking. the eye as an input modality provides fast but inaccurate responses [93]. Also, gaze input often relies on an awkward dwell-time approach [84]. Thus, eye input is often used within multi-modal input, for instance, eye and foot [37, 44, 48]. These input modalities are natural and promising but will not be further explored and evaluated within this work.

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.

4 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 3-Related Work), we distilled five categories of designs of display surfaces for visualisation view management (see Figure 3-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 [17, 23, 58], flat layout wall displays (see Figure 3-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 limits 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 [73], BodyLenses [47], DynamicNetwork [51], Immersive Small Multiples [58], Fiesta [52], VisualLinks [72], Immersive Space to Think [57], and Dynamic Network Plaid [51].

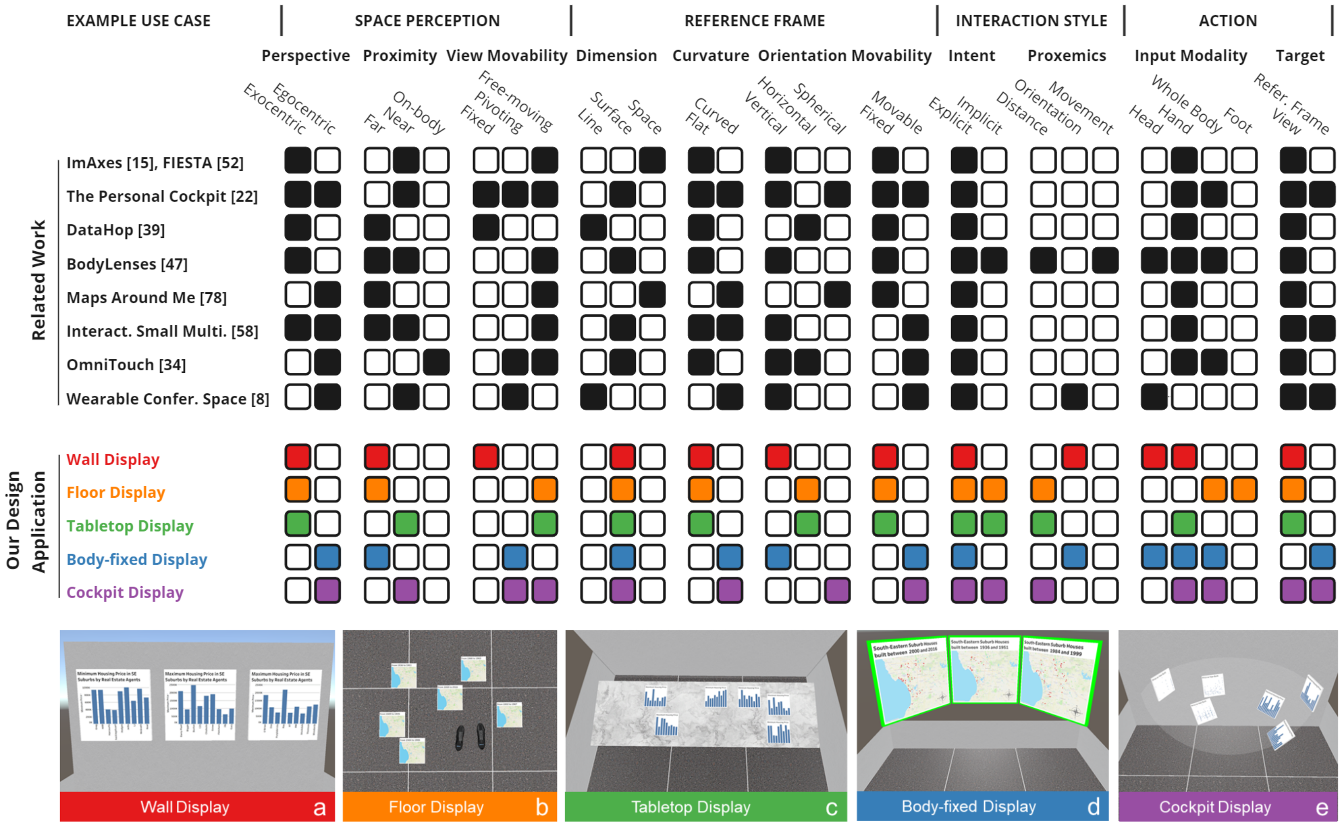
🟧 ***Floor Display*** – Floor-based interactions have been widely explored in HCI research, which roughly consists of four groups: (1) projection based system such as Kickables [82], drone.io [11], and HMD Light [92]; (2) sensor only, foot-centric systems such as smart floor [67], Z-tiles [74], and SmartCarpet [30]; (3) underfoot displays or projections such as Multitoe [1]; and (4) floor-based signage using a glass surface with a capacitance system such as TapTiles [18]. 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 3-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 3-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 3-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 [95], immersive space-time cube analysis [26], and immersive heatmaps study [49].

🟦 ***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 [24], in-Situ Visual Analytics [21], 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 3-d).

🟪 ***Cockpit Display*** – This design category is inspired by the Personal Cockpit [22], where users have an arm-reachable panel to interact with (see Figure 3-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



	EXAMPLE USE CASE	SPACE PERCEPTION								REFERENCE FRAME										INTERACTION STYLE					ACTION					
		Perspective		Proximity			View Movability			Dimension			Curvature		Orientation			Movability		Intent		Proxemics			Input Modality				Target	
		Exocentric	Egocentric	Far	Near	On-body	Fixed	Pivoting	Free-moving	Line	Surface	Space	Flat	Curved	Vertical	Horizontal	Spherical	Fixed	Movable	Explicit	Implicit	Distance	Orientation	Movement	Head	Hand	Whole Body	Foot	View	Refer. Frame
Related Work	ImAxes [15], FIESTA [52]	■	□	□	■	□	□	□	■	□	□	■	■	□	■	□	□	■	□	■	□	□	□	□	□	■	□	□	■	□
	The Personal Cockpit [22]	■	■	□	■	□	■	■	■	□	■	□	■	■	■	□	■	■	■	■	□	□	□	□	□	■	■	□	■	■
	DataHop [39]	■	□	■	□	□	■	□	□	■	□	□	■	□	□	■	□	■	□	■	□	□	□	□	□	■	□	□	■	□
	BodyLenses [47]	■	□	■	■	□	□	□	■	□	■	□	■	□	■	□	□	■	□	■	■	■	□	■	■	■	■	□	■	□
	Maps Around Me [78]	□	■	■	□	□	□	□	■	□	□	■	□	■	□	□	■	■	□	■	□	□	□	□	□	■	□	□	■	□
	Interact. Small Multi. [58]	■	■	■	■	□	□	□	■	□	■	□	■	■	■	□	□	□	■	■	□	□	□	□	□	■	□	□	■	■
	OmniTouch [34]	□	■	□	□	■	□	■	■	□	■	□	■	□	■	■	□	□	■	■	□	□	□	□	□	■	■	□	■	□
	Wearable Confer. Space [8]	□	■	□	■	□	□	■	□	■	□	□	□	■	■	□	□	□	■	■	□	□	■	□	■	□	□	□	■	■
Our Design Application	**Wall Display**	🟥	□	🟥	□	□	🟥	□	□	□	🟥	□	🟥	□	🟥	□	□	🟥	□	🟥	□	□	🟥	□	🟥	🟥	□	□	🟥	□
	Floor Display	🟧	□	🟧	□	□	□	□	🟧	□	🟧	□	🟧	□	□	🟧	□	🟧	□	🟧	🟧	🟧	□	□	□	□	🟧	🟧	🟧	□
	Tabletop Display	🟩	□	□	🟩	□	□	□	🟩	□	🟩	□	🟩	□	□	🟩	□	🟩	□	🟩	🟩	🟩	□	□	□	🟩	□	□	🟩	□
	Body-fixed Display	□	🟦	🟦	□	□	□	🟦	□	□	🟦	□	□	🟦	🟦	□	□	□	🟦	🟦	□	□	🟦	□	🟦	🟦	🟦	□	□	🟦
	Cockpit Display	□	🟪	□	🟪	□	□	🟪	🟪	□	🟪	□	□	🟪	□	□	🟪	□	🟪	🟪	🟪	🟪	□	□	□	🟪	🟪	□	🟪	🟪

Figure 3: 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)

studies on visualisation view management have also found that participants tend to position views in an egocentric wraparound layout [60, 66, 78] 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.

4.1 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 [25, 37, 80, 88, 90], via various sensors (e.g., pressure sensors) [46, 63, 77, 94], and external devices [44, 48]. 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 between 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.

5 USER STUDY

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 4. 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.

5.1 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 [65, Chapter 12] for multiple shared encoding views and the example of a multi-view overview-detail visualisation tool designed by Craig and Kennedy [16], we consider two fixed 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 [65, 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 5). *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 5).

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 5). 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 4-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 4-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 4-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 4-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 5). 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 5). Participants can also grab and rearrange the views using their hands or feet. While rearranging, the views will have a yellow border (see Figure 5).

Foot interactions are implemented via two external devices (see Figure 4-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 4-e); a yellow circle means the pressure meets the threshold of being able to move the touched visualisation view (see Figure 4-f); and a blue circle means the pressure meets the threshold of being able to select the touched visualisation view (see Figure 4-g). The threshold for selection is bigger than that of the pressure applied when walking, which is to say that moving is easier with lighter strength than selection.

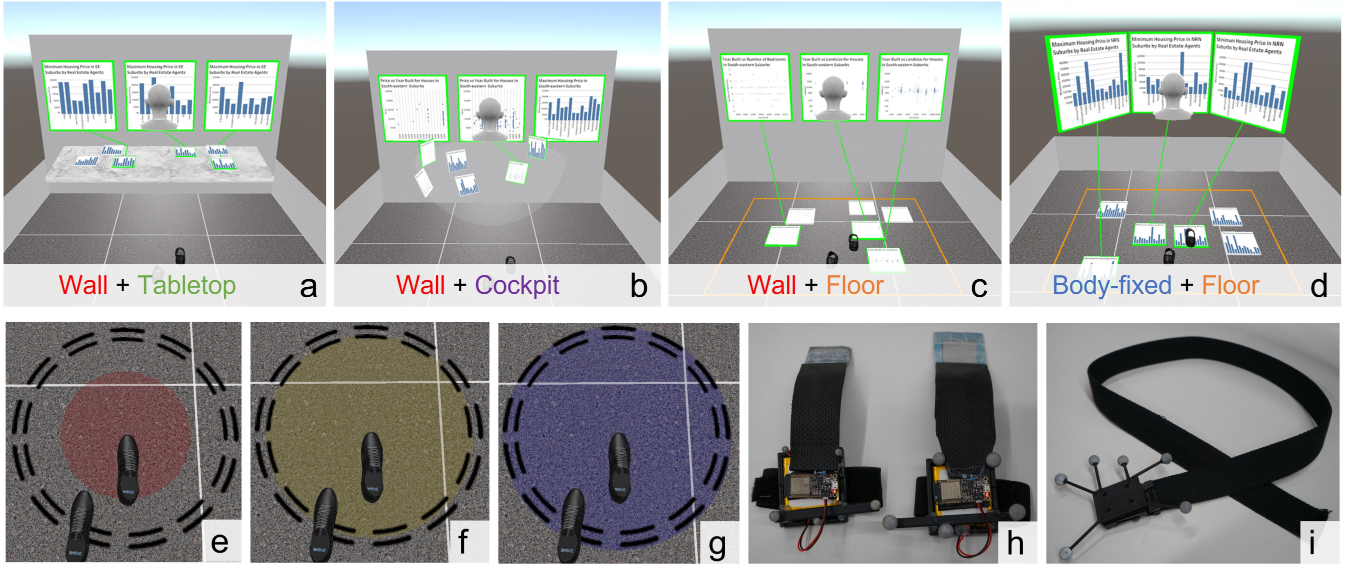


Figure 4: The top figures show the four prototypes that were explored and evaluated in our qualitative study: (a) 🟩 *Tabletop Display* + 🟥 *Wall Display* , (b) 🟪 *Cockpit Display* + 🟥 *Wall Display* , (c) 🟧 *Floor Display* + 🟥 *Wall Display* , and (d) 🟧 *Floor Display* + 🟦 *Body-fixed Display* . The 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.

This design allows participants to select views easily and reduce the chance of an accidental tap caused by normal locomotion.

After a pilot study, we choose to have six views in the *Landmarks* area and three 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*.

5.2 Task

We use a housing auction dataset collected from the *[removed for anonymity]* 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 the 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.

5.3 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 them 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[2] 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 4-i).

A pair of custom devices were fabricated in order to sense foot pressure and track the position of the feet (see Figure 4-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 (see Figure 1-d).

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 [9] for interactive components. The source code is publicly available[3] and may be downloaded via GitHub.

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.

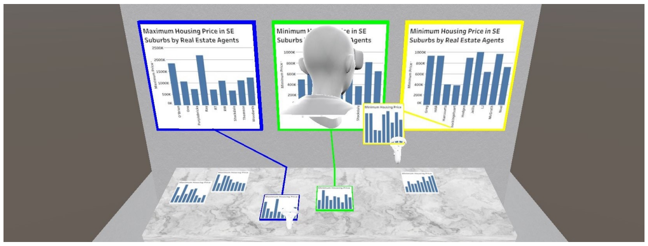


Figure 5: A participant is working on the question to find the extreme values from multiple views. The blue-border view means the view is pinned, the green-border view means the view is highlighted by proxemics, and the yellow-border view means the view is being moved by the participants.

5.4 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 performed a series of training scenes to gain familiarity with the four 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 [35] in a 7-point Likert scale, (3) ten questions adapted from the System Usability Scale [10] 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 × 4 prototypes × 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.

5.5 Results

Quantitative Results – We did not find a significant difference 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 6-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 posthoc test using Mann-Whitney tests with Bonferroni correction only shows the significant differences between prototype 🟥 *Wall Display* + 🟩 *Tabletop Display* and 🟧 *Floor Display* + 🟥 *Wall Display* ($p = .013$,

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

[3] DataDancing code online repository: https://github.com/JiazhouLiu/DataDancing

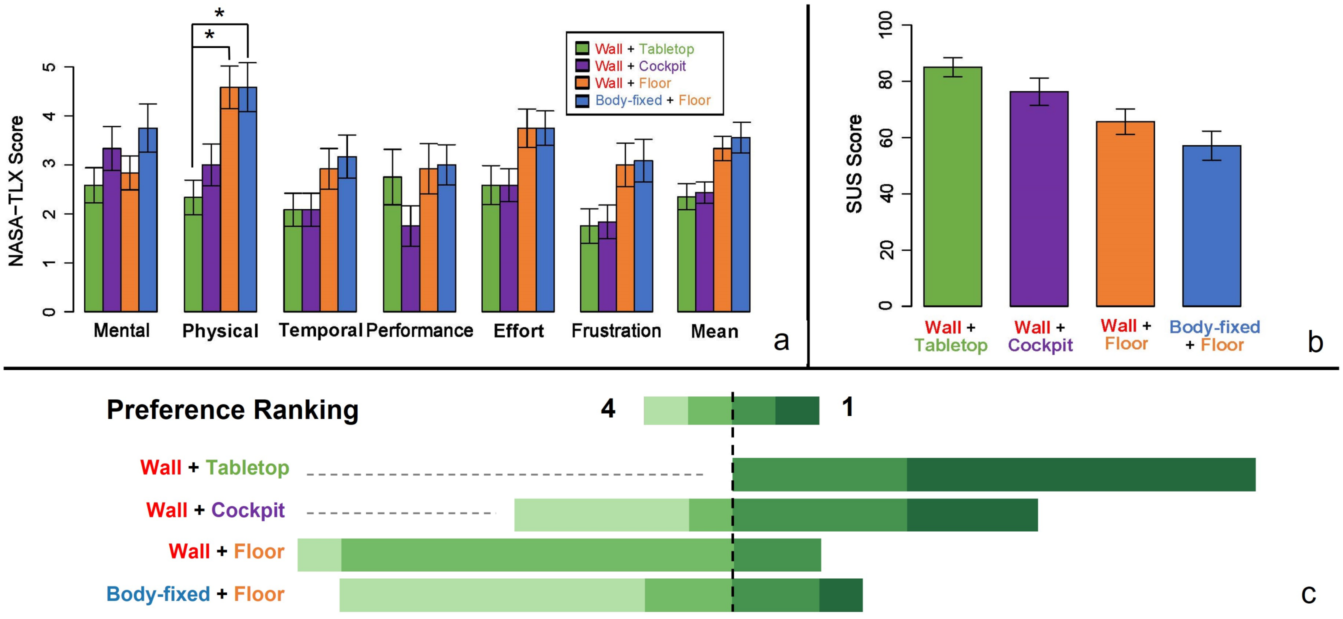

Figure 6: Each participant's responses on the (a) NASA-TLX evaluation and (b) SUS evaluation on each prototype, and (c) preference for each prototype. In the NASA-TLX, performance was rated in reverse order (lower is better). Error bars denote standard error. Asterisks in this figure represent the level of significance: * means $p < 0.05$.

r = .63) and between prototype 🟥 *Wall Display* + 🟩 *Tabletop Display* and 🟧 *Floor Display* + 🟦 *Body-fixed Display* (p = .026, r = .59) for the physical demand.

Figure 6-b shows the raw SUS score assessed by all participants for each prototype condition. According to Lewis and Sauro [56], 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 6-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.

5.6 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 6-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 6 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. [54] 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 6. 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. [58] 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 [10] 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., [68]. However, our qualitative results lead us to agree with the investigation by Klamka et al. [48] 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 [36, 48].

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*".

6 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. As illustrated in our supplemental video, 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.

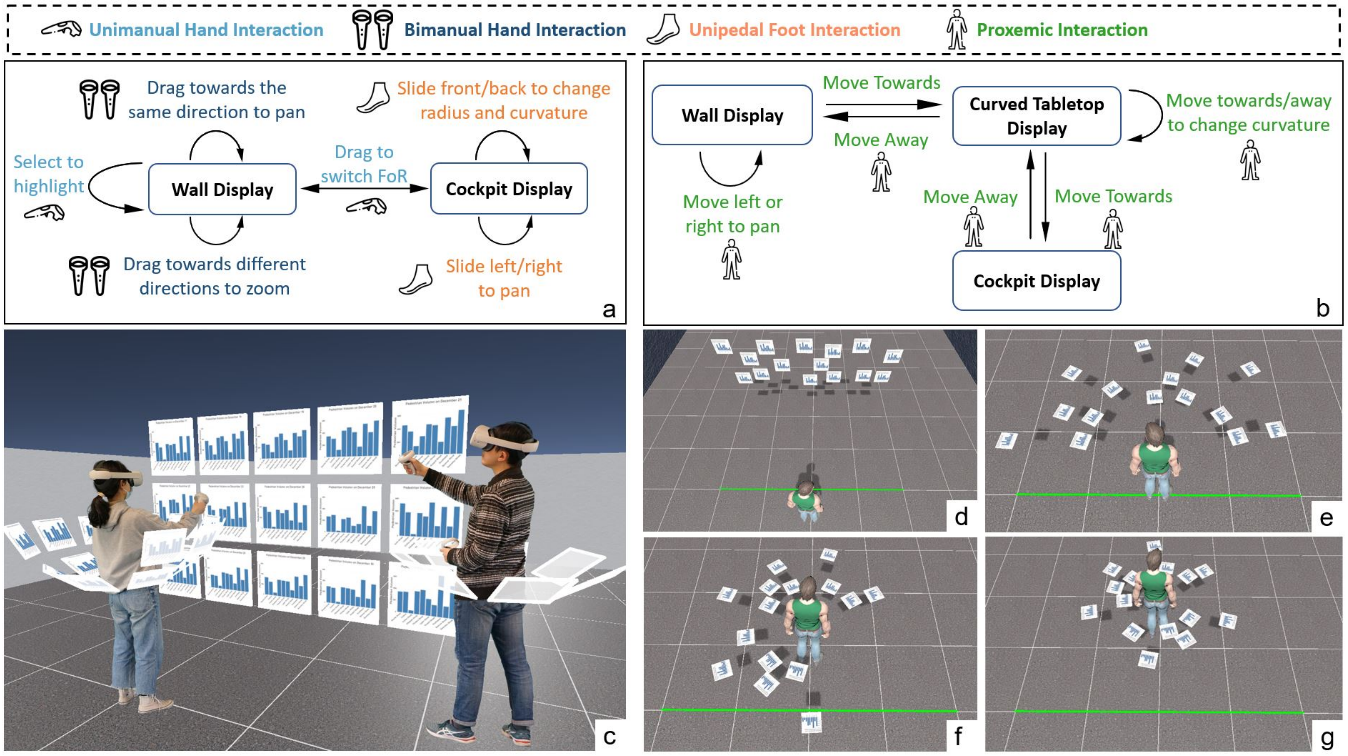

Figure 7: The top two figures show the state model of the hybrid interfaces: (a) multi-modal interaction and (b) proxemic interaction. The bottom figures illustrate example scenarios for each of the hybrid interfaces: (c) a collaboration scenario with a public wall display and a private cockpit display for each user; (d)-(g) using proxemics to interact with visualisation views by changing their reference frames and the geometry.

6.1 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 ego-centric 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-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. [48] also suggested that foot input is better for supporting secondary navigation tasks, such as zooming and panning. Moreover, considering the deficient visibility of 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 [54, 58]. 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 Liu et al. [58] 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. [88] and use sliding only, which was also the most natural interaction observed from 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-a.

6.2 Proxemic Interaction

We further explore proxemic interaction to interact with views and switch between different surfaces. Inspired by the related work [32, 73, 89], 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-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-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-b.

7 CONCLUSION AND FUTURE WORK

Our paper 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. We then conduct a user study that explores and evaluates the usability of four designed techniques. From the study results, we propose design implications on visualisation view management for 3D surfaces and spaces. Based on the implications, we implemented two hybrid prototype interfaces that demonstrate the use of our design space, focusing on the foot and proxemic interactions, respectively.

Besides, 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 comes 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 be 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 [48] 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 [88] 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.

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