A Design Space of Multi-Display Spatial Interactions for Visualization Tasks

Kaden V. Gryphon
kb0125@uah.edu
University of Alabama in Huntsville
Huntsvile, Alabama, USA

Veronica Vu
ptv0002@uah.edu
University of Alabama in Huntsville
Huntsvile, Alabama, USA

Haeyong Chung
hc0021@uah.edu
University of Alabama in Huntsville
Huntsvile, Alabama, USA

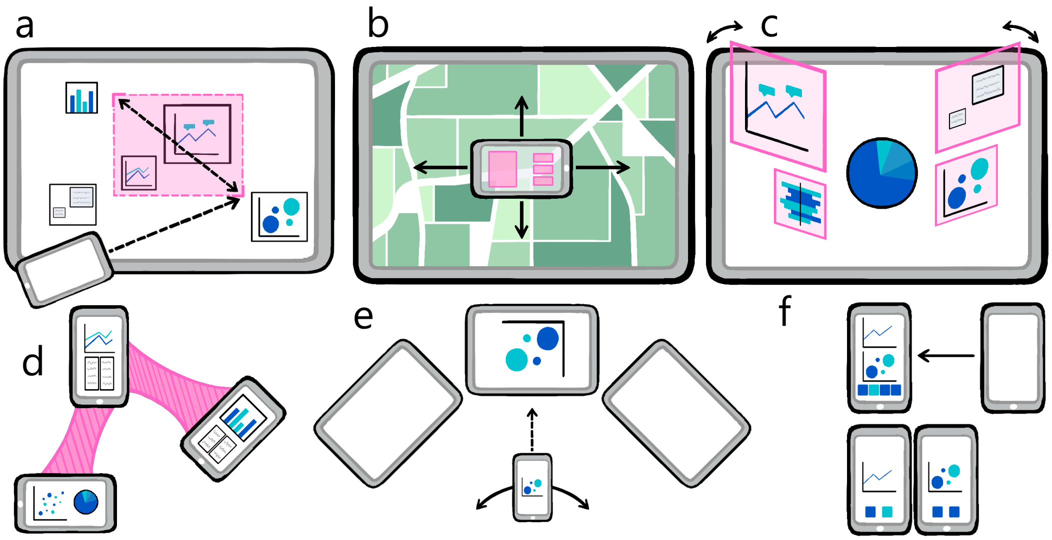

Figure 1: Examples of spatial interaction techniques using multiple displays to support different visualization tasks and the design choices for their Composition, Spatial Relationship, and Input dimensions. (a) Select: Using a mobile display as a pointer to select a group of visualizations: Mobile+Static, 6DoF, Range, (b) Navigate: Navigating an overview display with a detailed mobile display: Mobile+Static, 6DoF, Range, (c) Visualize: AR visualization that follows the user's position so they are always visible: AR, 6DoF, Synchronized, (d) Coordinate: AR links that connect displays containing related data together: AR, 6DoF, Synchronized, (e) Share: Picking a display to send a visualization to by pointing a mobile display at it: Mobile, Direction, State, (f) Organize: Putting mobile displays together offloads visualizations to the empty display: Mobile/Personal, 6DoF, Flag/Trigger.

ABSTRACT

This paper presents a design space of spatial interaction techniques for multi-display visualizations. By analyzing 56 papers on multi-display tools and techniques, we identify the three dimensions and their associated design choices for different types of spatial interactions using multiple displays and devices. This work aims to provide guidance for designing interactive multi-display visualizations that meet different requirements of visual analysis and sensemaking tasks while also inspiring future design ideas. Visualization researchers can create new multi-display visualizations by using combinations of the design choices associated with different visualization tasks. Our design space also allows them to explore areas of spatial interactions that have been underutilized to their full potential or to understand the requirements for new spatial interaction techniques for multi-display visualizations.

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CCS CONCEPTS

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; **Visualization design and evaluation methods**.

KEYWORDS

multiple displays, spatial interaction techniques, design space, device tracking

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1 INTRODUCTION

In our daily lives, we often use different displays and devices for personal and work purposes. Multi-display environments can provide a larger physical space beyond a single screen and allow users to take advantage of their spatial and physical abilities. Multiple displays can also enhance visual analysis and sensemaking by leveraging spatial interactions to gain valuable insights and explore various types of data [12, 36, 37]. Thus, the visualization research community has been exploring the use of spatial interfaces for multiple displays and devices [3, 6, 9, 19].

Although several multi-display tools and techniques have been introduced recently, incorporating spatial interaction into multi-display visualizations remains challenging. This is because most existing visualization tasks are mainly designed for the traditional desktop setup that relies on a mouse and keyboard. Furthermore, there is still a lack of comprehensive understanding regarding the design choices of spatial interaction techniques based on multiple displays and devices for supporting visualization tasks.

This paper aimed to explore and analyze the design space of multi-display spatial interaction in the visualization context. To achieve this goal, we conducted a semi-structured review of previous research papers on multiple displays and devices and created a taxonomy for multi-display spatial interactions for visualization tasks. Although existing taxonomies focus on organizing interaction techniques for multiple displays as a whole [7, 11], they are not sufficiently tailored to address multi-display spatial interactions in visualization tasks. Therefore, we introduce a new taxonomy that categorizes and organizes three design dimensions and their associated design choices.

In this paper, we identify a design space for multi-display spatial and physical interactions by analyzing 136 spatial interactions from 56 papers. This design space is defined by three dimensions: *Composition, Spatial Relationship*, and *Input*. We also identified 14 design choices that fall within these dimensions. By considering different combinations of these design choices characterized by the three dimensions, we identified 136 viable spatial interaction designs suitable for visualization tasks. For example, Figure 1 shows examples of six popular designs accompanied by visualization tasks that can be supported through multi-display spatial interaction.

This paper explores a wide range of multi-display techniques and systems to help visualization researchers and designers understand the potential designs and requirements of spatial interfaces in multi-display environments. Our analysis of design choice combinations also sheds light on current trends in spatial interaction research, identifying areas within visualizations that have been relatively more popular or underexplored. Additionally, the paper discusses the opportunities and challenges that lie ahead, guiding future research directions in this field.

2 RELATED WORK

Spatial interaction techniques provide a user interface that enables the control and manipulation of digital content in a spatial manner. They involve physical movements, gestures, or spatial relationships to manage and manipulate digital objects or elements on a screen or within a virtual environment [5, 15].

Several studies in Information Visualization (InfoVis) and Human-computer Interaction (HCI) have examined spatial interaction techniques that can support various visualization tasks. These techniques involve spatial actions, such as moving, rotating, grabbing, pointing, and stacking user interfaces in a three-dimensional space. They are utilized to support various visualization tasks, including visualizing, filtering, navigating, sorting, grouping, and linking data points based on the spatial attributes of displays. Hakala et al. specifically focused on the challenges and techniques in developing effective spatial interaction techniques for data visualizations on small displays, such as mobile devices [19]. They proposed approaches for adapting spatial visualizations to limited screen space. Similarly, Bruckner et al. introduced a model that quantifies the concept of spatial directness in interactive visualizations [6]. This model involved mapping different spaces, such as data, visualizations, interactions, and user spaces. Their methodology aimed to help practitioners better understand interaction concerns that could impact usability. Additionally, it suggested appropriate interaction strategies for specific data types, visualization approaches, and interactive environments.

Various taxonomies and frameworks have been employed to categorize and understand spatial user interfaces in the visualization field. Besançon et al. presented a comprehensive overview of spatial interfaces within the context of 3D visualization [3]. Their survey examined a range of spatial interaction techniques, including tactile, tangible, mid-air, and hybrid interactions. Brudy et al. categorized interactions based on their temporal and spatial characteristics, such as the continuity of interaction and the distribution of devices in space [7]. Lee et al. proposed a design framework prioritizing a human-centric approach for natural user interface designs in InfoVis [39]. They advocated for integrating natural gestures and movements, such as touch and gesture-based interactions, into the design process.

Interactive lens techniques are widely used in spatial interaction research within InfoVis. Prior works explore the design space of techniques that involve different display settings and interaction modalities, such as gaze-based interaction and head tracking [68], as well as tangible views and spatial interaction [70]. Tominski et al. surveyed interactive visual environments that serve as the technological foundation for interactive lens techniques [73]. They explored the lens techniques based on data types, such as geospatial, temporal, and multivariate data, as well as corresponding user tasks like select, filter, and abstract/elaborate. VisTiles introduced a framework that utilizes a collection of mobile devices to spatially distribute and coordinate visualization views, facilitating the exploration of multivariate data [36]. This framework offered the potential to create a spatial interface that supports data exploration.

Our design space focuses on spatial interaction techniques for visualization tasks using multiple displays and devices. These techniques utilize the physical movement or spatial relationships of one or more displays in 3D space to enhance data exploration and interaction in visualizations. By leveraging spatial awareness and physical movements across multiple displays, these techniques aid in identifying patterns, making comparisons, and gaining insights from the data.

In fact, several research works have examined the design of multi-display visualizations and applications. Chung et al. proposed design considerations for visual analysis in the context of multiple displays [11]. They identified three inherent challenges associated with visual analysis and provided insights that helped visualization researchers create and evaluate new visual analysis tools. Yuan et al. conducted large-scale data analysis to uncover various patterns related to multi-device usage in everyday life [76]. Their study shed light on device-switching behaviors, temporal usage patterns, and the influence of context on multi-device interactions.

Terrenghi et al. conducted a study that primarily focused on the spatial aspect of display ecology [72]. They developed a taxonomy based on human factors, such as visual angle and social engagement, including one-to-one versus one-to-many relationships. The taxonomy serves as a framework for analyzing the usage of these displays in real-world contexts and assists designers in creating more effective collaborative systems. VisTiles introduced a framework that utilizes a collection of mobile devices to spatially distribute and coordinate visualization views, facilitating the exploration of multivariate data [36]. This framework offered the potential to create a spatial interface that supports data exploration. Marquardt et al. introduced AirConstellations, an interaction technique that enables users to control multiple devices using in-air gestures [48]. They also proposed a comprehensive design space for manipulating devices in 3D space within a semi-fixed system.

Unlike previous studies that explored multi-display taxonomies, our design space thoroughly examines various designs of spatial user interfaces based on multiple displays and devices. Our assessment offers a more comprehensive classification for characterizing spatial interactions with one or more displays in the interactive visualization context.

3 METHODOLOGY

Our review method utilized a semi-structured review method [66] for identifying and analyzing multi-display spatial user interfaces found in existing research papers. To facilitate our review, we adopted a collaborative review process, somewhat aligned with the four-step flow of PRISMA [42]. However, instead of employing predefined criteria or quantitative synthesis to answer research questions, we sought to analyze the salient dimensions of multi-display spatial user interfaces in a more qualitative manner.

S1. Collecting: We began this review by amassing 209 papers encompassing various studies, techniques, and applications relevant to multiple displays and devices. These papers spanned various domains, including InfoVis, visual analytics, HCI, ubiquitous computing, multimedia, gaming, mobile applications, and augmented reality. We conducted searches for papers published between 2013 and 2023 in digital libraries such as IEEE Xplore, ACM Digital Library, Google Scholar, etc. We focused on publications from renowned conference proceedings and journals in interactive visualization and HCI.

Initially, three authors conducted independent explorations of the literature employing diverse keywords such as display ecology, multi-display environment, multi-screen data analysis, multi-display settings, multi-touch displays, cross-device interaction, multi-display gaming, immersive display, tangible views, multiple views, multi-display interaction techniques, mobile devices, spatially-aware, multi-touch, wearable displays, display wall, smartwatch, multi-user, collaboration, multi-surface user interfaces, etc. Furthermore, we meticulously examined the collected papers' references to identify additional multi-display papers. Once a relevant multi-display paper was identified through this process, the authors added it to shared file storage.

S2. Screening: The screening phase involved a comprehensive assessment of each collected paper by all three authors individually and collaboratively. We initiated this process by reviewing the abstract of each paper and engaging in discussions to ascertain whether the multi-display articles contained pertinent information for the design of spatial user interfaces. Each author's insights and perspectives on the papers were documented within a shared spreadsheet; we then further elaborated on specific interaction techniques and shared our impressions during regular meetings.

It should be noted that we excluded papers that did not encompass any form of spatial interaction or lacked potential for visual analysis techniques and applications within their multi-display environment. For example, we omitted papers describing multi-display techniques where a stationary tabletop display served as a controller using its touch interface for a stationary projector wall display, as such setups did not facilitate physical spatial interactions (e.g., [40]). We also encountered various immersive visualization papers centered around Virtual Reality (VR); however, these were not included in the review. This is because, in VR, users are unable to interact with physical displays, thereby eliminating the potential for multi-display spatial interactions. Papers relying solely on traditional user input devices such as keyboards and mice for interaction with displays were also excluded. Additionally, user studies not applicable to data visualization tasks, such as those focused on finding the optimal configuration for multi-display applications, were not considered.

In cases where one author proposed excluding an article that others believed should be included, all authors would then assess the full text to arrive at a consensus decision during our meetings.

S3. Grouping: With all the recorded descriptions in hand, we proceeded to define our dimensions (Section 4) and associated design choices. As we continued reviewing the remaining papers, we correlated each spatial interaction technique with the relevant dimensions within our design framework. After selecting a set of multi-display spatial user interface papers, all the authors collaborated to categorize the identified designs through discussions and with the help of written notes. For each multi-display system and technique, we recorded relevant information concerning groups of spatial interfaces in our spreadsheet. By referencing these shared records and discussing them, we were able to cluster the papers based on their common characteristics and applications in the area of spatial user interfaces. This iterative grouping process led us to identify three dimensions. By leveraging these dimensions and the distinctive characteristics of multi-display spatial interactions, we were also able to pinpoint, incorporate, and refine design choices characterized by these three dimensions.

S4. Validating and Finalizing: To ensure the accuracy of our classification efforts, we conducted ongoing reviews and refinements of the dimensions and their associated design choices for each paper within our shared spreadsheet. This process was a collaborative endeavor, involving discussions among the authors to assess and improve the classification of spatial interactions collectively. We evaluated the relevance and significance of these classifications in the context of specific visualization tasks, drawing insights from Heer and Shneidermann's taxonomy [23] (Section 5). During this phase, we reached a consensus regarding the dimensions and design choices for multi-display spatial interaction techniques.

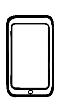
Our review process resulted in the identification of 56 papers encompassing a total of 136 distinct spatial interactions. These findings are documented in Table 1 and in a supplementary document. Each spatial interaction is accompanied by its respective reference source, pertinent design space categories, associated visualization tasks, and a concise description.

4 DESIGN SPACE

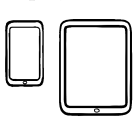
This design space aims to classify and organize spatial interactions with one or more displays. This design space has three dimensions: Composition, Spatial Relationship, and Input.

4.1 Dimension 1: Composition

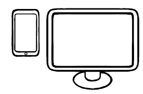
We define Composition as the combination or arrangement of two or more displays and devices within the context of data visualization, specifically for spatial interaction techniques. The dimension of composition determines the types of displays utilized in the spatial interaction and plays a role in determining the scale and origin of the environment. The composition of displays has a significant impact on how display content is distributed and organized across the displays. For instance, in the case of a large visualization, it may be divided into smaller sections, with each display in the multi-display environment dedicated to showing a specific section for focused analysis tasks. These choices can range from fully mobile and ad-hoc setups to larger display configurations or even include the use of augmented reality (AR) headsets. There are five design choices associated with this dimension, characterized by the composition of displays.



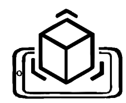
Single: In multi-display ecosystems, spatial interactions often involve two or more devices. However, these ecosystems can also support solo device interactions, which are performed by a single device itself. We classify these solo device interactions under the 'Single' composition category. For instance, two devices might synchronize by bumping them together, but to unsynchronize them, you only need to shake one. Similarly, a single device might switch modes from sending to receiving files by being flipped over, but it may engage with other devices spatially to select which files to send or receive. We only include interactions in this 'Single' device composition when paired with another spatial interaction that utilizes one of the other multi-display compositions. *Examples:* Clearing a selection by shaking the display, changing the mode by flipping the display over [70], and altering the display's shape by folding it [78].



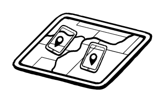
Mobile/Personal: The interaction involves the use of multiple mobile displays, such as tablets, phones, and smartwatches. *Examples:* Combining two displays with graphs automatically scales the data to ensure they utilize the same time frame [36]. When exploring a database, users can enter search queries on separate mobile devices and stack the displays to perform an "AND" operation on the combined queries [32]. By physically bumping two mobile displays together, they merge into a single extended display [13]. These interactions are typically more flexible and ad-hoc, as all the devices are mobile and can be easily added or removed as required during visual analysis.



Mobile+Static: The interaction involves using at least one stationary display, such as a TV, monitor, tabletop display, or tiled display wall, along with at least one mobile display. These setups are commonly employed for Overview+Detail type applications. They are also frequently utilized in team or group settings, where the static devices serve as shared space while the mobile devices cater to personal space. *Example:* The user can utilize tilt controls on the personal display to move a detail/overview lens around a tabletop display [26].



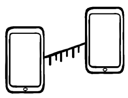
AR: The interactions make use of Augmented Reality (AR) displays or headsets, which offer spatial interaction possibilities that are not readily achievable with traditional displays. While 2D elements can be shown on other displays, projecting them in physical space allows users to exploit a larger physical space when visualizing data. AR overlays simulate displays that can take any shape and size and can be synchronized to track other devices automatically. AR displays can also be used to display stereoscopic 3D objects and visualizations that are impossible with traditional flat displays. *Examples:* Displaying orthographic projections of a 3D model being created by the user on AR displays positioned at the edges of a traditional display [57]. This approach provides additional visual context in physical space. Other examples include projecting 3D building models and bar charts onto a map [14], as well as projecting 3D medical scans using a mobile display to extract 2D slices from them [45].



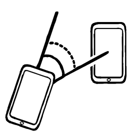
Tangible: The interaction involves utilizing multiple displays as a tangible controller. This type of interaction entails placing smaller devices, such as smartphones or tablets, in contact with a tabletop to facilitate interactions between displays. The advantage of this approach is that it provides a more intuitive and physical means for users to interact physically with the data or model they are working with instead of using an indirect mouse cursor. *Example:* One example of this interaction is using a handheld display as a net to scoop up AR charts and select them [62]. Another example involves the use of small cube displays to map out a chemical reaction [50]. These cubes are employed to position chemicals on the tabletop and can be twisted like dials to adjust parameters such as concentration. Furthermore, the cubes can be tapped together to initiate a reaction.

4.2 Dimension 2: Spatial Relationship

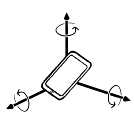
Spatial relationships among displays refer to how multiple displays are positioned, rotated, and arranged in a physical space to support spatial interaction in visualizations. It involves understanding the relative positions, proximity, orientations, and distances between the displays and how these factors impact the user's perception and interaction with the visualizations on different displays. Designing spatial relationships among displays is crucial for developing effective spatial interaction techniques. By considering the physical arrangement and orientation of displays, designers can leverage the spatial characteristics of the displays in interacting with visualizations. There are five sub-dimensions to consider: Distance, Direction, 6DoF, Independent, and Touch.



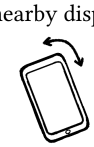
Distance: This type of interaction uses the distance between two displays or a display and a specific point in the environment, such as the center of a table. The direction of the interaction is not specified, so it is only known that the target is located somewhere on a sphere or circle centered around the display. *Examples:* In a video call where each participant is on a different display, moving one display away from the group mutes the rest of the participants, allowing for a private conversation with the individual [48]. Similarly, in a cluster of mobile displays, pulling one display away from the group triggers a mode switch, such as opening an annotation window [56] or returning the user to the main menu [75].



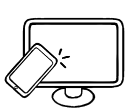
Direction: In these interactions, one display is aware of the direction of a target display relative to itself. *Examples:* A user can tilt their tablet towards a wall display or another tablet to duplicate their screen onto it [49]. Another example is when a user swipes a file toward the target display to share it [12, 74]. Additionally, a user can utilize their phone as a pointer to upload or download information from a public display [8].



6DoF: Six degrees of freedom (6DoF) tracking captures the position and rotation along all three axes, providing a comprehensive set of a display's spatial information. This tracking method encompasses both the three positional and three rotational dimensions. *Examples:* In an AR application, a graph's data can be projected into the third dimension and synchronized with the position of the display [37]. Another example is using a mobile display to view 2D slices of a 3D visualization [67]. Additionally, when multiple mobile displays are in proximity, an arrow on the screen can indicate nearby displays, facilitating file sharing between them [46].



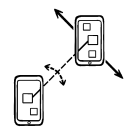
Independent: The Independent relationships prioritize tracking data collected by a single display about itself. In these interactions, the relative positions of the devices are irrelevant, although input from multiple displays is still utilized. *Examples:* Tilting a handheld display can be used to manipulate a selection box on a table display [26]. Another example is folding the screens of a smartwatch to switch between different modes [78]. Additionally, when viewing a video clip on a mobile device, moving the device from left to right can be used to scrub through the timeline [43].



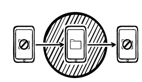
Touch: In this case, the interaction relies on physically touching one device against another. This touch-based interaction enables various functionalities, such as file transfer and combining multiple displays, to create a larger display. *Examples:* a phone's corner can be used as a pen to select a range of cells from a spreadsheet, with the selected data then transforming into a chart or table on the phone itself [52]. Additionally, bumping devices together can be used to register them into the display ecosystem, establishing a connection between them [20].

4.3 Dimension 3: Input

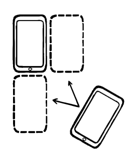
In our design space, the Input dimension refers to how users utilize the spatial properties and relationships of displays to provide input for data visualizations. The spatial relationships among displays determine the type of input information for data visualizations across different displays. In simpler terms, users can utilize the spatial arrangement, positioning, or orientation of displays relative to each other to input information into data visualizations. We categorize four types of input common for interactions in data visualization: Synchronized, Flag/Trigger, State, and Range.



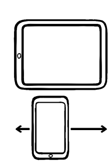
Synchronized: These interactions do not directly involve user input. Instead, these features utilize spatial movements of displays to update visualizations on the moving display or another display as users naturally move their mobile displays around the environment. This category is commonly associated with interactions that display AR elements and align them with the position of mobile displays. *Examples:* Using AR to display the origin of a graph that extends beyond the boundaries of the other display's screen [37]. Rendering partially visible links that connect data across displays even as the displays are moved [74]. Moving a mobile display through a 3D visualization updates the mobile display to show 2D slices of the visualization [69]. A low-detail map is projected on a wall display, while a mobile display shows a detailed view that can be navigated by moving the mobile display around the map on the wall display [61].



Flag/Trigger: These interactions possess a binary state or trigger that is controlled by spatial interactions like distance, physical gestures, or touch. This resembles the action of pressing a button or flipping a switch. *Example:* Turning file sharing on and off is analogous to whether a display is within or outside the shared group area [48]. Completing a "pouring" gesture between two phones serves as a trigger to generate a composition of their data [33]. When two displays are placed edge to edge, they are triggered to transform into a shared workspace [71].



State: These interactions use spatial input (e.g., distance, direction, etc.) to determine whether the display is in one of a finite set of states. These states are not arranged sequentially, which sets them apart from ranges. They often require the user to select an option. *Example:* In the task of sharing a visualization (Figure 1e), the user chooses a specific display to point their handheld display at. The user also decides on which edge to place the displays side by side. Placing the display on the right edge could extend the visualization to the newly positioned display while placing it on the bottom edge could offload UI elements.



Range: These interactions determine the position of the display within an infinite range of states. This range can represent the spatial region where the display is located or the degree of rotation it has. These interactions typically emphasize the movement of the display rather than its final position, often requiring more precise tracking. *Example:* One example is using a phone as a physical slider to select or browse through data on another display [36, 75]. Another example involves using a handheld display to accurately point to a specific location on a wall display for file transmission [48]. Additionally, tangible cube displays that can be twisted like dials to modify the displayed values are also utilized [50].

5 ANALYSIS OF THE DESIGN SPACE

Our paper review examined a total of 136 combinations of the design choices extracted from 56 papers. Each spatial interaction feature in these papers was analyzed across three dimensions of the design space to identify its specific combination. Out of the hundred potential combinations, only 33 combinations were found to incorporate a feature. While certain combinations were prevalent, approximately half of them featured only a single spatial attribute. Furthermore, we assigned a data analysis or visualization task from Heer and Shneiderman's taxonomy of tools that facilitate the effective and flexible utilization of visualizations [23]. This enabled us to identify patterns between task goals and commonly employed spatial interactions. In Table 1, we present the number of features corresponding to each combination of design space choices and data analysis task. Using this table, we have uncovered several patterns linking analysis tasks to specific design space combinations. We examined a design space pattern and scanned the corresponding row to identify the most common associated tasks, or conversely, we started with a task and explored the column to identify prevalent patterns.

In this section, we will provide a more detailed breakdown of the six most frequently encountered analysis tasks. However, we have also identified several common visualization tasks that often do not rely on spatial interactions. For instance, tasks such as Filter, Derive, and Sort are typically carried out using traditional interactions involving GUI controls with mice or keyboards, and then they are combined with spatial Select interaction. Similarly, annotations are generally applied using a stylus or keyboard on a display without requiring spatial interaction. Subsequently, these annotations can be shared or organized more spatially.

5.1 Visualize

The central element of the visualization tasks is Visualize. While most other tasks involve interacting with or controlling multi-display visualizations in some way, certain features revolve around the visualizations themselves. In our design space, the Visualize tasks primarily rely on AR. AR offers unique opportunities for spatial interactions that are not feasible with traditional displays. The most prevalent pattern identified in our review involved 17 features that aligned with this AR-based visualization approach. An example is utilizing AR to create personalized annotations and visualizations on a large wall display in a collaborative setting. In such a scenario, each user can view their own notes and overlays on the wall display without obstructing or disrupting the work of others [59].

Figure 2a illustrates a spatially-aware visualization where one of the features overlays 3D AR models onto simple block models [14]. The device composition is **AR**, as it employs AR to project complete 3D models. The spatial relationship is **6DoF**, as overlaying the AR model requires precise positional data. The input type is **Synchronized**, as the AR model follows the movement of the block.

5.2 Share

The second most common task identified in this review was "sharing." In collaborative settings, data sharing among collaborators is one of the fundamental tasks for effective group work. The objective of spatial interaction in this context is to make sharing intuitive and seamless. Two primary types of sharing were observed, differing in their level of precision.

The first type is based on the Direction relationship, where the user points their device in the direction of the device they wish to share with (Figure 1e). Due to the finite number of available devices for sharing, this type exhibits a state-based granularity. The majority of patterns in this group involve State and Flag/Trigger inputs. On the other hand, the second type of sharing utilizes 6DoF to precisely select the location on the target device where the data is to be shared. This is more commonly observed in Mobile+Static compositions, as larger displays provide users with the ability to organize data. As the user can choose any position on the display to place the shared data, these interactions involve Range input.

In addition, there are other sharing interactions exploring alternative methods, such as using distance as a trigger for data sharing availability. However, the majority of interactions can be categorized into two input options: choosing a target display (**State**) or selecting a location on the target display (**Range**).

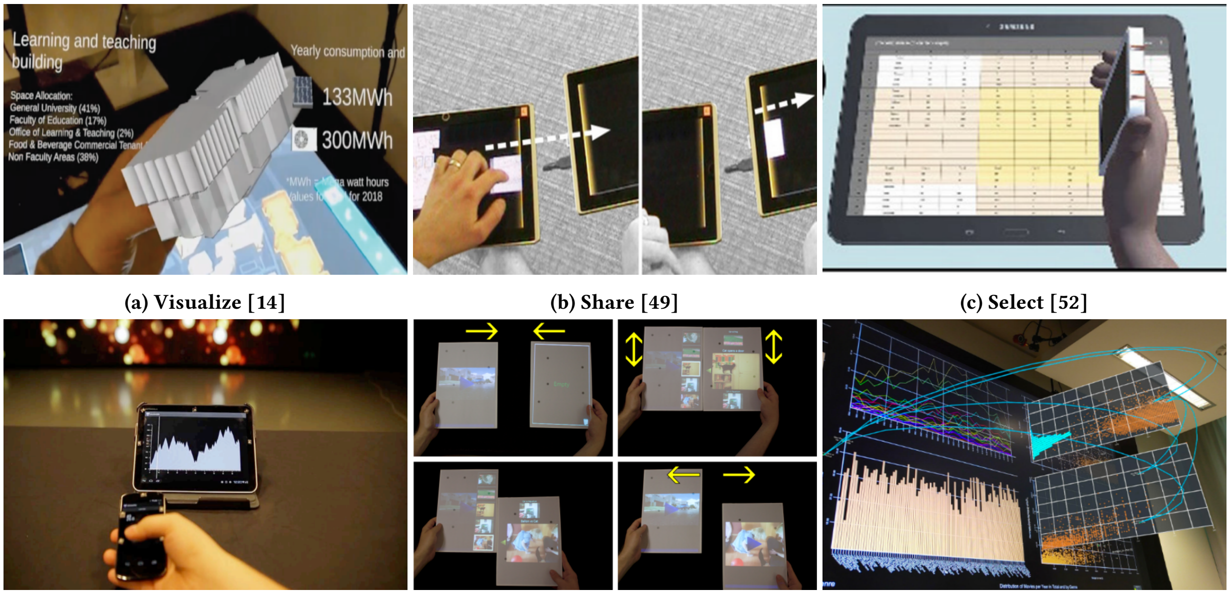
Figure 2b illustrates spatially-aware tablets that can detect nearby displays and their relative directions, allowing users to transfer files from one display to another [49]. The device composition is **Mobile/Personal**, as all the displays used are handheld. The spatial relationship is **Distance**, as the ability to share between displays is only enabled when they are in close proximity. The input type is **Flag/Trigger**, where the distance between the displays acts as a trigger to activate or deactivate file sharing.

5.3 Select

When exploring data, the need to select individuals or groups of data points arises. The act of selection is often tied to other tasks, such as creating a new visualization by selecting a group of data points or filtering data by selecting specific data points.

In spatial interactions, selection tasks commonly involve using handheld devices such as phones or tablets as substitutes for a mouse. When these devices are employed for selections, they are either used as pointers to make selections from a distance (Figure 1a) or as styluses for direct interaction. The latter method constitutes the majority of tangible interactions. For example, in AR visualizations, a phone can be used as a "net" to physically scoop up the desired visual elements [62]. Spatial selection tasks offer more unique interactions beyond emulating virtual pointing with a device. One example involves a large display with multiple audio sources, where only the source closest to the user's handheld device plays its audio [63]. Another spatial selection task entails shaking a handheld display to clear the data it had previously selected [43, 70].

Figure 2c demonstrates how an artificial "fingerprint" on the phone case enables a tablet to detect the position of the phone, allowing the user to select a range of data on the tablet [52]. The device composition is **Tangible**, as the phone is used as a physical pointer against the tablet. The spatial relationship is **6DoF**, as the



(a) Visualize [14] (b) Share [49] (c) Select [52]

(d) Navigate [75] (e) Organize [43] (f) Coordinate [59]

Figure 2: Example of the six popular data analysis tasks from our review. (a) Visualize: AR, 6DoF, Synchronized (b) Share: Mobile/Personal, Distance, Flag/Trigger (c) Select: Tangible, 6DoF, Range (d) Mobile/Personal, Range (e) Organize: Mobile/Personal, 6DoF, Flag/Trigger (f) Coordinate: AR, 6DoF, Synchronized.

precise position of the phone on the tablet is utilized. The input type is **Range**, enabling the user to select arbitrary data ranges.

5.4 Navigate

Another data analysis task that exhibits a consistent spatial interaction pattern is navigation. These tasks are primarily implemented using Mobile+Static devices with 6DoF and Range input. In this setup, a larger static display serves as the platform for displaying broad information or an overview, while a handheld device shows a more detailed view (Figure 1b). Typically, these interactions involve navigation in two dimensions over the static display rather than utilizing the full six degrees of freedom. Alternatively, the Mobile+Static composition can be replaced with an AR composition, where the AR model replaces the static display. In such cases, 6DoF is fully utilized, allowing the handheld device to extract slices of a 3D projection. This approach can be employed to navigate space-time-cube visualizations [70] or view medical scans [45].

Figure 2d illustrates how spatially-aware phones enable users to explore a graph by physically sliding the phone to select a range for a detailed view [75]. The device composition is **Mobile/Personal**, as it exclusively involves phones. The spatial relationship is **6DoF**, as the precise position of the phone relative to the other phone is crucial. The input type is **Range**, allowing the user to select any position between the two ends of the graph.

5.5 Organize

One commonly discussed advantage of multi-display ecosystems is built upon the fact that spatially-aware mobile devices have the ability to spatially arrange data in physical space [1, 10, 36]. Organization tasks exhibit greater variability in their design space combinations. The 19 organization task features encompass twelve different design space combinations, but the prevailing trend is to use spatial interaction as a trigger to offload UI elements or visualizations onto separate displays. For instance, when a blank display is positioned adjacent to a crowded display, certain charts and UI elements can be transferred to the blank display (Figure 1f).

Figure 2e showcases a spatially-aware video editing tool. When an empty display is placed next to a display that contains a video, a list of related videos pops up as an option to be moved to the empty display [43]. The device composition is **Mobile/Personal**, utilizing paper displays exclusively. The spatial relationship is **6DoF**, as the exact position of the papers is used to control the selection. The input type is **Flag/Trigger**, where bringing the empty display next to the display with a video serves as the trigger to initiate this interaction.

5.6 Coordinate

The Coordinate tasks involving spatial interactions were less prevalent than anticipated. One expected advantage of spatially-aware devices is that visualizations can be dynamically updated when users organize devices in physical space to maintain relationships between data across devices. However, only a few features take advantage of this capability. For example, VisTiles can align the axes of charts on adjacent devices [36], MARVIS employs AR ribbons to connect related data [37], and RAMPARTS [74] and SAViL [10] use partially out-of-frame lines to link virtual documents spread across multiple mobile tablets. Although some non-spatial coordination features were used in conjunction with spatial elements,

			Data Analysis Task										
Composition	**Relationship**	**Input**	**Visualize**	**Share**	**Select**	**Navigate**	**Organize**	**Coordinate**	**Filter**	**Derive**	**Annotate**	**Sum**	**Cited papers**
AR	6DoF	Synchronized	17			1	3	3			1	**25**	[14, 29, 34, 37, 58–60]
Mobile+Static	6DoF	Range		4		6	1		1			**13**	[16, 27, 38, 54, 63, 67, 68, 70]
Mobile/Personal	Distance	Flag/Trigger	1	3	2	1	2	2			1	**12**	[35, 36, 48, 49, 56, 64, 71, 75]
Mobile/Personal	Direction	State		6			2	1				**9**	[8, 25, 44, 47–49, 74]
Mobile/Personal	6DoF	State	1	2			2	3				**8**	[33, 35, 36, 43, 48]
Mobile+Static	6DoF	Synchronized	3	1		2	1					**7**	[22, 31, 46, 51, 61, 68, 69]
Tangible	6DoF	Range	1		3	1	1				1	**7**	[36, 37, 50, 52, 55, 62]
AR	6DoF	State	1	3	1					1		**6**	[18, 37, 65]
Mobile/Personal	6DoF	Range		3	1	2						**6**	[36, 43, 48, 53, 75]
Mobile/Personal	6DoF	Flag/Trigger					3			2		**5**	[33, 43, 48]
Mobile/Personal	6DoF	Synchronized			1	1		2				**4**	[4, 41, 56, 74]
Mobile/Personal	Touch	Flag/Trigger		1	1			1	1			**4**	[13, 20, 30, 32]
Single	Independent	Flag/Trigger	1		2							**3**	[43, 70]
Mobile/Personal	Distance	State			2		1					**3**	[22, 27, 48]
AR	6DoF	Range			1	2						**3**	[34, 45]
Mobile/Personal	Independent	Flag/Trigger					1	1				**2**	[35, 48]
Single	Independent	State	2									**2**	[70, 78]
AR	Direction	Range			2							**2**	[21, 28]
Single	Independent	Synchronized					1					**1**	[37]
Mobile/Personal	Direction	Flag/Trigger				1						**1**	[56]
AR	Distance	Flag/Trigger	1									**1**	[57]
AR	6DoF	Flag/Trigger			1							**1**	[37]
Tangible	6DoF	Flag/Trigger	1									**1**	[62]
Mobile+Static	Touch	Flag/Trigger					1					**1**	[51]
Tangible	Touch	Flag/Trigger								1		**1**	[50]
Mobile/Personal	Independent	State		1								**1**	[44]
Mobile+Static	6DoF	State			1							**1**	[63]
Tangible	6DoF	State							1			**1**	[14]
Single	Independent	Range				1						**1**	[43]
Mobile/Personal	Independent	Range		1								**1**	[77]
Mobile+Static	Independent	Range				1						**1**	[26]
Tangible	Independent	Range							1			**1**	[14]
Mobile+Static	Touch	Range		1								**1**	[64]
Sum			**29**	**26**	**19**	**19**	**19**	**13**	**4**	**4**	**3**	**136**	

Table 1: On the left is the list of possible design space combinations, excluding combinations that did not have any relevant papers. The top lists common data analysis tasks. The numbers are the number of features we found that match that design space pattern and analysis task.

strictly spatial coordination features were relatively uncommon in this review. Additionally, most coordination task features utilized a Mobile/Personal device composition.

Figure 2f illustrates an AR-enhanced wall display. AR replicas of visualizations on the wall display are projected and aligned with the user's position to ensure they are always viewable at an optimal angle [59]. The device composition is **AR**, incorporating AR elements. The spatial relationship is **6DoF**, as the exact position of the user is leveraged to control the angle of the AR visualizations. The input type is **Synchronized**, as the user's movement automatically updates the AR visualizations without further instruction.

6 USE OF THE DESIGN SPACE

Our design space can serve as a framework for planning the device setup and implementation of a new multi-device visualization tool. While the design space abstracts the physical implementation of spatial features, the design choices still imply specific hardware and software requirements. Specifically, the **Composition** dimension entails the type and number of devices necessary for the desired feature. The **Spatial Relationship** dimension provides insights into the tracking requirements, while the **Input** dimension specifies the required level of precision and the types of input data for visualizations, such as continuous, ordinal, categorical, etc. By carefully considering these three dimensions, designers can develop more effective systems that cater to the diverse needs of users in various analysis and sensemaking contexts. Developers can also utilize these requirements in conjunction with a taxonomy such as Hightower's [24] to determine the most suitable hardware for their specific feature.

Implementing spatially-aware multi-display systems can be challenging due to the need for each display to track the physical properties (e.g., shape, size, form factors) and spatial properties (e.g., location, orientation, proximity, topology) of other displays. Two main implementation challenges arise in this context.

The first challenge lies in how displays with appropriate capabilities (in terms of computational resources, display resolutions, and form factors) are selected and deployed for the different analysis goals. Certain data analysis tasks, such as filtering, sorting, and deriving insights, can be computationally intensive, particularly when dealing with large data sets or suboptimal data storage. By leveraging our design space, visualization researchers and designers can consider their target analysis tasks and make informed decisions regarding the allocation of computational resources across devices. The **Composition** dimension is valuable for guiding and planning the selection of devices for running computationally demanding tasks. For instance, in Mobile+Static compositions, the large static display is likely to be connected to a more powerful PC, allowing designers to plan for its use in more intensive processes.

The second challenge involves selecting appropriate tracking methods. 6DoF tracking data can facilitate the implementation of distance, direction, and other spatial relationships. However, it's important to acknowledge that incorporating 6DoF tracking can be challenging or unfeasible for certain projects. Implementing 6DoF typically requires either external tracking methods (e.g., motion capture systems) or devices specifically designed for inside-out tracking. External tracking may not be viable in certain settings, and the availability of inside-out tracking for devices is still limited.

The design space addresses the spatial and physical relationships between devices/displays separate from the hardware used to implement them. Thus, designers can employ the design space to analyze the features of their tool and identify the specific relationships it utilizes. If the interaction relies on distance relationships, implementation could utilize more accessible hardware, such as Bluetooth, instead of relying on external trackers[17]. The **Input** dimension within the design space can help minimize the tracking hardware requirements. For instance, if a spatial feature only requires State inputs, high-fidelity tracking may be unnecessary for that particular feature. A coarse method for estimating the general location of a device may be sufficient for State or Trigger inputs, even if it falls short for Range inputs.

7 DISCUSSION AND FUTURE WORK

In this section, we further discuss the research challenges and opportunities that arise when reviewing and analyzing multi-display spatial interaction techniques. We derive these ideas from a thorough exploration of the design space and choices involved, as well as an analysis of the resulting combinations of the design choices in relation to visualization tasks.

7.1 Design Considerations Based on User Feedback in Prior Studies

In our review, we learned the key distinction between multi-display visualizations and traditional visualizations: the expanded potential for physical space. This extended capacity allows users to harness spatial user interfaces beyond a single virtual raster space for data analysis. The importance of physical space in data comprehension and insight formation has been highlighted in previous studies [2].

Our paper review also identified noteworthy design considerations that encourage users to leverage these physical and spatial abilities. We derived three key design considerations from recurring user feedback in previous studies.

Enable to Pause Spatial Input: A recurring observation in the existing multi-display studies highlighted concerns about the potential interference of spatial input with the smooth manipulation of displays. Several studies recommended giving the user the option to temporarily pause spatial input. This enables users to freely reposition displays for improved visibility or organization without inadvertently triggering spatial features. [36, 70].

Promote Paper-Like Design: Another piece of user feedback from previous studies is to replicate the experience of working with paper documents and other commonly used traditional tools. This approach is based on the idea that such interaction methods are universally familiar and provide users with a more natural learning curve. [45, 49, 70].

Mitigate Overwhelming Interfaces: One recurring concern is that users might become overwhelmed by an excess of spatial gestures or struggle to remember how to activate specific features. To address this, the multi-display system can offer users flexibility by enabling them to choose which spatial interactions remain active. This way, users can customize their spatial interactions to align with frequently performing tasks.

Integrate Multimodal Feedback: Integrating visual, audio, or tactile feedback whenever available for multi-display visualizations is advisable. This approach ensures that users are informed when spatial interactions are initiated. For example, displaying a marker on a screen indicates nearby displays suitable for file sharing or having a display vibrate to notify the user when it joins or leaves a display cluster.

7.2 AR-Enhanced Spatial Interactions in Multi-Display Environments

Interestingly, we have observed that the most popular combination of the design choices (AR, 6DoF, Synchronized) involves the utilization of AR technology (Table 1). It is worth noting that the number of AR-enhanced multi-display visualizations has recently witnessed an increase, primarily due to the growing availability of AR technology. We believe there is potential for exploring additional spatial interaction approaches that incorporate AR headsets with existing display technologies like mobile devices, wall displays, and desktop environments. This integration not only offers users more flexibility in input gestures but also provides them with a larger workspace, enabling them to fully leverage the physical space available.

Additionally, we could see that various combinations of displays and AR visualizations can offer solutions to overcome limitations in spatial interaction support with AR displays. For instance, AR often does not provide the same level of interactivity as the real world. Consequently, in multi-display spatial interaction, handheld displays and devices play a crucial role in bridging this gap, allowing users to tap the screen, hold the device, and experience feedback through vibrations. These mechanisms highlight the significance of considering a hybrid AR and physical display space. While handheld devices can simulate AR-like settings with movable and tangible interactive elements, such as AirConstellations, they ultimately cannot fully replicate the freedom offered by an AR space [48].

7.3 Visual Representations for Supporting Spatial Interactions

Our research primarily focuses on spatial interaction in multi-device setups within the area of data visualization. From our review, we have also identified potentially important aspects that were not originally included in our proposed design space. We recognize that alongside the three dimensions in our design space, various visual representations can be considered to facilitate spatial interactions for multi-display visualization tasks.

During our review, we discovered that visual cues displayed on each display play a crucial role in facilitating spatial interaction by providing appropriate visual feedback and guiding users in their interactions. For navigation tasks, detailed data can be visualized on smaller tangible displays. These mobile displays enable users to move freely around a larger display and explore different sections of a large visualization on the large display [70]. To accomplish this visualization task using spatial interaction, each display should be color-coded to differentiate it from other displays, and their corresponding area on the overview will be bordered with a similar shape and color. The size and position of the area of interest will be updated based on the movement of the user's device. The bordered-box shape is commonly used in applications where multiple users want to explore detailed information about a specific region of a shared visualization using their own personal devices. This visualization approach allows users to move around freely while still maintaining awareness of the relative location of their data.

Additionally, highlighting and overlaying data elements on displays can be employed to help users perceive relevant information more accurately and quickly. This technique is used in various scenarios, such as node-link diagrams and adjacency matrices [31], or in the context of 2D blueprints and 3D architectural models [14]. In PaperVideo [43], the corner of the display is utilized as a timeline selection tool, enabling users to physically move the display and choose which portion of the video to cut and paste for video editing. An arrow indicator points to the location of the corner of the selection display on the video display as the device is relocated spatially, emphasizing the focal point of the selection.

While our focus in this paper remains on the spatial interaction aspect of data visualization in multi-display environments, we acknowledge the potential for further research to explore a more comprehensive design space that encompasses these visual representations within the context of spatial interaction techniques.

7.4 Limitation

Our design space has a limitation where certain sub-dimensions are not mutually exclusive. Specifically, the 6DoF design choice in the Spatial Relationship dimension encompasses several aspects of multi-display spatial interactions, but this design choice requires more precise description and division. A similar situation occurs with tangible display compositions. Although some devices are built for tangible interactions, many of these interactions could also fall into different design choice categories, such as Mobile/Personal, Mobile+Static, or AR. In these dimensions, interactions cannot be easily placed into just one category; instead, they need to be assigned to the most specific category that fits each interaction.

8 CONCLUSION

We present a comprehensive design space that organizes and analyzes spatial interactions using multiple displays for various visualization tasks. Our review encompassed 56 papers exploring a wide range of multi-display ecosystems. The versatility of our design space allows it to encompass various setups, including combinations of large stationary displays with mobile displays, fully mobile ad-hoc ecosystems, and AR environments. By leveraging our review findings, we identified patterns linking our design space with commonly associated data analysis tasks. This identified design space and assessment can offer designers a solid foundation, inspiring them with ideas on how to realize their planned features within the design space and enabling them to establish implementation requirements for hardware and software for spatial interfaces during the planning phase.

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