A Design Space for Spatio-Data Coordination: Tangible Interaction Devices for Immersive Information Visualisation

Maxime Cordeil* Benjamin Bach† Yongchao Li‡ Elliott Wilson§ Tim Dwyer ¶
Monash University

ABSTRACT

We introduce the concept of "*spatio-data coordination*" (SD coordination) which defines the mapping of user actions in physical space into the space of data in a visualisation. SD coordination is intended to lower the user's cognitive load when exploring complex multi-dimensional data such as biomedical data, multiple data attributes vs time in a space-time-cube visualisation, or three-dimensional projections of three-or-higher-dimensional data sets. To inform the design of interaction devices to allow for SD coordination, we define a design space and demonstrate it with sketches and early prototypes of three exemplar devices for SD coordinated interaction.

1 INTRODUCTION

Numerous applications require three-dimensional spatial understanding and reasoning. In Scientific Visualisation applications where the data has intrinsic geometry—such as tumour or particle flow visualisation—the importance of true three-dimensional spatial representation is obvious. However, in the field of Information Visualisation where abstract data (*abstract* meaning without an intrinsic geometry) is also commonly considered, studies have demonstrated that spatial position is the most effective channel for mapping a quantitative data attribute to a visual representation [8]. It is common to visualise two different data attributes mapped to two spatial dimensions as in, for example, scatterplots [24], space-time-cubes [2, 19], and multi-dimensional scaling [28]. It is tempting to extend such a mapping to three different data attributes in three spatial dimensions, but 2D screens are problematic for accurately representing and interacting with 3D objects and spaces.

Virtual and Augmented Reality displays (V/AR) have recently reached a new level of maturity as consumer products with high-resolution displays and precise, low-latency head-motion tracking are available. These factors, together with the benefits of stereovision and kinestetic depth [25, 26] greatly improve human perception of 3D space and could fuel a new consideration of 3D data visualisations. Moreover, accurate head-tracking enables embodied navigation in a visualisation; allowing the viewer to walk around the data, switch from overview to detail and to "step-inside" the data. Mid-air interaction with accurately tracked hand-held controllers further allows users to point, select or otherwise interact in V/AR [37].

Thus, there is a compelling case to try to use these new immersive environments for abstract data visualisation such that three distinct data attributes are mapped to three spatial axes. It is a long held assumption that understanding of 3D abstract data visualisation can be enhanced by interacting with the visualization as if it were in the real environment [39]. It is our position in this paper that we need to take care in designing such immersive data visuals, to align the dimensions of the data with the affordances of the devices used to interact with them. We call this property *"Spatio-Data (SD) Coordination"*, which means a one-to-one mapping of positions, directions, and actions from the physical environment of the user to the virtual space of the data.

We hypothesise that *SD coordination* can help to bridge the gap between visual and physical space and make interaction with three-dimensional representations of data more immediate. Two-dimensional interaction devices (e.g. mice, touch-screens and pen input) have the appealing property that they offer precise control through movements constrained to a plane, and hence mapping directly to the display space, and in the case of a 2D data visual, directly to the 2D data space. We want to explore how such interaction—constrained to the space of the data—can be brought to 3D data and immersive environments. To achieve this, we systematically explore the design space for interaction devices that offer precise and intuitive interaction for three-dimensional data visualizations.

In this paper, we present a six-dimensional design space that informs the design of interactive devices for SD coordination. Our design space emerged through a three-part methodology: surveying existing literature, discussing potential designs, and crafting several prototypes for three novel interaction devices.

2 INTERACTION FOR 3D DATA VISUALISATIONS

Most tasks in visualisation require some sort of selection and navigation mechanism [1, 13, 41]. In 3D visualisations, this includes selecting values and ranges along each dimension, selecting specific elements in each combination of dimensions, defining cutting planes, selecting points and shapes in space, or magnifying the space through lenses [9]. For 3D visualizations of abstract spatio-temporal data, Bach *et al.* [2] describe abstract high-level *operations* for navigation and exploration. Their operations involve the definition of cutting planes, "drill-cores" and arbitrary 3D shapes. Some of these operations can be extended to general 3D visualisation.

Currently, there is a range of modalities available to perform interactions in 3D spaces, loosely classifiable into: mouse-based; surface+touch-based (e.g., [3, 18, 42]); midair-based (e.g., [4, 31]); and tangible user interfaces. Each technology is briefly presented in the following in the context of visualisation.

2.1 Mouse and Surface+Touch Interfaces

Yu et al [42] present a computer-aided way to select 3D point clouds on touch screens, based on point density within the user-drawn lasso. Lopez et al [23] discuss tablet-based navigation on stereoscopic display for scientific 3D visualisation such as structural biology. They present the t-box technique, a cubic widget designed to manipulate the visualisation (rotation by dragging the cube's faces, translation by dragging the cube's edges and scaling by pinching the cube). They also made use of the tablet's gyroscope to enable rotation of the 3D model from the tablet orientation.

2.2 Mid-Air Interfaces

There has been little research on mid-air interaction in the context of data visualisation. Laha and Bowman [21] proposed the *volume*

*e-mail:maxime.cordeil@monash.edu
†e-mail:benj.bach@gmail.com
‡e-mail:yli956@student.monash.edu
§e-mail:elliott.wilson@monash.edu
¶e-mail:tim.dwyer@monash.edu

cracker, a technique that uses a Leap Motion (a commercial vision-based hand-tracker) and allows—via mid-air interaction—the direct manipulation and separation of volumes in scientific visualisations. Miranda et al. [27] studied the use of gestures to support 3D scatterplot InfoVis tasks. They found three main categories of issues using mid-air gestures: the size of the tracking volume; ambiguity of the gestures; and ambiguities in depth perception while using a 2D screen.

A recent application paper presented a 3D scatterplot and coordinated views in virtual reality, using a head-mounted display and a Leap Motion controller [37]. Using mid-air interactions a user can scale and rotate the visualisation as well as select data points by defining volumes inside the visualisation.

2.3 Tangible User Interfaces

Tangible user interfaces (TUIs) use physical artifacts for interaction [11]. Studies have shown positive user feedback from directly touching physical models [17,36] and the immersiveness of a virtual environment can greatly benefit from any sort of tangible interface. Our goal is to investigate this direct mapping from interaction to the visualization for 3D abstract data visualisations.

TUIs for 3D visualisations have been designed to support navigation, selection, and menu interaction, as summarised by Jankowski et al. [15]. Some TUIs conceptually extend the mouse in that they allow for basic navigational input, e.g. camera rotation or menu selection [10,30,33,38,40]. ITU Research patented the TouchCube [40], a cube input device with touch-sensitive faces and edges. This device does not track absolute orientation in the user's hands. Rotations are performed with drag interactions on opposite faces. Similarly, Rubikon [32] implements interactions on a rotatable Rubix cube, including discrete rotation in 3D environments. Other cube-shaped devices have been used for navigation menus and setting state variables [30]. However, these devices do not support selection tasks, nor are they specifically designed for data visualisations.

A third class of devices emulates the virtual space in the user's physical space by mapping dimensions, positions and actions between both spaces. An early example of such a tangible user interface for navigating 3D visualisations was presented by Hinckley et al. [14]. It consisted of a physical rubber band to define a cutting plane in the visualisation. Another such device is the CubicMouse [12] allowing for selection inside a 3D volume through movable rods and buttons mounted to the device. Kruszynski and Liere [20] 3D printed a coral model and attached sensors to enable pointing on the model. The orientation of the 3D printed model was tracked and synchronised with a higher resolution visualisation of the model displayed on a 3D stereo monitor. PaperLens [34] presents a hand-held cutting plane, movable in 3D space, onto which virtual imagery is projected. Finally, CAPTIVE [6] is an AR system consisting of a cube wireframe and a pointing device. While the wireframe is used to track rotation and absolute position of the visualisation, the pointing device is used to point to positions inside the wireframe.

3 Spatio-Data Coordination

We define Spatio-Data (SD) coordination as *"a mapping of interactions from a physical interaction-space into a digital visualisation-space "* (Figure 1). Similar to the infovis reference model [5,16], the components of SD coordination are as follows and illustrated in Figure 1:

Data space: contains the data in some sort of structured form, such as lists, tables, or graph structures.

Visualisation space: describes the visualisation or *abstract visual form* [16], i.e. the visual mapping from data to visual attributes. In the context of three-dimensional data visualizations, this visual mapping includes the assignment of three-dimensional positions and shapes to data objects (e.g. 3D graph layout, point positions in a scatterplot, traces in a space-time cube, etc.). Hence the name visualisation 'space'. Physically, the visualisation space is located in computer memory, imperceptible to the user.

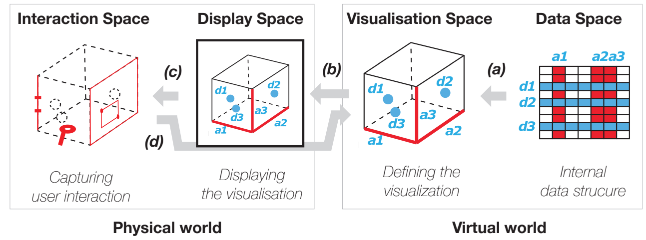


Figure 1: SD coordination between physical *interaction space*, and virtual *visualisation space*. A high-dimensional data space is mapped into a (lower) 3-dimensional visualisation space (a), which in turn is rendered onto some display (b) perceivable by the user (c). Attributes become dimensions, data elements points in this space. Interaction happens in interaction space and is mapped to the visualisation space (d). In the interaction space, a device like a slider can be aligned to a data axis for range selection on that axis, or a touch surface can be aligned with two data axes such that two touch points create a selection across two data axes. By contrast, a Vive controller interaction is typically not constrained to data dimensions.

Display space: In order to make the visualisation and corresponding state changes visible to the user, the visualisation space must be rendered into the physical world of the user, creating a *physical presentation* [16]; this rendering can happen on two-dimensional computer screens, stereo-screens, CAVE systems, or head-mounted virtual and augmented reality displays. We call the physical rendering medium the display space, situated in the user's physical environment.

Interaction space: a bounded part of the user's physical environment, such as a part of her desktop or her entire office; as long as the space lies entirely within the user's reach.

Interaction: is any purposeful action performed by a user in the interaction space and which aims to change the state of the visualisation, creating, for example, a selection or a navigation action. Every interaction is replicated into the visualisation and state changes are made visible in the display space.

For example, consider a visualization of a multi-dimensional scaling in three dimensions. The *data-space* may contain hundreds of dimensions associated with the individual data points. Through multi-dimensional scaling, the number of dimensions associated to each data point gets reduced to three. These three dimensions are then mapped to three orthogonal spatial dimensions in the visulisation space (x,y,z). Eventually, this three-dimensional euclidean space is rendered, e.g. into a VR environment using an HMD.

In order to allow for spatio-interaction, we assume the interaction space has the following three characteristics:

i) It has to be of **euclidean** nature and occupy a well-defined, bounded part of the user's physical environment.

ii) The mapping between interaction and visualisation space has to be **orientation-congruent**, i.e. it has to preserve the space's orientation. For example, any position or movement towards the right of the user in the interaction space results in a movement to the right of the user in the visualisation space. The same holds true for all spatial dimensions (up-down/top-bottom, right-left, and towards-away from the user). Devices that allow for altering the orientation of the interaction space relative to the visualisation space (e.g., [10]), are not included in our design space.

iii) Finally, we assume a "**computer-in-the-loop**", i.e. a computer that processes input and generates an output in the form of a visualisation. Data physicalisations without a computer (e.g. [35]) are not included in our design space.

SD coordinated interaction devices are any devices and systems

Design Space Dimensions

Device	4.1	4.2	4.3	4.4	4.5	4.6
Dynamic Barcharts [36]	Ds	P	UM	TI	PD	D
3D printed Coral [20]	Hn	P	SM	*None*	PD+SH	D+I
Cubic Mouse [12]	Hn	P	SM	TI	SC	I
Paper Lens [34]	Hm	P	MC	*None*	2D	D
CAPTIVE [6]	Hn	P	SM	*None*	2D	I
CubicMouse [12]	Hn	P	SM	SM	TI,TC	I
NaturalMotion [7]	Ds	NP	SM	SG	2D	I
Touch-sensitive Cube	Hn	P	SM	SG	*All*	D+I
Physical Axes	Ds	P+N	RC	TC	SH	D
Virtual Mid-air	Hm	N	UM	TC	SH	D

Table 1: Design space coverage of related work and our prototypes. Column headers refer to dimensions in Section 4.

that use such a direct mapping between interaction and visualisation space and that satisfy the three conditions above. We believe that designing interaction systems for SD coordination decreases a user's cognitive load when exploring the data. Ideally, display and interaction would hence be "the same" in the user's physical environment, i.e. the user interacts with the visualisation where the visualisation is perceptually situated.

In the next section we propose a design space to inform the design of novel SD coordinated interaction devices for 3D visualisations.

4 Design Space for Spatio-Data Coordinated Interaction Devices

SD coordinated interaction devices include a wide range of device types and modalities; mid-air interaction, physical interactive cubes [12], and physical cutting planes [34]. Specific design choices are independent of any particular technology (future development of which may be hard to predict) but rather, depend on the context of interaction; i.e., the character of the data (e.g. dense/sparse, large/small, static/dynamic [2]), the type of interaction that is required (e.g. selection, navigation, view changes), type of visualisation (e.g. bar chart, space-time cube, 3D-fluid simulation) and the specific physical setup (e.g. laboratory, public space, desktop).

The first two dimensions, *size* and *physicality*, refer to physical properties of the interaction space. The next three dimensions *selection, navigation*, and *menu interaction* describe choices enabling particular types of interaction, and the last two dimensions *data display* and *input-output mapping* describe the nature of the view space and its relation to the interaction space. Together, these dimensions inform our designs in Section 5. Table 1 classifies the interaction devices and techniques cited in our related work according to our proposed design space for SD coordinated devices.

4.1 Interaction Space Size

We describe the size of the interaction space relative to the human body. We also consider the degree of physical effort, e.g. amount of body movement to interact with the controller.

Hand-size (Hn) devices comfortably fit into one hand or may require additional support from the other hand for better comfort (e.g. [6, 12]). Hn spaces do not necessarily require more than finger and hand movements to be usable.

Desktop-size (Ds) interaction spaces exceed hand-size and, if physical, may require some solid support; they may comfortably fit on a desktop or a table in a meeting room with observers sitting around (e.g., [6, 10]). Ds spaces require arm-movement during usage, but the person can stand or sit comfortably close to the interaction space.

Human-size (Hm) spaces extend to the space around the user and permit full body-movement, including relocation and stretching. Unlike hand and desktop-size, Hm spaces allow the user to "step-inside" the data space and relocate herself within the data space.

Future technology may permit additional extremes, e.g. millimetre-wave radar [22] could offer minute **finger-size** gestures while wireless AR would offer **world-size** interaction. The size of the interaction space may have implications on the precision of interaction and the number of elements that can be handled; larger spaces support easier selection of individual elements (slices, points). Smaller spaces require less movement and effort from the user.

4.2 Degree of Interaction Space Physicality

The components of the transferred visualisation into the user's space can be supported by physical structures for reference or interaction. The degree of physicality describes *how much* of the visualisation space is represented by physical structures in the user's environment.

Non-physical(N) components of the visualisation space (e.g. axes, data points) are not represented through any physical object in the real world that can be used for interaction.

Physical (P) components of the visualisation space are represented through some physical object in the real world that can be used for interaction. For example, touch sensitive surfaces on a 3D barchart.

Physical structures can guide a user's movement by constraining it (e.g. to a line or a plane), or provide haptic feedback. Physical structures can also allow the user to move and rotate the entire visualisation space.

4.3 Navigation Support

Navigation changes the viewer's viewpoint relative to the interaction space, through rotation, pan (translation) and zoom (scaling).

No/limited control (NC) the viewer has no means to change their perspective of the visualisation space.

User motion (UM) describes viewpoint changes through body movement of the viewer. The viewer can walk around the visualisation space in virtual or augmented reality, approach and step-back.

Space motion (SM) describes designs where the interaction space's rotation and translation are transferred to the virtual space. Technically, device motion can be implemented through gyro or acceleration sensors [6].

Restricted control (RC) rotation around the vertical axis is sufficient to reach every part in the design space, for example if a physical interactive device is mounted on a rotatable support.

Mixed control (MC) covers designs that enable both user motion and complete or restricted device motion.

4.4 Support for Menu-Interaction

Selection and navigation interactions target the interaction space itself. However, most visualisation systems require further functionality: e.g. triggering a selection, filtering, or changing a visual mapping. Such functionality is not referenced in the interaction space and must be accessible through additional commands or controllers. The respective interaction modalities can vary a lot, including **touch interaction (TI)** on physical structures, **tangible controllers (TC)** [12, 36], **specific gestures (SG)**.

4.5 Display Space

Technically, the interaction space can be independent from the visualisation space and the way data is displayed to the user. Solutions include:

2D-interfaces (2D) can be designed for 3D data, showing, e.g. projections and sub-parts in parallel. 2D-interfaces or 3D data also include small-multiples and animation techniques [2].

2D-projections (2Dp) render the 3D data on a 2D screen using perspective or orthogonal projections.

On-screen stereo (OS) render the 3D data on a 2D screen using perspective or orthogonal projections.

Cubic displays (CD) render the data on six 2D-displays, one for each cube face, and which are arranged to resemble a cube. This could be actual 3D cubes with active displays or passive projections.

Physical displays (PD) the display is tangible, including shape-changing displays that can extrude into 3D physical space.

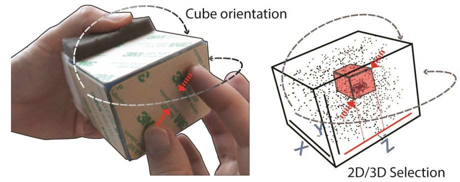
Stereoscopy/Holography (SH) captures designs where the visualisation space is rendered in 3D; stereoscopic display techniques (specific stereo screens, HMD) in Virtual/Augmented Reality.

4.6 Mapping Interaction Space to Display Space

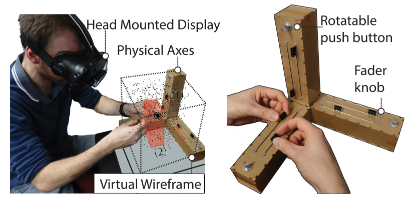
This dimension describes the spatial relation between interaction space and display space.
Direct (D): Interaction space and visualisation space appear to be located at the same spot, i.e., the effect of an interaction is displayed at the physical location where the interaction happens (e.g., [6, 34]). For example, in a virtual environment with mid-air interaction, highlighting a data point by moving one's finger to the perceived position in physical space is considered a direct interaction. Similarly, touching a data point in a physical data model is direct interaction.
Indirect (I): Interaction space and visualisation space are offset (e.g., [12, 14]). In the following section, we will use this design space to generate new interaction devices.

5 Design Examples and Implications

Our design space is both descriptive and generative. It is descriptive in that we can describe existing devices, and it is generative in that it allows us to create novel interaction devices by combining values from each dimension. For example, a three-dimensional scatterplot visualisation describes a cube-shaped visualisation space, which can be decomposed into three visualisation components: edges, cube faces, and interior volume with data points. We now discuss three designs for SD coordinated interaction devices for this cube visualisation space and describe prototypes we crafted for each of them such that each device represents a distinct point within our design space (as described in Table 1).
Touch-sensitive Cube: a hand-sized tangible cube with rigid faces and edges (Figure 2(a)). Touch sensitive faces and edges allow for selecting values on either, in a constrained and eyes-free manner. Interactions with one cube face allows 2D gestures to define a selection volume that passes through the entire data volume: e.g., a "pinch" gesture would create a selection volume with rectangular cross-section. Alternatively, the user might "draw" an arbitrary cross-section for the volume. Multiple 2D face selection can define a selection volume bounded in all three spatial dimensions. The cube is equipped with a gyroscope and accelerometer, tracking movement and rotation to enable navigation of the visualisation, e.g. moving it relative to the user's viewpoint. Thus, the affordances of this design allow users to rotate and manipulate the visualisation space in their hands in an ecologically correct way [29]. Proprioception enables users to quickly navigate and access the faces and edges, without necessarily needing to look at the cube model in their hands.
Physical Axes: maps data axes to three physical range selection controls mounted orthogonally to one another (Figure 2(b)). Thus, the *Physical Axes* is a physical representation of the three axes of the Euclidian data space that allows interaction with the axes themselves but also enables users to reach inside the cube volume with their hand. A hologram of the visualisation is rendered within the *Physical Axes* using a virtual reality head-mounted display (e.g. HTC Vive) or a mixed reality head-mounted display (e.g. Microsoft Hololens). This creates a direct mapping of the interaction in the display space. To support reaching inside the cube and potentially selecting and pointing to data objects, the device is desktop size. A user's hand position is tracked through a Leap motion controller and clicks as well as menu interaction are triggered through buttons attached to the axes. As axes are solid physical objects, they carry physical sliding knobs (Figure 2(b)) allowing for precise value and range selection in each dimension, and also allow for volume selection.
Virtual Mid-air: Operated by unconstrained mid-air gestures (Figure 2(c)), with visualisation displayed in complete virtual reality (HTC Vive). Without any physical model of the data space, the interaction space can be human-sized, allowing for interaction with



(a) Touch-sensitive cube



(b) Physical Axes design

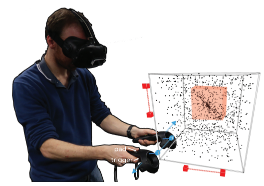

(c) Virtual mid-air design

Figure 2: Three designs for SD coordinated interaction.

data that requires higher spatial resolution or authentic scales such as a human body.

Our three designs mark three specific points in our design space and each can undergo individual adaptations within each design dimension. Building these prototypes helped us to discuss and adjust our design space. Futhermore, none of these designs dictate the nature and technology of the display space or the mapping between interaction and display space. Different parts of the visualisation space can be made physical depending on the material and specific setups. Collaboration may benefit from larger interaction spaces and direct mapping.

6 Discussion

In this paper, we introduced the concept of *Spatio-Data Coordination* and provided a six-dimensional design space to inform the design of interaction devices exploiting this concept. We explored and evolved our SD coordination design space by prototyping three possible interaction devices. We hypothesise that SD coordinated interaction and the devices it inspires will reduce the mental load of users by encoding the affordances of a visualisation into the user's physical space. Eventually, we hope our design space will motivate evaluation of SD coordinated interaction devices by providing a first terminology and systematic separation of dimensions, suited to comparison in controlled user studies. Yet, while there may be differences across design choice within a dimension (e.g. hand-size vs. human-size), we expect interaction effects across dimensions. For example, a direct mapping between interaction and display space may work better with desktop and human sized interaction spaces, while hand-sized interaction spaces may require an indirect mapping and a large display space. A pilot study we conducted showed promising results. However, we have to address technical issues such as touch sensitivity on the cube. Our plan is to evaluate our three devices in a more controlled study to better understand their efficiency and usability issues such as cognitive load.

REFERENCES

[1] R. Amar, J. Eagan, and J. Stasko. Low-level components of analytic activity in information visualization. In *IEEE Symposium on Information Visualization, 2005. INFOVIS 2005.*, pages 111–117. IEEE, 2005.

[2] B. Bach, P. Dragicevic, D. Archambault, C. Hurter, and S. Carpendale. A descriptive framework for temporal data visualizations based on generalized space-time cubes. In *Computer Graphics Forum*. Wiley Online Library, 2016.

[3] H. Benko and S. Feiner. Balloon selection: A multi-finger technique for accurate low-fatigue 3d selection. In *2007 IEEE Symposium on 3D User Interfaces*. IEEE, 2007.

[4] R. Burgess, A. J. Falcão, T. Fernandes, R. A. Ribeiro, M. Gomes, A. Krone-Martins, and A. M. de Almeida. Selection of large-scale 3d point cloud data using gesture recognition. In *Doctoral Conference on Computing, Electrical and Industrial Systems*, pages 188–195. Springer, 2015.

[5] S. K. Card, J. D. Mackinlay, and B. Shneiderman. Readings in information visualization: using vision to think, 1999.

[6] A. Chakraborty, R. Gross, S. McIntee, K. W. Hong, J. Y. Lee, and R. St Amant. Captive: a cube with augmented physical tools. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1315–1320. ACM, 2014.

[7] S. Clarke, N. Dass, and D. H. P. Chau. Naturalmotion: Exploring gesture controls for visualizing time-evolving graphs. 2016.

[8] W. S. Cleveland and R. McGill. Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American statistical association*, 79(387):531–554, 1984.

[9] D. J. Cowperthwaite, M. S. T. Carpendale, and F. D. Fracchia. Visual access for 3D data. In *Proceedings on ACM CHI*, pages 175–176. ACM, 1996.

[10] J.-B. de la Rivière, C. Kervégant, E. Orvain, and N. Dittlo. Cubtile: a multi-touch cubic interface. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pages 69–72. ACM, 2008.

[11] G. W. Fitzmaurice, H. Ishii, and W. A. Buxton. Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 442–449. ACM Press/Addison-Wesley Publishing Co., 1995.

[12] B. Fröhlich and J. Plate. The cubic mouse: a new device for three-dimensional input. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 526–531. ACM, 2000.

[13] J. Heer and B. Shneiderman. Interactive dynamics for visual analysis. *Queue*, 10(2):30:30–30:55, Feb. 2012.

[14] K. Hinckley, R. Pausch, J. C. Goble, and N. F. Kassell. Passive real-world interface props for neurosurgical visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 452–458. ACM, 1994.

[15] J. Jankowski and M. Hachet. A survey of interaction techniques for interactive 3d environments. In *Eurographics 2013-STAR*, 2013.

[16] Y. Jansen and P. Dragicevic. An interaction model for visualizations beyond the desktop. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2396–2405, 2013.

[17] Y. Jansen, P. Dragicevic, and J.-D. Fekete. Evaluating the efficiency of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2593–2602. ACM, 2013.

[18] T. Klein, F. Guéniat, L. Pastur, F. Vernier, and T. Isenberg. A design study of direct-touch interaction for exploratory 3d scientific visualization. In *Computer Graphics Forum*, volume 31, pages 1225–1234. Wiley Online Library, 2012.

[19] M. J. Kraak. The Space-Time Cube revisited from a Geovisualization Perspective. *Proceedings of the International Cartographic Conference*, pages 1988–1996, 2003.

[20] K. J. Kruszyński and R. van Liere. Tangible props for scientific visualization: concept, requirements, application. *Virtual reality*, 13(4):235–244, 2009.

[21] B. Laha and D. A. Bowman. Design of the bare-hand volume cracker for analysis of raw volumetric data.

[22] J. Lien, N. Gillian, M. E. Karagozler, P. Amihood, C. Schwesig, E. Olson, H. Raja, and I. Poupyrev. Soli: Ubiquitous gesture sensing with millimeter wave radar. *ACM Trans. Graph.*, 35(4):142:1–142:19, 2016.

[23] D. Lopez, L. Oehlberg, C. Doger, and T. Isenberg. Towards An Understanding of Mobile Touch Navigation in a Stereoscopic Viewing Environment for 3d Data Exploration. *IEEE Transactions on Visualization and Computer Graphics*, 22(5):1616–1629, May 2016.

[24] MATLAB. *version 7.10.0 (R2010a)*. The MathWorks Inc., Natick, Massachusetts, 2010.

[25] J. P. McIntire, P. R. Havig, and E. E. Geiselman. Stereoscopic 3d displays and human performance: A comprehensive review. *Displays*, 35(1):18–26, 2014.

[26] J. P. McIntire and K. K. Liggett. The (possible) utility of stereoscopic 3d displays for information visualization: The good, the bad, and the ugly. In *3DVis (3DVis), 2014 IEEE VIS International Workshop on*, pages 1–9. IEEE, 2014.

[27] B. P. Miranda, N. J. S. Carneiro, C. G. R. dos Santos, A. A. de Freitas, J. Magalhães, B. S. Meiguins, et al. Categorizing issues in mid-air infovis interaction. In *Information Visualisation (IV), 2016 20th International Conference*, pages 242–246. IEEE, 2016.

[28] R. Pless. Image spaces and video trajectories: Using isomap to explore video sequences. In *ICCV*, volume 3, pages 1433–1440, 2003.

[29] J. Rasmussen and K. Vicente. Coping with human errors through system design: Implications for ecological interface design. *Int. J. Man-Mach. Stud.*, 31(5):517–534, Nov. 1989.

[30] J. Rekimoto and E. Sciammarella. Toolstone: effective use of the physical manipulation vocabularies of input devices. In *Proceedings of the 13th annual ACM symposium on User interface software and technology*, pages 109–117. ACM, 2000.

[31] G. Ren and E. O'Neill. 3d selection with freehand gesture. *Computers & Graphics*, 37(3):101–120, 2013.

[32] A. Roudaut, D. Martinez, A. Chohan, V.-S. Otrocol, R. Cobbe-Warburton, M. Steele, and I.-M. Patrichi. Rubikon: a highly reconfigurable device for advanced interaction. In *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems*, pages 1327–1332. ACM, 2014.

[33] B. Salem and H. Peeters. Intercube: A study into merging action and interaction spaces. In *IFIP Conference on Human-Computer Interaction*, pages 57–70. Springer, 2007.

[34] M. Spindler and R. Dachselt. Paperlens: advanced magic lens interaction above the tabletop. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, page 7. ACM, 2009.

[35] S. Stusak, A. Tabard, and A. Butz. Can physical visualizations support analytical tasks. *Posters of IEEE InfoVis*, 2013.

[36] F. Taher, J. Hardy, A. Karnik, C. Weichel, Y. Jansen, K. Hornbæk, and J. Alexander. Exploring interactions with physically dynamic bar charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 3237–3246. ACM, 2015.

[37] R. Theart, B. Loos, and T. Niesler. Virtual Reality Assisted Microscopy Data Visualization and Colocalization Analysis. In *Proc. of BioVis Workshop at IEEE VIS*, 2016.

[38] K. Van Laerhoven, N. Villar, A. Schmidt, G. Kortuem, and H. Gellersen. Using an autonomous cube for basic navigation and input. In *Proceedings of the 5th international conference on Multimodal interfaces*, pages 203–210. ACM, 2003.

[39] W. Willett, Y. Jansen, and P. Dragicevic. Embedded data representations. *IEEE Transactions on Visualization and Computer Graphics*, pages 1–1, 2017.

[40] T. Yasutake. Touch sensitive input control device, Mar. 17 1998. US Patent 5,729,249.

[41] J. S. Yi, Y. ah Kang, J. Stasko, and J. Jacko. Toward a deeper understanding of the role of interaction in information visualization. *IEEE transactions on visualization and computer graphics*, 13(6):1224–1231, 2007.

[42] L. Yu, K. Efstathiou, P. Isenberg, and T. Isenberg. Cast: Effective and efficient user interaction for context-aware selection in 3d particle clouds. *IEEE transactions on visualization and computer graphics*, 22(1):886–895, 2016.