VIZSSTA: A HYBRID TABLET AND AUGMENTED REALITY INTERFACE FOR SPACE SYNTAX DATA ANALYSIS

by

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The thesis is dedicated to my mom(Sawarnjit Kaur), dad (Amrik Singh), my brother(Arshdeep Singh), and my grandmother(Sakinder Kaur). Thank you for your endless love and support.

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Abstract

I developed a hybrid tablet and head-worn augmented reality(AR) interface called VizSSTA, a system designed to support analysis of Space Syntax data. Space Syntax is a family of quantitative approaches for characterizing physical environments and predicting how they will be used. VizSSTA provides an interactive floorplan on a tablet display, renders related space syntax analysis data in layers above the tablet display (in AR), and uses the area around the display to render additional floorplans (such as different floors of a building) or an expanded floorplan in AR. In a within subjects comparative study (n=48) I explored how layers above the display promote understanding of how two spatial attributes (Openness and Visual Complexity) are related to each other and to the raw visibility ("isovist") data, to promote understanding of how isovist perimeter and connectivity are related, and how well participants can identify regions with similar space syntax attributes across large floorplans. In the study I compared VizSSTA against a tablet-only interface. Quantitative and qualitative results indicate that VizSSTA helped participants comprehend the space syntax attributes and their interrelationships. VizSSTA yielded more accuracy for tasks involving identifying how isovist shape and size are related to openness and visual complexity, facilitated detection of similar regions across a large floorplan, and enhanced comprehension of how isovist perimeter and connectivity correlate. A number of limitations of the current implementation of VizSSTA are explored, including ergonomic issues involving the AR headset, and related modifications are proposed.

List of Abbreviations Used

AR	- Augmented Reality
VR	- Virtual Reality
ABD	- Above the tablet Display
ARD	- Around the tablet Display
IV	- Information Visualization
HMD	- Head Mounted Display
HWD	- Head-worn Display
TLX	- Task Load Index
SUS	- System Usability Scale
HHD	- Handheld Displays

Acknowledgements

I would like to express my deep and sincere gratitude to my supervisor Dr.Derek Reilly for the unwavering support and advice of my Master's study and research. His guidance and overall insights made this an inspiring experience for me. I would like to extend sincere thanks to my mentor Saman Bashubaghi from Ericsson team, for providing his continuous guidance and valuable suggestions. It is impossible to thanks to my family especially my parents and brother, who gave me the encouragement I needed throughout this process. I would like to thank GemLab team who supported me greatly and were always willing to help me. I would like to thank my friends, this journey would have been much difficult without you.

Chapter 1

Introduction

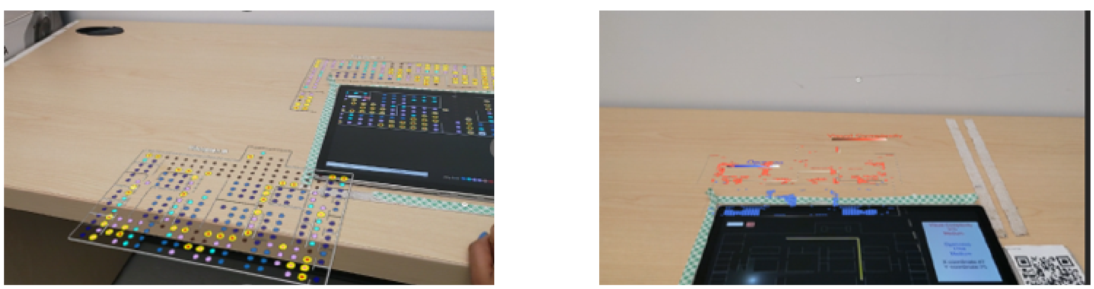
Information visualizations act as a tool to reconstruct abstract data into a meaningful interactive or non-interactive visual representation that is easy to understand [38]. The user's ability to interact with data in Information visualizations(IVs) enhances the data's understandability by enabling users to explore data, identify correlations, search, and generate new relations from the data [85, 91]. As the amount of data increases, the users may require more screen space to manage multiple visualizations simultaneously. Using multiple or large physical monitors to display such IVs occupies more space in a room and is not a portable or mobile solution [17]. One advantage of Augmented Reality head-mounted displays(AR HMDs) is to create an immersive environment by offloading the user interface components such as menus or windows to virtual monitors that do not occupy physical space and are portable [39]. A considerable amount of research has been conducted to combine IVs in AR HMDs with mobile devices devices [67, 55, 66, 49]. Through the early works in AR during the 1990s, the term "Hybrid Interfaces" was coined for interfaces with head-mounted displays combined with conventional displays [42]. Mobile Data Visualizations(MobileVis) is a significant field of research due to the wide adoption of touch-enabled phones and tablets as primary computers [67, 79].

Space syntax [12] refers to a set of methodologies used to analyze the spatial characteristics of urban areas. A significant amount of work has been done to incorporate properties of the space in numerous fields like gaming (AdventureAR, Scavenger Hunt) [83, 27, 33], storytelling in AR [89] and urban planning & architecture [62, 59, 103]. Space syntax has also been used for the placement of story elements as per story requirements [89] such as a crime will happen in a place of low visibility, and a party event will happen in an open space. It has been used across gaming domain [83] to create an immersive gaming experience for the users where the placement of game objects is as per the spatial properties of a given place such as keys to open chest is placed at a location of low visibility. Space syntax has also been used to increase player engagement by making the game more challenging as the levels in the game progress [33]. This was achieved by relating the placement of the object type with the amount of visibility or exposure at that given point, considering the game's difficulty. Placing medicine and other key items such as weapons for the players at low visibility will make the game challenging across progressing game levels. Placing the objects at high visibility at the beginning of the game motivates the game players to acquire the objects easily. Space syntax also identifies how strongly the properties of the environment affect the navigational behavior of the users through a space [59, 62], concluding that the users tend to spend more time navigating through complex spaces to observe the intricate details of the complex environment and relatively less time navigating through open spaces. Isovist, also called the visibility region, refers to the region visible from a given point in space. The space's complexity and openness were measured through the isovist area and jaggedness [59, 62]. A key challenge expressed by the researchers in applying the space syntax to various domains is understanding the space syntax attributes and their underlying mathematics [51, 68, 14, 88, 89]. As per the prior work in space syntax [51, 68, 14], it is not easy to understand the space syntax attributes; hence various space syntax attributes have not been much explored across domains like isovist and convex analysis. Moreover, the space syntax tools require expertise to operate, making the application of space syntax more challenging [51]. Space syntax tools can output floorplan analysis in the form of CSV data. This data can be projected in scatterplots or heatmaps through information visualizations. IV can help users understand the data better since the visual form of data amplifies the comprehension of the data [85, 91]. It can also help identify relationships, trends, and patterns in the data [91] which may be otherwise hard to find. As a visual representation of data conveys more information, the users can also interact with the visual graphics by applying filters and zooming/panning the data [85]. Using the virtual space around the conventional displays to display the data dates back to the early nineties [101]. Projecting data in AR has been proven effective in terms of sensemaking by offloading the data into the large space [67, 74]. This also eliminates the requirement of using multiple or large physical monitors to display data visualizations which occupy more space in a room and is not portable or mobile solution [79]. The combination of conventional displays and AR has also been proven effective in improving task performance [46]. While there has been a considerable amount of recent work exploring the potential of immersive visualization [54, 66, 77, 67, 79, 74] including preliminary work in the space syntax domain (through AR or VR displays) [89, 83], work remains to be done to understand the benefits of immersive visualization for the space syntax attributes. The interface displayed a focused region of a large floorplan on the tablet and the rest of the floorplan (context region) around the tablet. The participants were assessed on their ability to identify regions with similar space syntax attributes across the entire floorplan and understand how connectivity and isovist perimeter correlates.

Displaying the space syntax visualization in AR was supported by the literature [81, 68, 51, 14]. These works identified a lack of clear guidelines to make space syntax more comprehensible for the general audience [68, 81]. Also, complex formulae makes it furthermore challenging to understand space syntax attributes. This has led to scarce publications across space syntax analysis, such as isovist analysis, which has less research than axial analysis [14]. In my preliminary work with other developers and story authors to develop and evaluate Story CreatAR [89], we used spatial rules to place story elements as manual placement of the story elements becomes time-consuming if the elements are supposed to be placed in a large space. It is also challenging if the story location is changed, and it requires manually moving the story elements from one location to another. The tool enabled the users to assign the spatial rules with the story elements and automatically placed the story elements as per the rules.

Story CreatAR illustrated authors difficulties, comprehension how the space syntax attributes are misinterpreted by the users who have less familiarity with space syntax. The author's feedback in Story CreatAR helped to identify demanding activities that could boost comprehending the space syntax attributes, such as identifying regions having similar spatial attribute values across a floorplan and visually examining the relationships between spatial attributes such as isovist area and isovist perimeter.

In this thesis, I evaluated two different display techniques for displaying the space syntax attributes in AR- displaying the visualizations above the tablet display and by extending the visualizations around the tablet display (on performing zoom and pan operations) as shown in Fig: 1.1. I compared each technique against a baseline non AR visualizations presented on the tablet. VizSSTA (VIsualiZation of Space Syntax attributes in Tablet AR), through the ARD(ARound the Display), allows the user to zoom into large floorplans without losing any context. Users can also filter the information of interest, like filtering high visibility regions that can be used later to identify patterns such as how high or low visibility/openness regions are distributed throughout the floorplan. VizSSTA, through the ABD(ABove the Display) interface, implements design above the tablet display by projecting the isovist layer in the tablet and then projecting the space syntax attributes on top of it in AR. This helps to compare the isovist size and shape at a given point in space with its corresponding visual complexity and openness value. This helps determine how the spatial attributes are derived from the isovist and how isovist shape and size play a significant role in deriving the spatial attributes.



(a) (b)

Figure 1.1: VizSSTA interface (a) ARD:displaying a focused region of a large floorplan on the tablet and the rest of the floorplan (context region) around the tablet (b) ABD:displaying visualizations of space syntax attributes inlayers above the tablet display and allowing the user to filter to given attribute ranges by selecting a location on the tablet.

I created a low-fidelity prototype and collected feedback from peers through five pilot studies and arrived at the final prototype for evaluation through convenience sampling of the Dalhousie university students.VizSSTA was evaluated by Dalhousie University students, who had varying levels of familiarity with AR. I held one session, which comprised of two experiments: one experiment comprised of tasks in *Around* *the Display interface(ARD)* and *baseline interface(ARD without AR)*, and the other experiment included tasks in *Above the Display(ABD)* and *baseline(ABD without AR)* interface. I made an introductory video that helped the participants get familiarized with space syntax terminologies before the two experiments started. After this, participants performed a set of tasks detailed in Appendix C in both the experiments. I collected software logs, video recording of participants performing the tasks in both the experiments, self-reported data in the form of a custom questionnaire, Task load index(TLX)-rating, System usability(SUS), and semi-structured interview. I calculated the accuracy and time taken to complete the tasks through the software logs and videos and made behavioral observation notes. I found that the two interfaces, ABD and ARD, performed better than the physical monitor-only interface without AR(baseline) in terms of accuracy in completing specific tasks. ABD interface in AR proved to be more accurate than physical monitors(baseline) for tasks involving correlating the isovist shape and size in relation to visual complexity and openness at a given point. Although, the preferred mode of the interface as per the participant's self-reported data was physical monitors. ARD interface in AR helped the participants identify similar regions across the floorplan and understand the relationship between isovist area and isovist perimeter better than with the physical monitor alone. Participants also performed more zoom and pan operations to see both focus and context regions in the tablet version only for ARD. It was also observed that task accuracy was reduced as the participants found it challenging to see the overlapped information on a physical monitor(ABD). Through self-reported data, participants faced physical load challenges concerning the weight of the HMD due to the tablet's position with respect to the AR content. The learning effect was also observed as the participants took some time to get accustomed to the AR interface, leading to more habituation time to get familiar with interfaces. Owing to these challenges, participants took more time overall while doing AR tasks. Despite these challenges, participants performed better in the AR interface concerning specific tasks.

Implications for hybrid system and space syntax were assessed throught the result from the study. The users having no prior knowledge of space syntax domain were able to understand the space syntax attributes. The implementation also helped analyze that transfer error and learning effect was observed while working with hybrid systems. Research contribution were made toward helping the user identify regions with similar properties in 2D floorplan using tablet+HMD. Another research contribution was made towards understanding two spatial attributes (Openness and Visual Complexity) are related to each other and to the raw isovist data through a layered approach of displaying data above the display interface using tablet + HMD.

The thesis is structured as follows. Firstly, I present some introduction to the space syntax domain. I conclude the introduction with gaps in the space syntax domain. Then I discuss Information visualizations, augmented reality, immersive visualizations, and hybrid systems. This is followed by literature work on hybrid interfaces. Then I present my preliminary work, which elaborates on my background in the space syntax domain and the development of use cases through preliminary work. Then I detail the implementation of VizSSTA and design choices. Then I present the display evaluation, which includes the study design and data collection techniques—followed by the results from the user study I conducted. Then I provide a discussion regarding the system's limitations, contributions, study summary, and the implication of the results of the current system. Finally, I conclude with the final conclusions of the study.

Chapter 2

Background and Related Work

This chapter introduces the space syntax domain and gaps in the space syntax domain. Then I discuss the field of Augmented Reality, which helped make the design decisions during the implementation process. Through a study of related work in interactive visualization, I identified types of visualizations that can be used to present data, related research findings and design guidelines, and the relevance of projecting data through IVs. I also discuss hybrid systems and the advantages of using such systems. Then, I discuss the cross-device communication required among devices that are part of a hybrid system. I then discuss the hybrid interfaces and their impact in the AR domain and the design decisions and guidelines followed across such systems. Lastly, I conclude with the related work conclusion.

2.1 Space Syntax

Space syntax [12] is an area of study comprising techniques and methodologies to understand urban spaces and how human beings use these spaces [102]. The literal meaning of the word syntax in English [5] refers to rules that help define the language's meaning. Hence, Space syntax can be related to regulations that help determine the sense of space. Space syntax emphasizes the importance of space highlighted by Hillier in his book [102] "How the urban system is put together spatially is the source of everything else." Spatial understanding of a given space matters as many decisions made by humans, including movement, standing, and interaction, rely on their knowledge of the space. Space syntax acts as a prediction tool for recognizing patterns and how society or individuals organize themselves and function in a given space [102]. Space syntax helps to determine the relationship between humans and space. Considering how people usually utilize any given area, they tend to exhibit patterns [52] like arranging themselves in a group facing each other while communicating, walking in a line, standing in a queue, and gathering in open spaces. Isovists, also commonly known as the visibility fields [15], are the set of visible points from a given point and are used to analyze the spatial environment, as shown in fig:2.1. Suppose we consider a person at a point in a given space; what the person can see at that point is represented by the isovist. Isovists are the building block of a major class of space syntax analysis.

Space syntax, through visibility graph analysis, helps to analyze the floorplans/layouts of a space. It analyzes the connections in the space by dividing the entire space into a grid and assigning quantitative measures to each grid point, as shown in fig:2.6.

The placement of doors, walls, windows, and the number of rooms in a given space also play a crucial factor in the movement and visibility of the person [48].

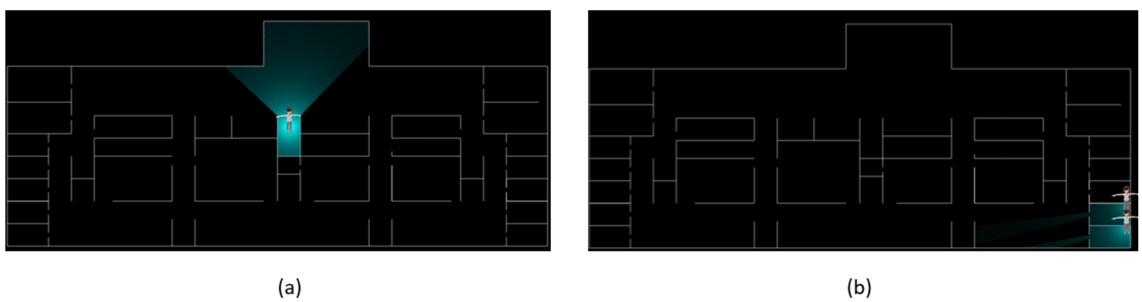


Figure 2.1: Isovist Analysis in VizSSTA: Visible region of the avatar at a point in the given Floorplan.(a) Isovist is large in the center of the floorplan where there are few walls.(b) Isovist is small in more enclosed regions of the floorplan.

Space syntax in previous research has been used to identify scenic spots/best viewpoints [59, 62] to create an environment exhibiting the properties that enhance the viewer's experience. This research referred to areas with maximum visibility with the best overview place and areas of least visibility with the best hiding place. This research emphasized how the participants reported a pleasing experience while traversing through a place possessing large and less complex/jagged isovist. Space syntax has been applied to various scales ranging from a floorplan of a single floor consisting of rooms and door/window information to large cities comprising of information about streets, buildings, etc.

Space syntax analysis broadly can be divided into different classes- convex, axial, and visibility graph analysis. Each analysis has been discussed in the later section of the related work. A considerable amount of work has been done in space syntax, and it has been used across various domains, including urban planning, anthropology, medicine, gaming, philosophy, cognitive and social science. As part of my literature review, I have explored the space syntax implementation across the gaming and entertainment domains. The motivation behind exploring these domains was owing to my preliminary research and use cases developed from this research 4: Story CreatAR is a tool for story authors that helped the authors in placing story elements as per spatial rules. I have discussed more about Story CreatAR in the section 4.

A study by Seung-Kwan Choi et.al[33] shows that the visibility model of the object placed among the different game levels helps control the game's flow and influences the behavioral pattern by motivating the players to progress in the game. In this study, the game objects: enemies, characters, and weapons were placed as per the spatial characteristics: easy to find and high visual exposure. Haunted House [27] is an escape room procedurally generated game developed using spatial properties. The game levels were made challenging by predicting the player's movements with the help of convex, axial, and visual graphic analysis through the DepthMapX [96] tool and performing object placement using convex, axial, and visual graphical analysis. Adventure AR and ScavengAR [83] walkable AR games use connectivity between two regions, openness of a given space to place game elements. The two proof of concepts support decision-making by allowing the designers to put the game assets at optimal locations, e.g., "keys" in areas that are hidden or difficult to find and "chests" at spots that are easier to find, hence creating an immersive AR experience also shown in Fig: 2.2.

Seeing or Being Seen [103] reveals the importance of a line of sight at a public attraction site to create an immersive and interactive visual experience to attract visitors to revisit the same place. According to this study, if a viewer's line of sight is presented with an engaging or attractive view, the average movement of the viewer decreases and increases the proportion of revisiting a space. The above research help to identify to how much extent the space syntax research has been used across various domains. Various commercial and research tools are available for conducting space syntax analysis, including DepthMapX [97], QGIS [80], and Grasshopper [26]. In this research, I am using DepthMapX.

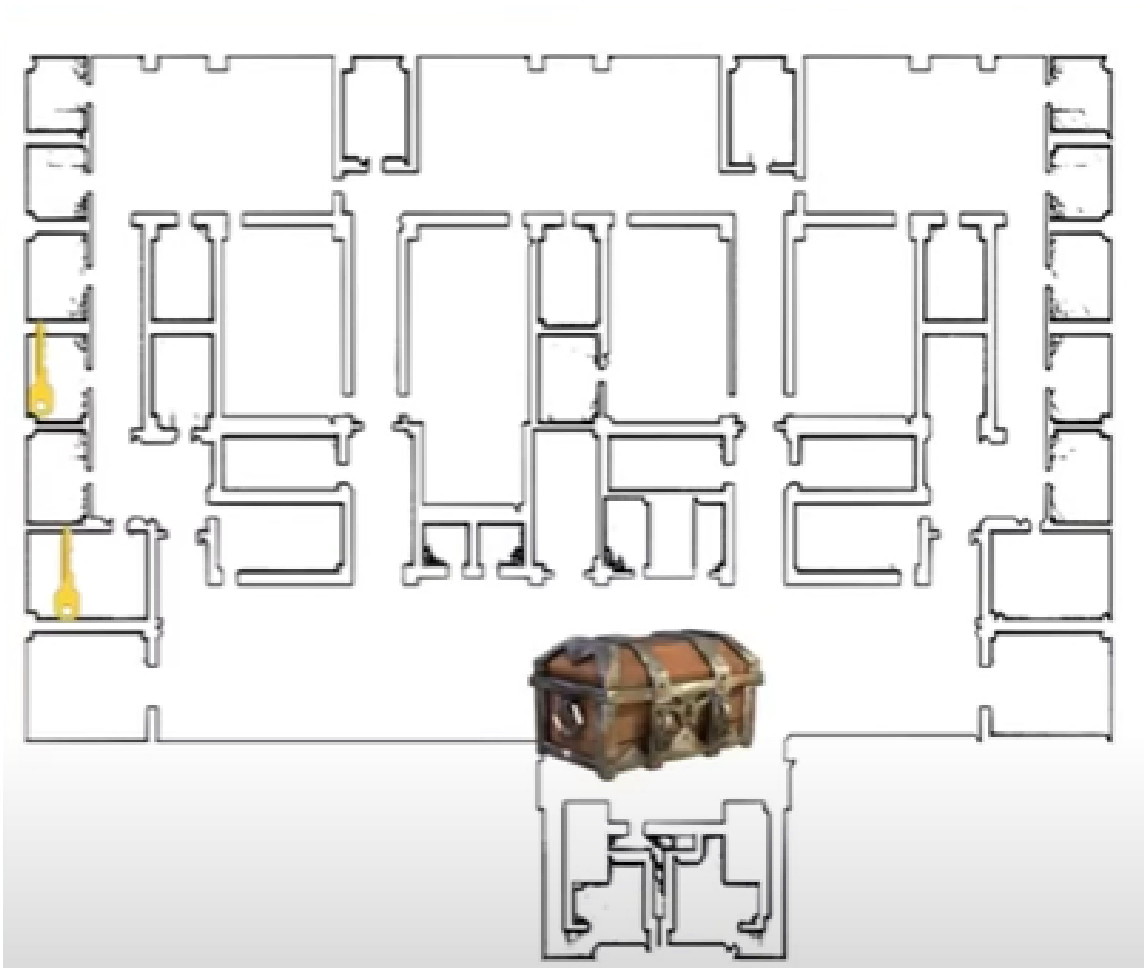


Figure 2.2: Mona Campbell building setup where the chest is placed in areas of high visibility or easy to find and keys in areas of less visibility in the corners.

2.1.1 DepthMapX

DepthMapX is an open-source multi-platform tool used for conducting spatial analyses of architectural systems and urban buildings [37]. Conceived at the Space Syntax Laboratory[97], University College London, it was created to perform isovist integration analyses to represent the urban spaces as visual networks. Isovist [95], in layman's terms, is described as a polygon representing the amount of space visible from a given point in space. Currently, DepthMapX supports convex, visibility graph, axial lines, agents analysis, along with isovist analysis [37]. The analysis is discussed in the later sections of the thesis. The various analyses convey specific information about the urban space: agent analysis provides the metrics relevant to movement

or flows in the area, and convex analysis describes how the regions in the space are interconnected. DepthMapX can analyze small and large urban spaces varying from buildings, cities, or regions. DepthMapX can help understand and analyze the area's spatial configurations and usability. DepthMapX offers a command-line interface and a graphical user interface for creating graphical visualizations representing the various phenomena, the visual representation of analysis is discussed in the later sections.
DepthMapX has been used in numerous research to evaluate the spatial qualities of a space and identify if any relationship exists between the space and various attributes like crimes and social behavior. It has been used for wayfinding, obstacle avoidance, and urban planning.

2.1.2 Attributes in Space Syntax

The classification of space syntax analysis can be divided into a couple of significant classes- Visibility graph analysis(VGA), Isovist analysis, Axial analysis, Agent analysis, and Convex analysis [53] —each type of analysis has a different meaning. This chapter will briefly introduce convex, axial, and agent analysis. I will be focusing on visibility graph analysis and Isovist analysis, given that our use cases evolved around these two concepts.

Axial analysis is mainly used for cities and streets. It conveys how humans traverse the city to reach from one point to another and how a point in space is visible from one place to another [12]. An axial map, also known as the linear map, is created by extending the longest lines of sight of movement from one location to another in the given space [12]. Figure 2.3 shows an example of the axial map of Barnsbury.

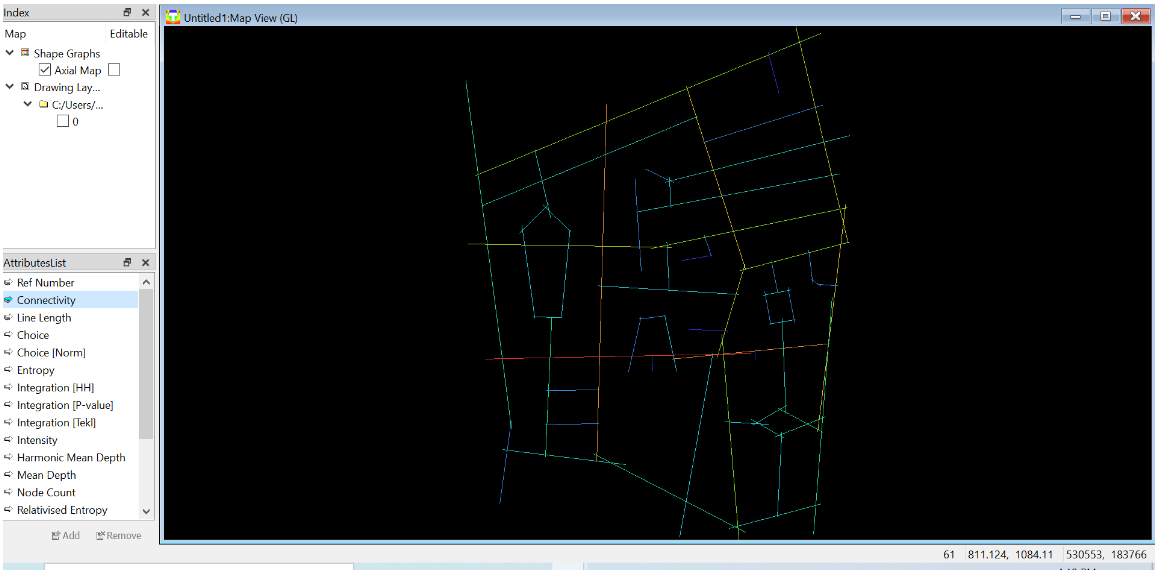


Figure 2.3: Axial Analysis in DepthMapX: Connectivity of the streets in Barnsbury. Figure generated by the author.

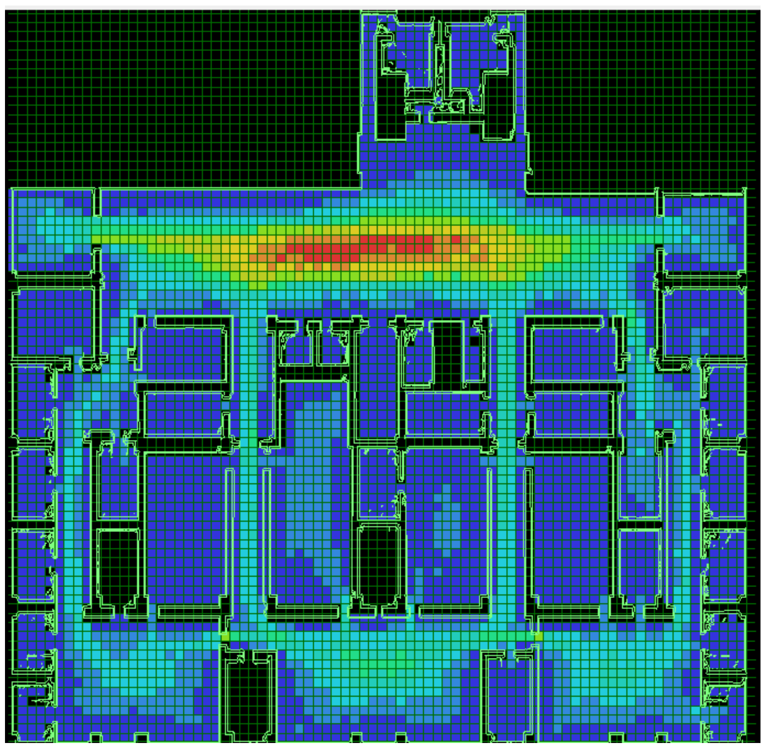


Figure 2.4: Agent Analysis in DepthMapX: Movement of agents across the fourth floor of Mona Campbell building.

Agent analysis is used to predict human movement patterns and wayfinding by comparing it with the individual navigational patterns of agents in the DepthMapX tool. One of the output attributes in agent analysis is gate count, which defines the pedestrian flow per time at a given point in space [10]. Figure 2.5 shows an example of the agent analysis as conducted in a Mona Campbell Building, Dalhousie University. This shows that the more agents traverse in the central open area displayed in red and less in the corners displayed in blue colors.

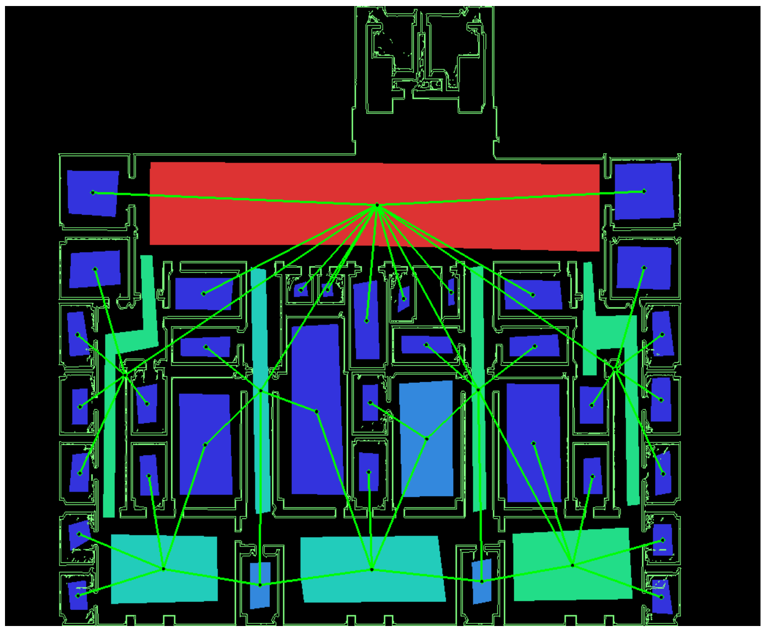


Figure 2.5: Convex Analysis in DepthMapX for the fourth floor of the Mona Campbell building.

The convex map uses convex space partitioning to create a set of enclosed areas in an urban place [12]. This analysis is an iterative process of identifying the biggest and fattest areas until the entire region is filled with convex spaces. The convex map enables the users to determine how well the convex spaces are connected. The convex map is a graph: each convex space is represented by a circle or "node," and a link between these spaces is represented by lines or "edges" [12]. Convex maps help identify depth:(how many syntactic steps are required to reach), connectivity, and how well integrated the places are with the entire space. In terms of connectivity within the convex analysis, a specific convex area with low connectivity conveys that many convex regions do not connect directly.

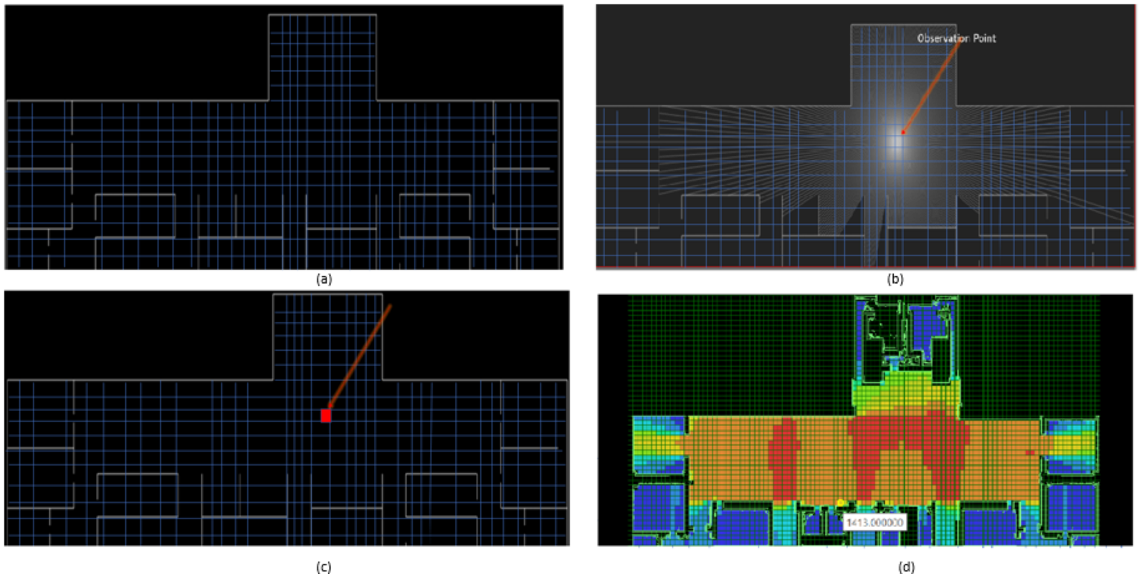


Figure 2.6: Grid Based Analysis in DepthMapX. Starting from top left:(a) the process starts with the creation of the grid (b) and at each grid point, the isovist is projected and (c) the isovist-based attribute is calculated (isovist area in this case), and a colour representing the value is assigned to that point; (d) the process repeats until the entire grid is filled.

Visibility graph analysis(VGA) is a graph-based representation describing mutual visibility between any given points in space [64]. It is achieved by creating a grid over the area denoted as nodes, and further, the connections between each grid point represent the visibility. For the simplicity of the graph, edges/lines are not drawn to represent the connection between any given point in the graph. Instead, the number of connections is represented through the values assigned to each grid. A color spectrum is used to assign the colors to each grid- Red denotes the high values, and blue corresponds to the low values of a specific measure [94]. Figure 2.6 represents the process of grid-based analysis and how the colors are assigned.

For the sake of simplicity of the thesis, we focus on the parameters related to the use cases explored in the study - connectivity, isovist area, and isovist perimeter.

Connectivity

Connectivity represents the number of visually accessible points in the space from a given observation point [98]. In Figure 2.7, red points in the space represent the locations with the most connectivity to all the other spaces in the floorplan. In contrast, blue points represent the points having low connectivity to all the other places on the floorplan. Connectivity, also called accessibility, is helpful in identifying well-connected zones in the floorplan.

Isovist Area

Isovist Area represents the spaciousness of an area [40, 78] and is represented by the space visible from the given point [89]. The more spacious the area [44] is, the more value the Isovist Area at the specific point. The place with the largest Isovist Area can be the best viewing area [59] since it corresponds to the openness of the space, and one with the low Isovist Area can be considered the best hiding spot [59].

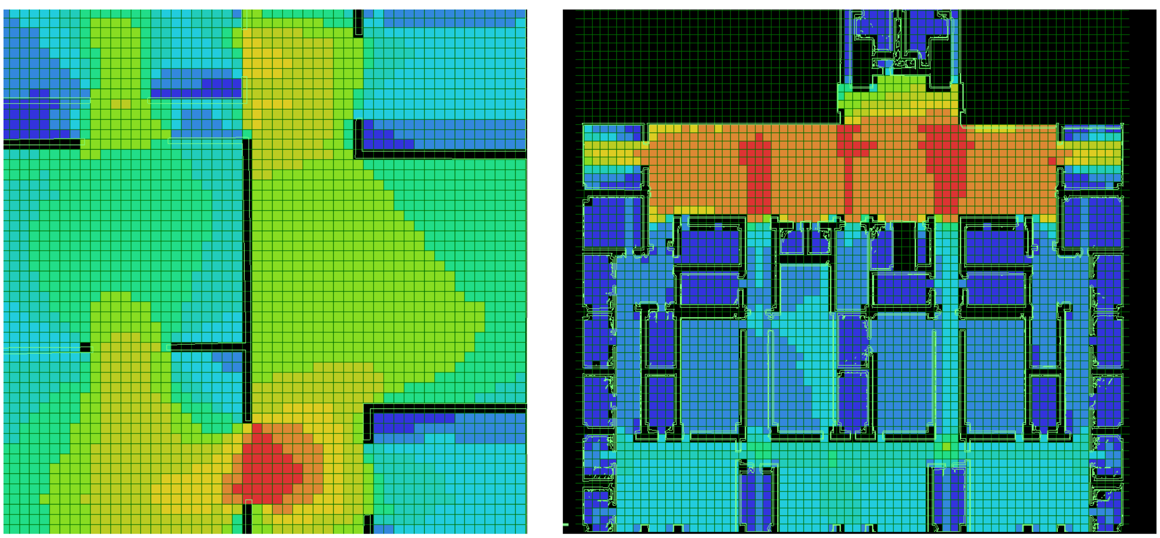


Figure 2.7: Left: Connectivity for a floorplan, this floorplan was created with the help of Roomsketcher [9] and inkscape [56]. Right: connectivity in the Mona Campbell building (4th floor), Dalhousie University. Both the images follow rainbow gradient: values varies from red to blue, red representing very high values to blue representing low values.

Isovist Area has been implemented to identify the places. Figure 2.8 represents the zones having high Isovist areas in red color. Mathematical Equation for Isovist Area [6]

$$Av = \pi/n \sum_{i=1}^{n} Li \tag{2.1}$$

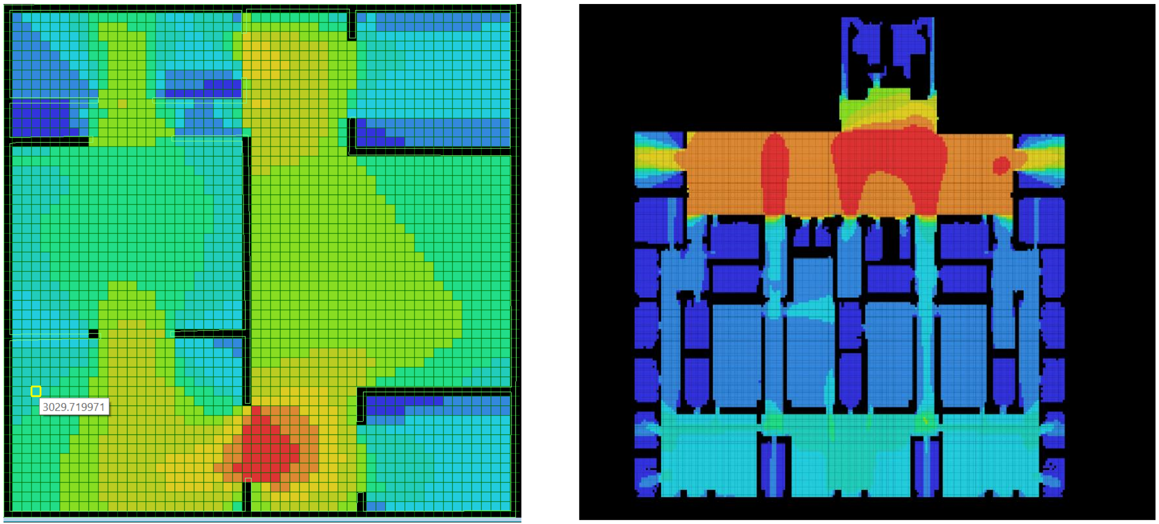


Figure 2.8: Left: Isovist Area for a self generated floorplan Right: Isovist Area in Mona Campbell Dalhousie University. Both the images follow rainbow gradient-values varies from red representing very high values to blue representing low values

where L represents the length of the edges

$$Li = \sqrt{(X_i - X_V)^2 + (Y_i - Y_v)^2} \tag{2.2}$$

Isovist Perimeter

Isovist perimeter [6] denotes the perimeter of the space occupied by the isovist. As the shape of the space becomes spikier, the perimeter of the space increases. A well-connected place in the space has an spiky and extended isovist. Regarding visibility, if the Isovist is spiky, there might be many regions in the space that are not visible. An open space will have moderate values for isovist perimeter, while a space with obstacles like walls, windows, poles, and others in the floorplan will have relatively high values. Figure 2.9 represents the different zones through the rainbow gradient. The mathematical equation [6] for isovist perimeter is:

$$Pv = k/n \sum_{i=1}^{n} Ei \tag{2.3}$$

$$Ei = \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2} \tag{2.4}$$

where E represents the edges, k represents the number of samples in a 360-degree view, and n represents the total number of samples.

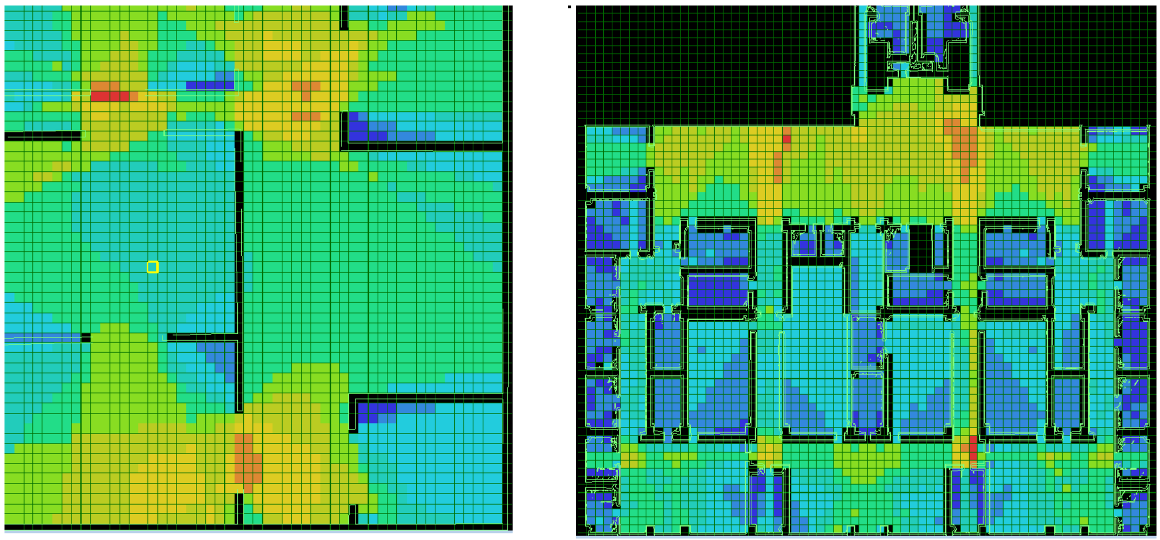


Figure 2.9: Left: Isovist perimeter for a self generated floorplan. Right: Isovist perimeter of the DepthMapX in Mona Campbell building, Dalhousie University. Both the images follow rainbow gradient- values varies from red to blue, red representing very high values to blue representing low values

2.2 Leveraging Space Syntax Understanding

This section highlights how the space syntax understanding is lacking among the general public and how the terminologies are generally misinterpreted [88, 68, 81]. Information visualization of space syntax attributes [68, 88] can help understand the space syntax attributes by reducing the amount of time and effort required to communicate the space syntax results. These visualizations, in turn can help in the decision making and predict pedestrian movements and traffic patterns. This can also help in better usage of the space syntax analysis: VGA, axial analysis, and convex analysis as the data presented through the IVs is easy to understand [55], and these analyses are lagging in terms of implementation owing to the complex nature, and lack of understanding [14, 51].

Information visualizations [68] have been used in space syntax analysis to identify pedestrian movements and traffic patterns. This research mentioned three different visualization techniques, which helped in the challenging decision-making by highlighting the significantly important or influential roads, networks, or places. The visualization technique highlighted important roads of intersection and high/medium/low pedestrian movements on top of the model map with the help of standard color scales used in DepthMapX. The visualization techniques were evaluated with a pedestrian movement survey conducted for eight hours to identify congestion and real-time pedestrian movements. These visualizations helped the decision-makers by focusing their efforts on significant places, such as focusing on critical intersections or where the pedestrian movements are high. Axial analysis parameters were used for the Space Syntax. This research also emphasizes the creation of open libraries, which can help visualize the space syntax, encourage space syntax usage, and help in decision-making. VizSSTA also uses highlighting having very low, low, medium, high, and very high areas as part of ABD and ARD for visibility graph analysis to bring attention to the aspects the users are interested in.

Despite the application of space syntax across various domains, there exist no clear guidelines in the absence of pre-existing knowledge or guidance in space syntax [68, 81]. The complex mathematical calculations make it furthermore challenging to understand the attributes [14, 81]. Another challenge raised in the adoption of space syntax by the architectural, design practitioners, and other policymakers is the translation of space syntax across various domains [14]. This requires making the space syntax terminologies more comprehensible for the general audience.

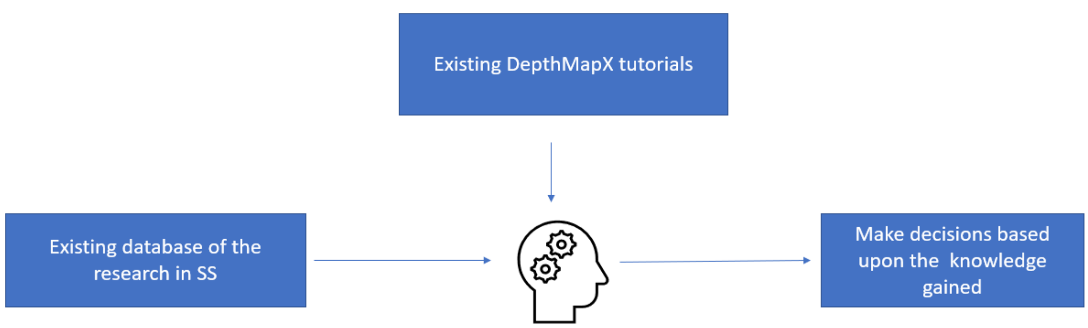


Figure 2.10: Research through student analysis which focuses on making decisions through small database of research findings of space syntax and existing DepthMapX tutorials.

An attempt [14] has been made to include space syntax into the design curriculum to facilitate understanding and proper usage of space syntax attributes. A student analysis was performed with third- year architecture students to identify how the decision-making process can be supported using existing resources. Third-year architectural students were asked to redesign historic hotels using the spatial properties of the area. As part of the existing resources, DepthMapX tutorials and brief summaries of space syntax papers and publications were used by the students, along with some examples of attribute usage. It was identified that the students felt that the information helped them make design decisions like what to design and what areas to focus on in the plan, as shown in Figure:2.10. This paper highlighted that using the DepthmapX tool is challenging as a VGA analysis requires setting a couple of mathematical values like radius for calculating the axial analysis and visibility relationships for VGA analysis. VGA analysis in the tool takes a long time varying from 10 minutes to hours. Additionally, the tool does not provide much interaction as expected by the designers. VizSSTA reduced dependency on the DepthMapX tool and similarly complex alternatives as it intends to help the users understand and explore space syntax propertiesand their relationship to the fundamental isovist. DepthMapX and other tools presume that the user is familiar with how higher level space syntax attributes are derived, or at least what they represent.

Publications exploring the attributes in space syntax in Isovist analysis are scarce, and current research appears to be more concentrated on applying axial map analysis [14]. Existing publications in Isovist analysis focus on attributes like connectivity, Isovist Area, and through vision which is relatively easier to understand.

2.3 Augmented Reality

Augmented Reality (AR) is a term coined in 1992 and refers to the technology of merging virtual and physical worlds by overlaying computer-generated images in a real-world environment [16, 101]. AR technology aims to enhance the user's field of view, hearing, and sense of interaction by integrating the real world with the digital world content in a way that does not replace all of the user's field of view with digital content. AR comes under the category of mixed Reality, which is the term used to refer to the concept of integrating the real-world and digital world.

Augmented Reality does not remove real-world objects but integrates the digital world into Reality. AR concept [11] has three essential requirements- interactive in real-time, registered in 3D, and combining real and virtual content. Various forms of AR have been developed and are just not limited to Head-Mounted Displays(HMD) like Google glass, and Microsoft HoloLens, among others. Other mobile technologies which support AR are termed Mobile AR, and devices that support such AR are tablets, PC, and mobile phones, among others. AR requires high accuracy for tracking and sensing [11] as the AR objects need to be aligned with the real-time objects. A pointing device acts as an anchor for the placement of AR objects in the real world [11]. The AR objects are placed in alignment with the pointing device. Augmented Reality works by placing the digital content by using physical markers like QRcodes in alignment with the real-world content, and this is called marker-based AR; markerless AR is also supported today, which tracks physical positions for the object's placement [16]. AR has been used in museums, medicine, gaming, sports industries, office, education, and training [16, 101]. AR is also used as a shared space [55] to discuss, view, and share different types of information among users.

As part of our research, the pointing device is a tablet, and I have used internal tracking through built-in HoloLens and QR-based markers for the placement of AR objects or holograms in alignment with the tablet.

2.4 Information Visualization

Information visualization refers to a graphical representation of information, also referred to as Infographics [91, 90], Infovis [91] and data visualization [91]. The origin of IVs happened in the late sixteenth century to support data exploration and ease of navigation across data [31]. The main objective of IV is to present data in a memorable and interactive or non-interactive format, which may assist users in identifying trends, exposing outliers, and identifying abrupt changes [63]. Early trends in IVs used maps, bar charts, scatterplots, line charts, and pie charts, among others, to represent data in an informative and meaningful way [63]. IVs are a computer-supported visual representation of abstract data which intend to amplify cognition [43]. Dynamic and interactive visualizations support features like zooming, panning, filtering, selection, marking, relating one data to another, and others [43].

Such visualizations help reveal patterns that may otherwise take several days to be recognized. IVs enable us to get insight from the data through data exploration and helps to answer unanswered questions. It also leads to data reduction as it helps to remove uninteresting patterns. Information exploration happens through interaction with the data. Users usually initiate interactions with a set of goals in their mind or to explore the data. The interaction process continues until the user is satisfied with the information or has received the desired information. Fig:2.11 represents how the cognition takes place as the information is presented. As per the current research [34, 54], there are four categories of information visualization for presenting data overview+detail, zooming, focus+context, and cueing. Overview+detail [24] refers to simultaneous information presentation where a spatial partition in a single view separates both overview and detail as shown in Fig:2.12 (a). Zooming and panning are tightly coupled with detail. One example of this is Google Maps, where we see a small window at the bottom as the detailed and full-screen size of the map as an overview. PowerPoint is another example. Fisheye lenses are one type of focus+context where the focused region and contextual information are presented in a single view without any separation also shown in Fig:2.12 (b). Zooming refers to visualizing the context and detail data with a separation view in a single display as shown in Fig:2.12 (c) and (d). Cueing enhances the data visualizations by highlighting, suppressing, or adding different identifiers to the selected information.

As part of the thesis, I have used the focus+context technique to project the data in ARD by keeping both the focus and context region in place and projecting both regions: the focus region in the tablet space and the context region in the AR space. I have also used cueing to highlight the data of interest both for ABD and ARD interfaces. The selected data among the layers in the ABD interface is highlighted, and non-selected data among the layers are removed. In the ARD interface, the data of interest is highlighted while the non-selected data remains as it is.

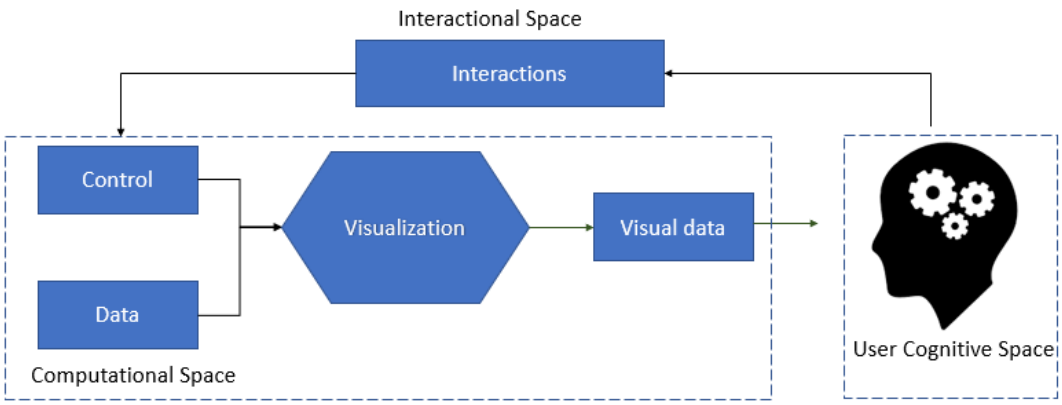


Figure 2.11: Information Visualization cognition space: User cognition space is expanded by giving control through the interactions over the visualizations created from the data. Additionally, interacting with visual data helps in understanding the data.

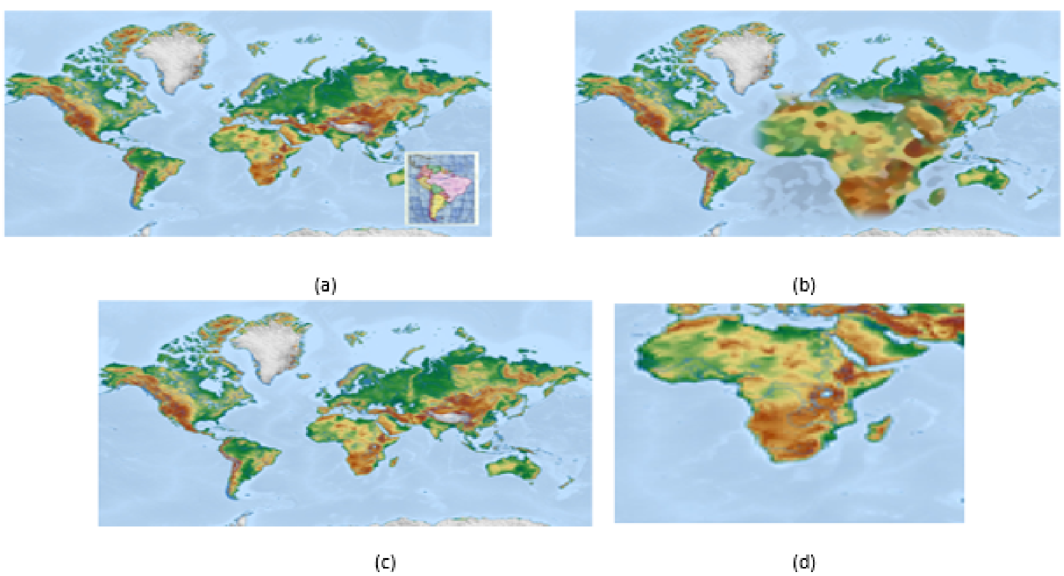


Figure 2.12: Types of Information visualizations: (a) is an example of overview+detail with a small window of focused region in the bottom,(b) represents focus+context view with zoomed region in center without any separation from its context, (c) and (d) illustrates zoom technique with separation between the focus (d) and context(c) region in separate windows.

2.5 Immersive Visualizations and Information Visualization in AR

Augmented reality supports representing large data sets in engaging and comprehensive visualizations by adding a dynamic and interactive layer into an existing visualization [63, 84]. The large effective display region in AR as compared to physical monitors helps to visualize large data sets [104]. Visualizations in AR often suffer from lower resolution, lower brightness, and colourfastness issues due to hardware constraints in current AR HWDs as compared to physical monitors [104].

IVs in AR help to visualize data for exploration by augmenting physical objects with rich digital data [84]. One example of this is looking through the mobile device/HMDs to identify what physical objects we are looking at [61, 70]. displaying the AR digital data along with the existing physical objects [61]. This is one potential use of AR for visualization and I am not exploring this in our research. Different ways to combine augmented reality with static visualization in the physical world are extended, composite, small multiple views, and multiple views [32]. The extended view combines static and virtual visualizations by presenting two different datasets in the same view. The composite view integrates virtual information in the form of extra details or another dataset on top of the static visualization to enhance comprehensibility. Small multiple views help to visualize different datasets with the same visual encodings. E.g., Dataset for the crime rate in 2001 and 2010(two different datasets) may be presented through a bar chart(same visual encoding). Multiple views refer to visualizing datasets through different visual encodings to allow different data perspectives. One view comprises static visualization and the other of virtual visualization. E.g., Representing information in a dashboard through pie charts and line charts. I have used an extended view of the IV in AR for ARD to present the information around the tablet display. Additionally, I have used a composite view of the IV for ABD to present the information above the tablet. Figure 2.13 shows the different types of Augmented reality visualizations supported that can be combined with the physical world.

Carr et al. [30] describe the guidelines followed by designers of IV applications to design IVs. General view, filtering, zoom, details on demand, extract, and relate are high-level interaction goals [13] that are performed by the users when interacting with visualizations. I have followed the design guidelines to achieve these goals for

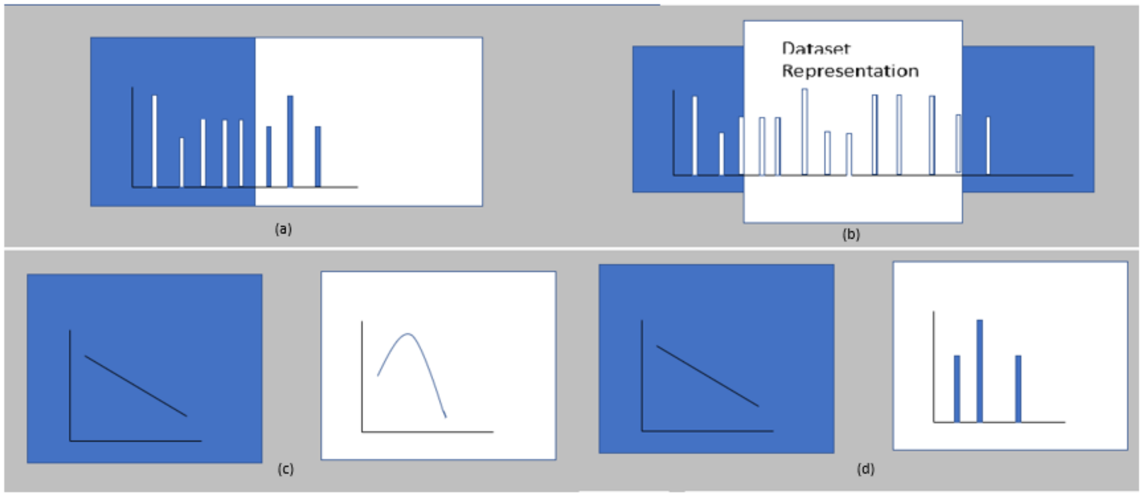


Figure 2.13: Different ways to combine the Augmented reality visualizations with the physical world:(a) illustrates extended view, (b) is an example of composite view, (c) illustrates small multiple views, and (d) illustrates multiple views.

visualizing the IVs for ABD and ARD as described in the Implementation section:5.2.3 of this thesis. As per these guidelines, while choosing visualizations, one needs to analyze the type of dataset for which visualization occurs carefully. One-dimensional visualizations are well suited for text, while two-dimensional data [63, 30] appears to be best for floorplans, scatterplots, bar charts, and similar. In this thesis, I have created 2D dimensional scatterplots to visualize the floorplan in AR.

2.6 Hybrid Systems

Hybrid systems [29] are created by integrating or fusing heterogeneous systems like tablets, tabletops, traditional desktops, LCDs, AR, VR, tabletop, and others. The objective of the hybrid systems is to strike a balance between the complex technologies by mitigating the tradeoffs like small screen size, hardware complexities, cognitive overhead through context switching, the field of view, cost, image quality and resolution, and others [55]. A Hybrid system offers a superset of the main features involved in the integration. E.g., Limited screen size has proven to be a limitation for traditional monitors. CAVE 2 [41] combines the traditional desktops with LCDs to visualize large and complex data. This research helps us use the continuous space above and around the displays for interaction and visualizing the data. Hybrid systems synergize the capabilities of one interface with another, resulting in systems with the best of both world features. Hybrid Systems also help reduce clutter created by dense visualizations in one interface, making it easier to understand, read, and recognize patterns. Moreover, fusing augmented reality interfaces with physical systems helps layer data and encourages side-by-side comparison. In order to reduce cognition overhead, some hybrid systems use only one system as input for interactions like click, drag, and hover. However, both the systems are used as output for visualizations [100, 77]. Hybrid systems created in Augmented Reality/Virtual Reality allow the users to move around the visualizations freely.

Cross-device communication is required to establish communication between the hybrid systems where one system's interactions are coupled with responses in another system [55]. Cross-Device Interactions [23]are categorized into multi-monitor workstations, multi-device environments, and ad-hoc mobile cross-device use. Within the scope of the thesis, I am exploring ad-hoc mobile cross-device use, which leverages the ubiquitous availability of tablets and Head-mounted displays. A layer of data is spatially distributed across multiple devices. To make synchronous cross-device communication among the devices such that the interactions happen simultaneously, one needs to make sure that tracking the devices involved in the configuration is either through outside-in or inside-out techniques. Outside-in techniques refer to detecting the devices through the depth sensing cameras or sensors present in the environment, while the inside-out approach utilizes built-in sensors, this approach is lighter in weight. In the thesis, I am using inside-out techniques for detecting the device in the environment with the help of markers and in-built camera in HoloLens.

2.7 Hybrid Interfaces

This section summarizes the contributions of the related work, before going through each related work in depth.

Information visualization in Augmented Reality with the help of hand-held devices or touch enabled systems such as tablets, smartwatches, mobile phones, and other devices combined with head mounted devices have been explored across various domains [13, 46, 67, 77]. Information visualizations using hybrid systems help create

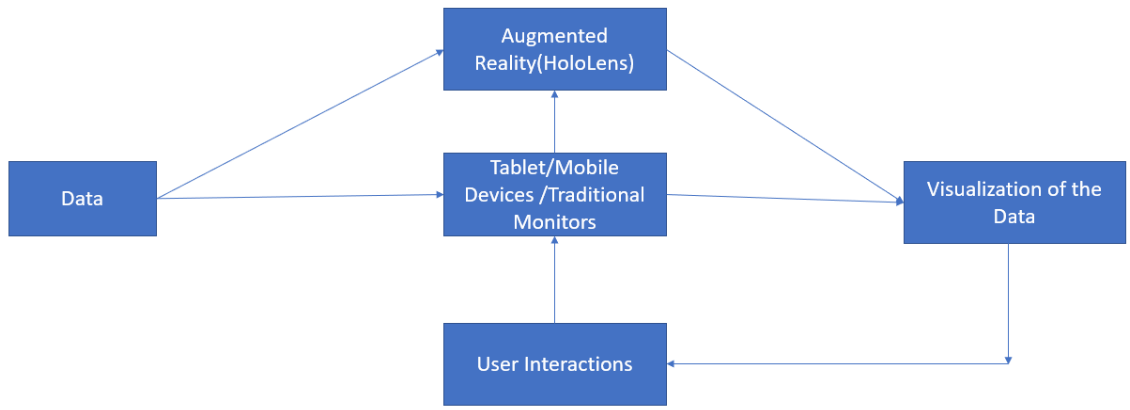


Figure 2.14: High Level implementation in Hybrid Systems- Data is projected through HMD and tablet/physical monitors/mobile displays and user interactions are supported through the tablet/physical monitors/mobile displays.

an environment where the users can perceive and interact with the information from the mobile displays, wearable devices, and other physical devices by expanding their cognitive space from 2D display to 3D display [57]. ARts(Augmented Reality with Tablets) by Hubenschmid et al. [54] display the 3D scatterplots on the tablet surface and allow the users to link individual scatterplots as per the proximity of the tablets. Langner et al. [67] arranged the 2D and 3D visualization above, around, and between the tablet surfaces. Langner et al. [67], and Hubenschmid et al. [54] helped in identifying how the visualizations can be distributed across the interfaces and how they can be aligned to the physical monitor. Harvard et al. [49] conducted a comparative study to compare techniques of displaying maintenance instructions in AR and through a document within the tablet. This helped identify that AR helps in a bigger picture and understanding the information better than information displayed on the tablet. The expert feedback on the prototypes in research by Langner et al. [67] helped in making the design decisions during the design and implementation process such as readability of the details in AR is essential, precise and efficient touch interactions can be supported in the hybrid systems, and inside-out tracking technique should be considered while supporting a non-laboratory environments. This is the only research identified in the literature review which used HoloLens v2 and conducted a feedback session with HCI and visualization experts to evaluate it. A study with HoloLens v2 [2] is vital to the current research as HoloLens v2 is the latest version of the Microsoft HoloLens, and it provides a larger field of view and better resolution and is lighter in weight than HoloLens v1. The research also provided the information that cross-communication can be established between the devices in the hybrid systems through the websockets by establishing a client-server communication. Numerous research [77, 36, 46, 100, 39, 55] explored on which interactions work best for hybrid interfaces. These systems influenced the design decisions for VizSSTA in terms of interactions supported in the tablet, or 2D displays are more accurate and easy to perform than the interactions in AR. I can conclude that intensive research has been done to implement hybrid interfaces. However, very little research has evaluated the prototypes through controlled studies.

With MARVIS(Mobile Devices and Augmented Reality for Visual Data Analytics), Langner et al. [67] offload components like menus, data, buttons, and legends to the AR space and provide a detailed information view on a tablet display. The main contribution of this research is an exploration of the design space of extending 2D displays with the help of AR. It used the space above and around the device and between two mobile devices for projecting data in AR. One of the visualization techniques used was the focus+context technique to display the IVs, and details on demand were used to show the data items in AR. One use case for this was extending the map visualizations outside of the tablet surface, as the small screen of the tablet display cannot preserve the context details while the user zooms or pans in. The information on crimes in a neighborhood was displayed through circles on top of the map. Each circle is the sum of the crimes committed in that specific area, and if the user clicks on the circle, the circle gets selected, and a double click shows details about that point. One other technique used to display the data was to show multivariate data in the form of bubble charts extended with glyphs in AR. The use case displayed the income per person for each year. If the user clicks on the bubble, a glyph appears, which shows how the data changed over time. The 3D data helped identify how the data developed over time. Expert feedback evaluated the proof of concept systems by identifying missing functionalities, successful aspects of the designs, and design issues and alternatives. VizSSTA implementation is similar to this research for ARD focus+context implementation. VizSSTA also extends the floor-plan visualizations outside of the tablet in AR once the user zooms in to the details. I have also incorporated the feedback given by the experts regarding the readability of the details and text. The text and details were made big enough to ensure that the details were readable.

Grubert et al. [46] is another research on hybrid systems that combines HMD with physical/mobile devices like smartwatches and mobile phones to extend the interface by placing menus, lists, zoomed-in views, and other interface elements beyond the device's physical screen. A controlled lab study helped analyze the MultiFi(Multi-Fidelity interaction displays on and around the body) system through two main tasks-information search(finding the lowest price label) and selection(navigating to the target). The system was compared across five conditions: hand-held and smartwatch, and HMD were baseline systems using standard input and output to display the visualizations. In comparison, body reference(BodyRef) interaction referred to a system comprised where the interaction space(output of the data) of AR was aligned with the user's body, and smartwatch reference(SWRef) referred to a system where the reference space of AR was aligned with the smartwatch/device. Task completion time, errors made throughout the task, subjective workload, and user experience through semi-structured interviews were used to evaluate the systems. One of the issues was confusion among the participants in selecting the output display for AR, mobile devices, and physical devices. It was observed that the SWref system reduces the task completion time compared to the time taken using wearable displays. This study used AR and physical devices as input devices, which confused the users while interacting. Heavy lab pieces of equipment were used, contributing to a higher perceived workload. This research influenced the design of VizSSTA, where I use a physical monitor as input and both AR and physical monitor as output for visualizations.

A case study by Havard et al. [49] with the participants evaluating two systems: one which presents information within AR through a tablet display and another system showing the information within a PDF document in the tablet. This comparative study was done to explore how the participant's expertise with the tasks impacts each system's usability. The system comprised manual instructions provided in AR or the tablet-only version without AR. It was evaluated by operators with expertise across three levels- Beginners, intermediate and advanced users. Their expertise was determined with the help of a questionnaire. The study comprised 20 participants, and data analysis included various factors like the total duration taken to complete the instructions, consultation duration(time taken to understand what the users are supposed to do), the duration for each task, NASA-TLX, operator's satisfaction through SUS and interviews. Each step's duration and duration to complete the entire task was extracted from the videos. Advanced users could understand all the tasks 34 percent faster in AR, given the AR content calibration is fast enough. Moreover, AR display also helps to see extensive views of the bigger picture and contextualize information better as the AR allows to zoom in and out of the information. This was concluded through a specific task that involved localization of the information. Also, AR has a low error rate as AR allows contextualizing the information on real objects. Since the prototype used a tablet to visualize AR, this added a constraint and made it difficult for beginners and intermediate users to use it. The participants had to place themselves correctly to visualize AR content. This research concluded that projecting AR information helps the user perform better as AR localizes the information in the real world and gives a better view of the data than looking to and fro in the document and performing the instructions.

Normand et al. [77] through an experiment evaluated whether a mobile display with a comprehensive view of content in AR through HMD provides an advantage over the phone-only display. A comparative study evaluated systems with three different kinds of interactions: Phone only, another with phone interactions and AR as output (PhoneInAROut), and phone and mid-air interactions as both input and output(MidAirInAROut). Twelve participants performed tasks that involved selection, zoom, pan, and drag to classify similar items into one container. The results were concluded with the help of task completion, error making while doing the selection, frequency of operations like zoom and pan performed in each task, and TLX. The quantitative data analyzed that there were more errors and interactions were difficult in AR(mid-air) than using the mode of interaction as a physical device like a phone. This was due to unreliable sensing by the AR hardware, and a few interactions were just tiring for the participants to perform. The results showed that participants did fewer zoom and pan operations across the MidAirInAROut. Participants did more physical navigation and found it difficult to perform operations in AR. The conclusion was that the users prefer the system PhoneInAROut systems over the two other- phones only and MidAirInAROut. This was owing to overall ease of use, speed, and performance. The selection error was also less as the participants were using the interactions which there were already familiar with. This research helped with the design process decision for input devices for interactions. This study also stated that using the latest and considerably lighter HMD device with a larger field of view would help reduce the latency and eliminate the issue of unreliable sensing.

Reipschläger et al. [39] present a 2D and 3D modeling hybrid system, also called augmented workstation, that presents a seamless integration of Microsoft HoloLens and Microsoft surface pro to visualize objects above and around the screen in the 3D reality space. The prototype extends traditional modeling and design space by offloading the UI components like menus and 3D models in the space above and around the physical display in AR. This system proposes L1, L2, and L3, three ways to invoke interactions in display and AR space as per the proximity of the 3D/2D objects with the display. Interactions in L1 space imply offloading UI components or 2D objects from the display into the AR space using touch and pen inputs on display. Touch interactions were supported in L1 due to better precision and were less challenging than mid-air interactions. L2 interactions were invoked when the components were at the edge or in close proximity to the display. These interactions were handled with the help of a frame around the display, which helps control and manipulate with 3D objects. L3 implies a weaker connection between AR objects and the display and refers to 3D models outside of the display, supporting mid-air interactions to manipulate the 3D instances. The paper highlights the challenges faced while creating the prototype, such as limited field of view and limited resolution due to the hardware capabilities of the HoloLens. Anchoring the 3D objects in AR with respect to the physical objects was another challenge that the researchers faced, hence manual anchoring was used. This research also highlighted that projecting AR objects on displays with light backgrounds creates an issue for the visibility of AR content. This research lacks a controlled study to evaluate the prototype.

Hubenschmid et al. [55] combines tracker enabled spatially aware tablets and head-mounted displays to project scatterplot visualizations in Augmented reality.

This prototype offers novel eyes-free interaction and voice commands to interact in AR and tablet setup. These interactions allowed the users to seamlessly interact with the tablet and AR by making selections on a tablet while not looking at it. The tablet interactions were mirrored in the Heads up display(HUD). This way, the users could perform the interactions on the tablet without looking at it. The user's head gaze was also used to place the objects in AR. This proof of concept visualized linked 2D scatterplots indicating that the data flows from one scatterplot to another. Linking between the scatterplots was done through the head gaze, and it helped the users to filter the data from the subsequent scatterplots by removing the data which is not contained in another scatterplot. This research sheds some light on why the tablet was used in this research due to its easy selection feature and mobility. Cross-device interaction in this system is established through the TCP and WebSockets. A study with 8 participants was conducted, and software logs and user feedback were collected to evaluate it. Selection through eye-free interaction was evaluated, and it was identified that participants preferred auditory feedback rather than visual feedback. Through the user feedback, it was determined that the users understood the visualizations quickly, although they looked complex initially. The logs determined that the participants required some time to get familiar with the system due to the less familiar eye-free interactions. The STREAM prototype also highlights the limitations of using the HMD-based interactions, such as they are less accurate and tiring. This prototype involved the usage of heavy pieces of equipment along with spatial sensors and HoloLens 1, which has a limited field of view and relatively more device weight. Moreover, this study was relatively short due to the heavyweight of HoloLens v1 and giving some time to the participants to get familiar with the HoloLens, also called the Habituation period.

Butscher et al. [54] explored yet another hybrid system that uses space above the tablet display to represent 3D models of the linked scatterplots in AR. Scatterplots are displayed on top of the tablet display, which allows them to arrange the scatterplots manually by rearranging the tablet devices. Each scatterplot was configured with the help of touch-based interactions, and 3D links between each scatterplot. This design allows the users to work on the different scatterplot visualizations independently and simultaneously as scatterplots are scattered across the mobile devices.

This paper explores the system with multiple mobile devices to provide an advantage over the tabletop systems as tabletop systems limit the physical movement and interactions like grabbing the visualizations due to the size and weight of the tabletop. ARTs(Augmented Reality with Tablets) use touch-based interactions due to their better accuracy than the gesture-based interactions in AR. It also highlights that small-sized mobile devices like tablets help the users' mobility by letting them carry the visualizations with them. One of the limitations of this setup is the overhead of linking the AR objects across multiple mobile devices due to accidental activation of the link. Additionally, users need to ensure that a sufficient number of mobile devices are there to project the linked scatterplot visualizations, as each tablet supports one scatterplot. If visualization has three linked scatterplots, a system with three tablets is required. This system also lacks evaluation through a user study.

Dedual et al. a hybrid system, [36] displayed 3D models over the 2D model on 2D surfaces, and both users with or without HMD could interact with it. Users without HMD could see the 2D models and could interact with 2D models. Two systems were developed for this research: A geometric modeling system and an urban visualization tool. 2D footprints and markers are placed on the surface for the Geometric modeling system. Markers render the 3D models in the AR space, while the users without HMD see the 2D footprints. The urban visualization tool projects the 3D models of the building. Markers were placed around the borders of the tabletop. Markers and headset position helped render the 3D models at the precise location and rotation. This prototype lacks a controlled study for evaluation.

Reichherzer et al. [82] introduced an interactive prototype that uses an HMD display to extend the mobile screen display space to view more information. The virtual data is displayed across different spaces: on the mobile display, aligned with the smartphone(device space), and aligned in world space(world-fixed). This research explores the different ways of object placement in AR and how the users intend to arrange the data in AR. Both hand gestures and head poses were supported to interact with the virtual objects. The user could just tap on the button to latch the virtual object with the gaze and put it anywhere in the world view as per their preference. Three applications were created for this prototype: map navigation, solving a puzzle by placing the tiles from a mobile display in AR space, and healthcare applications to compare their personal health data over a period of time. The map navigation allowed additional details around the mobile display space, while the healthcare application allowed the placement of the AR graphs of the desired data in world space or device space. On evaluating this prototype by a pilot study with 4 participants through a 5-point Likert-scale questionnaire. It was observed through the pilot study that the participants preferred to arrange the visualizations around the mobile display left, right, and bottom for the tasks involving comparing the heartbeats and steps over a period of time. The feedback conveyed that the participants would like to have zoom capabilities in the interface since the current prototype needs to be moved closer to see the zoom in the content. This study also lacks a user study to determine how the users like to place the objects in AR.

Zhu et al. [104] present an extensive review of the cross-device functionalities between HMD devices and 2D displays like smartphones/tablets/desktops. A detailed comparison concerning various parameters like resolution, precise input, head tracking, and familiarity with interactions for HMD devices. This extensive review identified that HMDs provide a larger field of view with less accuracy while interacting with data in AR. This research also explored interaction techniques offered in AR by offloading UI components and content transfer(3D models) from mobile phones to AR. A prototype with a combination of mobile phone and HoloLens v1 with external tracking was used for tasks like 3D object selection and manipulation. BISHARE(Bidirectional Interactions between Smartphones and Head-Mounted Augmented Reality) had six broader categories of interactions for both HMD-centric and phone-centric for content transfer between smartphone and AR, such as freehand air tap gesture to move AR content, knocking the phone against 3D content to get a 3D view in the phone. The participants found the phone-centric interactions easier to perform than the HMD-centric interactions as they did not require any prior training and were familiar with them.

Langner et al. [66] combined multiple mobile displays to extend the display space. VisTiles displays visualizations across mobile devices and explores the concepts of linked views, zooming and panning, filtering, and overview + detail views. A proof of concept was developed with a divide and conquer approach by displaying a portion of visualization across multiple mobile displays, also called Tiles. If the user zooms into one tile, the context region gets distributed across the other tiles. The user could filter the data across all visualizations by clicking on data on any one of the tile. Seven participants tried out all functionalities by themselves and participated in semi-structured interviews. It was reported that combining multiple mobile devices to extend views, and distributing UI components across different devices was less intuitive and more challenging.

2.8 Conclusion

Information visualizations in AR provide a larger field of view and help to offload components into the AR space. It also provides more control and freedom to see and analyze the data. Hybrid systems reduce cognition effort and support learning by providing visuals both in AR and on physical devices and limiting interactions in the AR domain. Hybrid systems using HMD and a tablet also do not require multiple mobile displays to visualize the data.

Chapter 3

Research Questions

As part of the current research, I was able to answer the following research questions:

3.0.1 Research Questions

1. How can spreading the floorplan data around the display with the tablet at the center help the user identify regions with similar properties in 2D floorplan superior to physical screen?

2. How can the layered approach of projecting raw and high-level data above the display interface using tablet + HMD enhance data comprehension superior to physical screens for space syntax?

Hypothesis for Above the Display visualization

1. HA: Projecting raw data and higher-level data in separate layers above the display enhances data comprehension over a physical display configuration.

2. HA0: Projecting raw data and higher-level data in separate layers above the display does not enhance data analysis (in the manners described) over a physical display configuration.

Participants in a controlled study were assessed on their ability to understand how two spatial attributes (Openness and Visual Complexity) are related to each other and to the raw isovist data.

Hypothesis for Around the Display visualization

1. HB: When presenting contextual data around a focus display, displaying elements above the 2D context plane enhances data comprehension over a strictly 2D focus+context configuration.

2. HB0: When presenting contextual data around a focus display, displaying elements above the 2D context plane does not enhance data comprehension over a strictly 2D focus+context configuration.

Chapter 4

Preliminary Work

This section presents preliminary work conducted as part of this thesis that motivated my research questions. I contributed to the development of Story CreatAR, as described Singh et al. [89], a tool for creating immersive AR narratives, designed for the Unity platform and HoloLens 2. The platform used both isovist and convex analysis for the spatial rules and object placement; much of my contribution to this project was to integrate existing tools for these analyses, and helping to design the ways that story authors would use space syntax information when creating stories. This experience provided an essential motivation for the visualization approaches studied in this thesis.

4.1 Introduction to Story CreatAR

I developed a tool Story CreatAR, a narrative tool created for authors that uses space syntax attributes to place story elements in AR. The problem in the current domain identified was that manual placement of the story elements becomes time-consuming if the elements are supposed to be placed in a large space. It is also challenging if the story location is changed and requires manually moving the story elements from one location to another. The main objective of developing this tool was to create a tool to help the authors place the story elements automatically by utilizing convex and isovist analysis. The tool offers authors to create and run the story in AR as per the spatial organization of the story elements, independent of the environment where their stories will be experienced. The tool offers realistic human-like avatars using Microsoft Rocket Box Avatars, spatialized audio and 3D objects.

The story authors define the placement rules, such as “a chest needs to be placed in an area of low visibility”, and “a party event will take place in an area with high openness”. Once the authors define the rules, the story elements are placed as per the rules. The tool offers the capability to preview the story in VR and later deploy

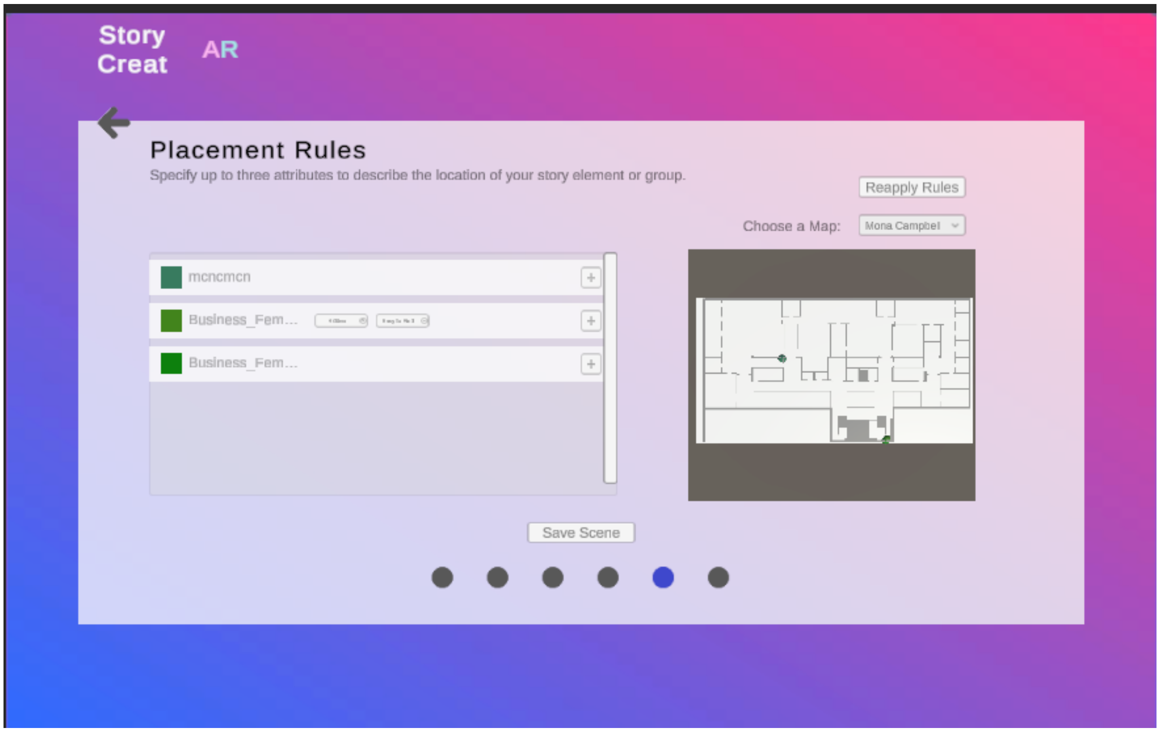


Figure 4.1: Story CreatAR UI screen with placement rules assigned to the story element BusinessFem. The story element placement is displayed in the floorplan.

it in AR once satisfied with the placement. The tool's design process involved using a 10 plus 10 design approach to identify the best design that helps the users navigate the tool. Various sessions, including bi-weekly meetings with Microsoft researchers, and expert interviews with art students and media artists, were done to identify the requirements and expectations of the users. The tool comprised multiple UI screens that enabled the users to create a story from scratch, including title, author, how many characters will be there, name of the characters, uploading audio, implementation of the spatial rules, and how they are supposed to be placed.

The Story CreatAR tool was evaluated by three Dalhousie film and media studies students. Each student created a story, namely Tyson Peak, Spill, and Standville museum, across multiple sessions, discussing space syntax analysis techniques and implementing various story sections through the tool. Throughout the evaluation, various questions were asked, particularly of interest to the space syntax domain were:

1. What spatial rules did authors use while implementing the story

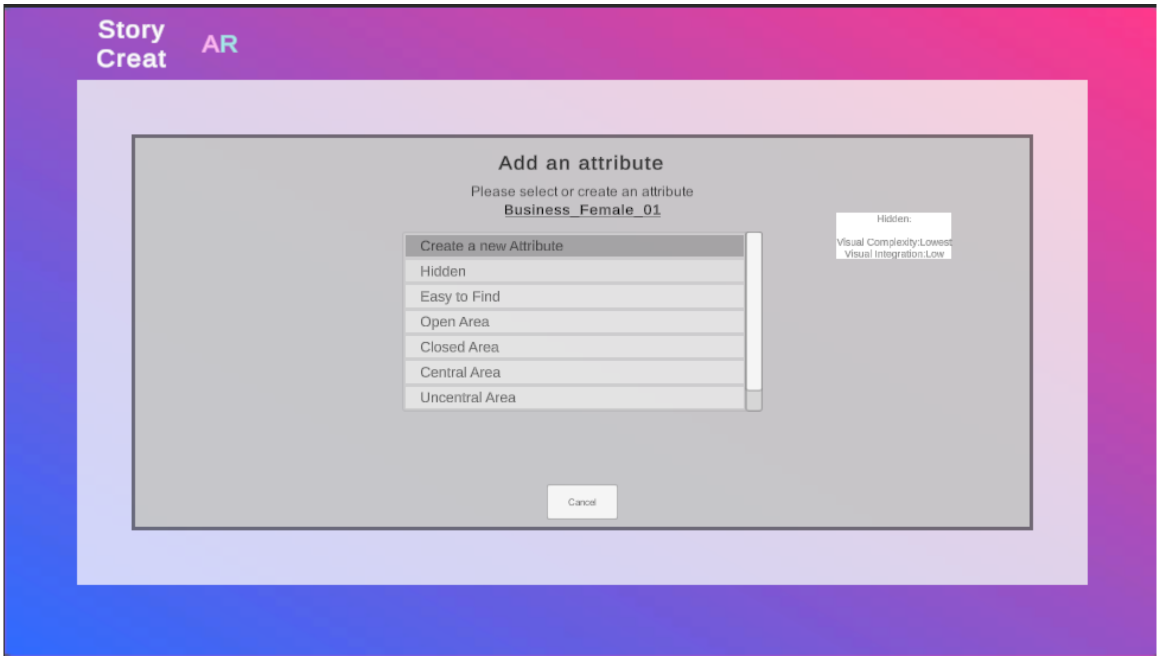


Figure 4.2: High level spatial attributes available to the user in Story CreatAR

2. What spatial characteristics rules were evident in the story but not expressed as spatial rules using the the Story CreatAR tool?

3. Did the authors understand the space syntax attributes?

4.2 Findings from the study with the authors

4.2.1 Confusion about the space syntax attributes

The Story CreatAR allows the users to first select the story elements from an in-built list available in Story CreatAR. Once the story elements are selected, the authors are given a set of spatial rules they can use to place the story elements. High-level names are given to the rules, such as a place having low visual integration, and low visual complexity is named as Hidden. Similar to this, six other spatial attributes are provided in the tool. The authors have the freedom to create their own rules by selecting the preferred level of openness, visual integration, and visual complexity as shown in Figure 4.3. The visual rules were associated with each story element using tags in the tool and the placement of the story elements placed as per those rules. DepthMapx VGA was used in the Story CreatAR tool.

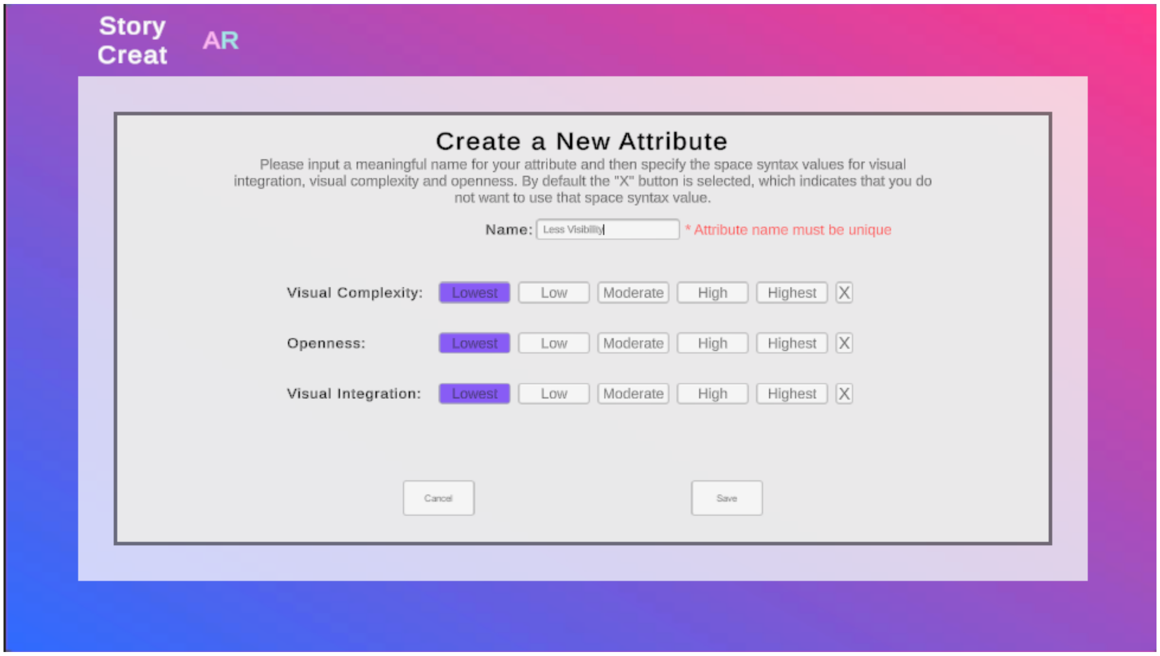


Figure 4.3: Story CreatAR enables the user to create rules by selecting preferred level of openness, visual integration and visual complexity

The tool also provides the ability to change the floorplan, and the placement of the story elements automatically changes as per the spatial rules set by the authors. During the initial discussion, the author was given a brief that they could use the tool's spatial rules or create their own rules as per the story requirement. The authors were brief about the spatial attributes using simple definitions and extreme cases. Each author created a story using the Story CreatAR tool. It was difficult for the authors to use the spatial rules as they had limited prior knowledge of the spatial rules. Research by Lerman et al. [68] also states that it is difficult to understand the space syntax attributes. The authors sometimes had preconceived ideas about the terminologies, which confused the authors and led them to misinterpret the terms. For example, one author said, "visual complexity: does that just mean where there's a lot of stuff?". I also tried to encapsulate spatial properties into familiar terms, as shown in the table, but these also confused the authors. For example, one author said "So all of these places [spatial attributes] (open area, closed area, central area, uncentral area),those all sound like room-to-room locations to me, whereas hidden and easy to find could mean a variety of things". Authors using Story CreatAR provided suggestions to improve upon the tool, several reflective of a need to define and visualize spatial properties:

1. One author stated that a way to understand the spatial rules is by comparing one space syntax attribute with another space syntax attribute and providing a simple definition.

2. Show possible or similar placements across multiple floorplans.

3. Through simple definitions and through simple use cases of the space syntax attributes.

Moreover, the authors also learned by exploring the different combinations of space syntax attributes. Output from DepthmapX as shown in Figure 4.4 provided some context to the authors with respect to spatial attributes. Through working with the authors, I determined that a tool to understand how spatial attributes are distributed across floorplans and that also provides an ability to compare the space syntax attributes would help them understand the spatial concepts.

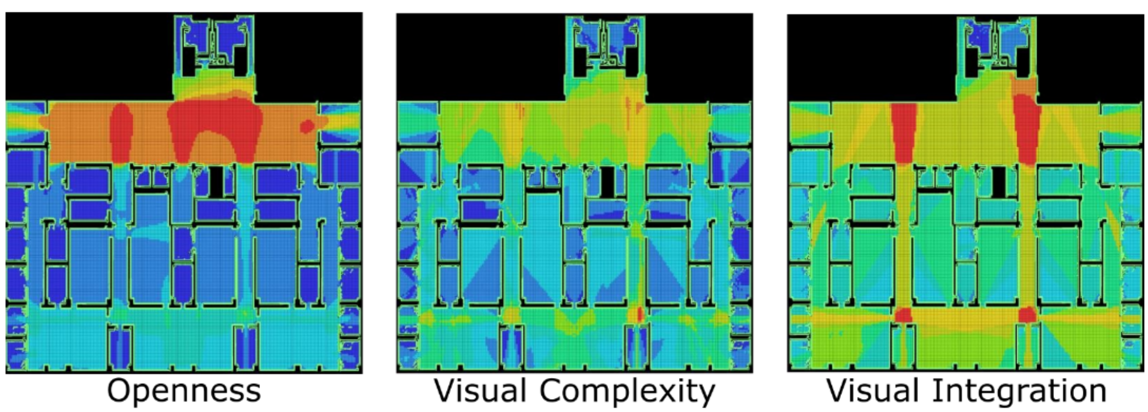


Figure 4.4: Output from the DepthmapX to provide context of openness, visual integration and visual complexity

4.2.2 Issues with existing space syntax tools

A couple of difficulties were identified while working with the DepthmapX tool. Various tutorials and manuals are provided to run the analysis. It takes the tool a lot of time to do visibility graph analysis (VGA), as noted by others [81], and requires some understanding to set appropriate values for grid size, global measures, and gate counts. These terms might make no sense to a user who is unfamiliar with the space syntax terminologies as highlighted by behbahani et al. [14]. Moreover, DepthMapX does not provide side-by-side spatial attribute views, which could help to compare the spatial attributes. The DepthMapX tool provides a view where we can see only a single spatial attribute at a given point of time.

Also stated as part of the work by Singh et al. [88] and Lerman et al. [68], a tool which helps to explore the space syntax attributes by comparing spatial attributes, how a spatial attribute is distributed across and by showing similar spatial attributes across different floorplans is required to help the general audience understand the spatial concepts better and operate the space syntax tools effectively without any challenges. Through the work in this thesis, I aim to empower the users with space syntax knowledge by providing freedom and control over space syntax visualization by exploring and comparing the space syntax attributes and highlighting possible locations with similar properties, and doing the evaluation.

4.2.3 VizSSTA

Preliminary work helped to identify sensemaking requirements that informed the design of Around the Display(ARD) and Above the Display(ABD).

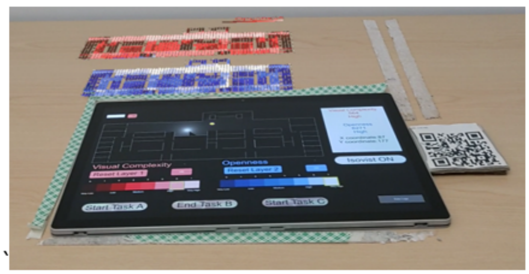
1. The authors expressed a desire to identify regions with similar properties in the floorplan, to identify possible placements of the story elements. For ARD, users were evaluated on how well they could identify regions with similar properties. Also identify how two spatial attributes are related.

2. Ability to compare spatial attributes so that they can correlate the spatial attributes and understand the spatial properties of an urban area. For ABD, users were assessed on their ability to understand how two spatial attributes (Openness and Visual Complexity) are related to each other and to the raw isovist data.

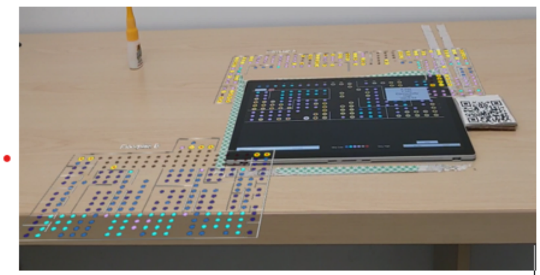
Chapter 5

Design and Implementation of VizSSTA

This chapter will discuss the design process and implementation decisions for VizSSTA.



ABD interface



ARD interface

Figure 5.1: VizSSTA, through the ARD interface, allows the user to zoom into large floorplans without losing any context. Users can also filter the information of interest, like filtering high visibility regions highlighted with yellow color. ABD interface, implements design above the tablet display by projecting the isovist layer in the tablet and then displaying the space syntax attributes on top of it in form of stacked layers in AR.

5.1 Above and Around the Display Design Process

Work in this thesis is part of the larger ARTIV(AR Techniques for Information Visualization) project, and the design of VizSSTA occurred alongside the design of similar systems for two other domains: analysis of time series data in BCI and analysis of multivariate geospatial statistics. All three have elements of ARD and ABD, hence the design process included aspects relevant to those other domains. The process of development and implementation of VizSSTA is broadly divided into three stages-

1. Stage 1- Brainstorming Ideas

2. Stage 2- Sketching and Low Fidelity Prototyping

3. Stage 3- Proof of Concept and Design Choices

5.1.1 Stage 1:Brainstorming Ideas

To better understand the space syntax domain, I identified some use cases where space syntax visualizations may help users make informed decisions. GEMLab researchers, including myself, developed the Story CreatAR toolkit [89]. I identified space syntax visualization requirements from our experiences designing the toolkit and working with authors who used the toolkit. Two primary requirements were comparing two space syntax attributes and identifying regions in the floorplan with similar properties. These two requirements were derived from the preliminary section. The authors stated that a way to understand the spatial rules is by comparing one space syntax attribute with another space syntax attribute and showing possible or similar placements across multiple floorplans. These requirements were essential to my research as they helped us concentrate on the aspects required by the authors and which may help them understand the space syntax attributes. Four GEM Lab researchers were involved in this process. I discussed ideas, opinions, and issues regarding the development process -interactions that need to be supported, represent 2D visualizations in AR, identify constraints for the prototype, move content from AR to tablet, etc. Each researcher individually produced a number of "sticky notes" on the Miro Board [7](online shared whiteboard), and three researchers did so with a specific domain in mind - space syntax, BCI, and geospatial data. After this, all the researchers worked together to identify issues, desired features, etc. Some applied to all domains considered, others of which were more domain-specific.

The entire process took place in two sessions. In the first session, each researcher identified issues that we may encounter, basic necessities for good visualizations in AR and VR, and hardware and software requirements for visualizations in AR. While exploring the existing literature, I also explored the AR toolkits [35, 87, 3] for visualization in AR and discussed what they support. The following toolkits in Unity were explored along with comments mentioned:

1. MapBox [3] supports AR tabletop kit and interactive visualization. (While uploading the dataset it asks for longitude and latitude)

Figure 5.2: Phase 1:Miro Board for Brainstorming Session

2. IATK [35] is a toolkit used for immersive analytics and it combines MapBox and VRTK packages. In a VIS 2018 paper, DXR [87] toolkit used for displaying data visualizations in AR is one of its literature review too.

These toolkits used the Unity 3D platform to build scatterplots, and line charts, among other techniques to project the data. After this process, all researchers involved in the study met for an affinity diagramming session [73]. The researchers reviewed the information collected by each researcher. They classified the ideas into themes- visual representation and layout, implementation software and hardware, embodied interactions, algorithms to be used and multimodal interactions.

These themes helped the researchers identify the areas which require more background information and the aspects I need to focus on while creating visualizations.

1. Interactions that need to be supported in the tablet and AR:

   (a) Cross-media brushing and linking: This feature was not supported as multiple views were not supported in the prototype.

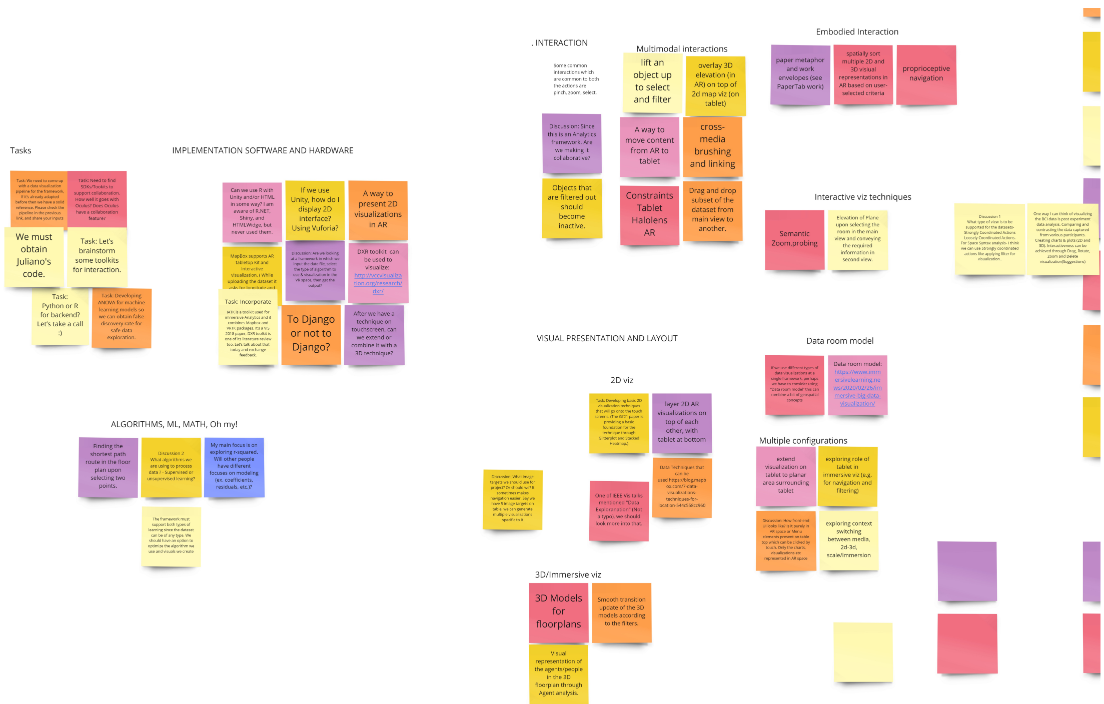


Figure 5.3: Phase 2:Affinity Diagram Session Outline

(b) Objects that are filtered out should become inactive: Objects that are filtered out were highlighted to separate out from unfiltered data.

(c) A way to move content from AR to tablet, Semantic Zoom, probing.

(d) Exploring the role of tablet in immersive viz (e.g., for navigation and filtering)

(e) For space syntax analysis- I think I can use Strongly coordinated actions like applying a filter for visualization.

These ideas highly influenced the interactions supported in VizSSTA to support semantic zooming, common interactions like pinch, zoom, and select and filter the data. Moreover, the discussion also influenced how the data will appear post selection and whether to make it inactive. Later on during the design process for VizSSTA, I used the technique of highlighting the selected data. This discussion also influenced how I can implore the tablet's role in the interactions. Later through the literature review, I analyzed that current research supports tablet interaction over AR interactions.

2. Software and hardware requirements and techniques required to establish the connection between Tablet and AR:

   (a) Can I use R with Unity and/or HTML in some way?

   (b) If I use Unity, how do I display 2D interface? Using Vuforia[1]?

   (c) A way to present 2D visualizations in AR.

   It helped identify how HTML with Unity can also be explored to present 2D visualizations in AR. It also helped to recognize that I also need to explore anchoring of the objects in AR whether to use Vuforia or any other thing. Later on during the design process, I checked Vuforia and native QR anchoring to identify which works best.'

3. Visual presentation and layout of the data in AR: Few notes from the discussion which helped with the design of ABD and ARD-

   (a) Layer 2D AR visualizations on top of each other, with a tablet at the bottom,

   (b) Developing basic 2D visualization techniques that will go onto the touch screens and extend visualization on the tablet to the planar area surrounding the tablet.

   VizSSTA ARD design evolved with 2D visualization techniques that will go onto the touch screens and extend visualization on the tablet to the planar area surrounding the tablet. VizSSTA ABD design revolves around layering 2D AR visualizations on top of each other, with a tablet at the bottom.

5.1.2 Stage 2: Sketching and Low Fidelity Prototyping

The sketching process in the HCI domain helps visualize the ideas and allows the researcher to support the development towards the next step [93]. Through sketching, design ideas go through a process of iterative development. I made the first sketches involving multiple windows appearing in AR for ARD and ABD.

All the researchers met to evaluate the first set of sketches. Through first set of sketches shown in Figure 5.4, it was observed that through the brainstorming

Figure 5.4: Sketching process: Initial sketches design for both ARD and ABD

session, I am focusing on making use of the space above and around the tablet, the content in AR should appear as AR objects rather than windows. This motivated us to make a second set of sketches shown in Figure 5.5 where the background in AR will be transparent and remove the contents, which makes the visualization as windows in AR. It was also observed through this process that the 2D visualizations would be helpful in our research as 3D visualization of the space syntax attributes over the floorplan did not have a use case. Moreover, creating 3D visualizations in AR will be an overhead provided that it does not have a context. Three iterations helped significantly arrive at the final set of sketches. The final design is for ABD and ARD reflects upon the result of the third set of sketches. During the final development of the prototype, the final sketches were immensely helpful as to how the final implementation should look in the tablet+HMD interface. This also reflected upon how visualizations will extend around the tablet display for ARD and how the layers will be stacked on top of the tablet for ABD, as can be seen in Figure 5.5.

5.1.3 Stage 3: Medium Fidelity Prototyping

During the initial research, a proof of concept as shown in Figure 5.6 was built using the unity platform [47] from the initial designs evolved from the sketching activity. Unity was used to create the prototype due to its robust nature and adaptability with

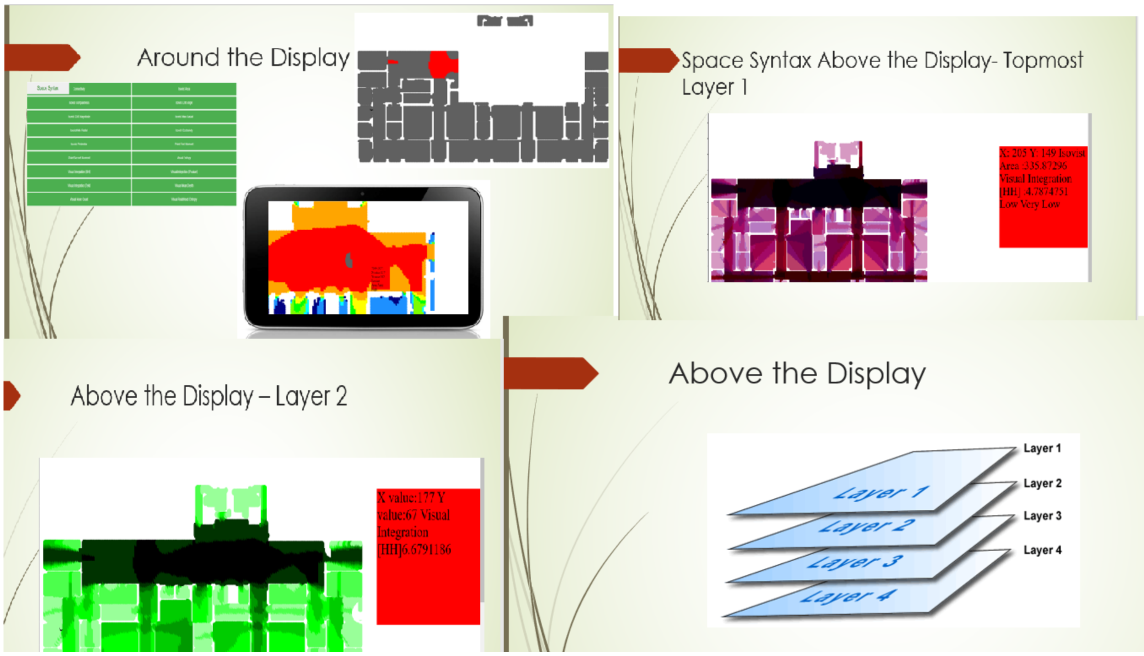


Figure 5.5: Second set of refined Sketches

AR.

The proof of concept was developed using data fetched from DepthMapX. The data fetched from DepthMapX is in CSV format. While creating the proof of concept, I represented one of the spatial attributes(Isovist Area) on the 3D floorplan using a HoloLens v1 headset. This model helped us determine the feasibility of creating spatial floorplan models from DepthMapX data. The floorplan creation through the DepthMapX created using the Unity game objects took a long time to load due to the number of data generated in the form of 3D objects. Hence, I decided to develop 2D spatial models on the web for further development as it took less time to display the 2D models developed through web in AR. Also, the web models supported cross communication between the tablet and HMD which made the implementation easier than using Unity game objects.

5.1.4 Design Decisions

In this section I list the design decisions for VizSSTA resulting from the design process just described and from reflecting on related research findings.

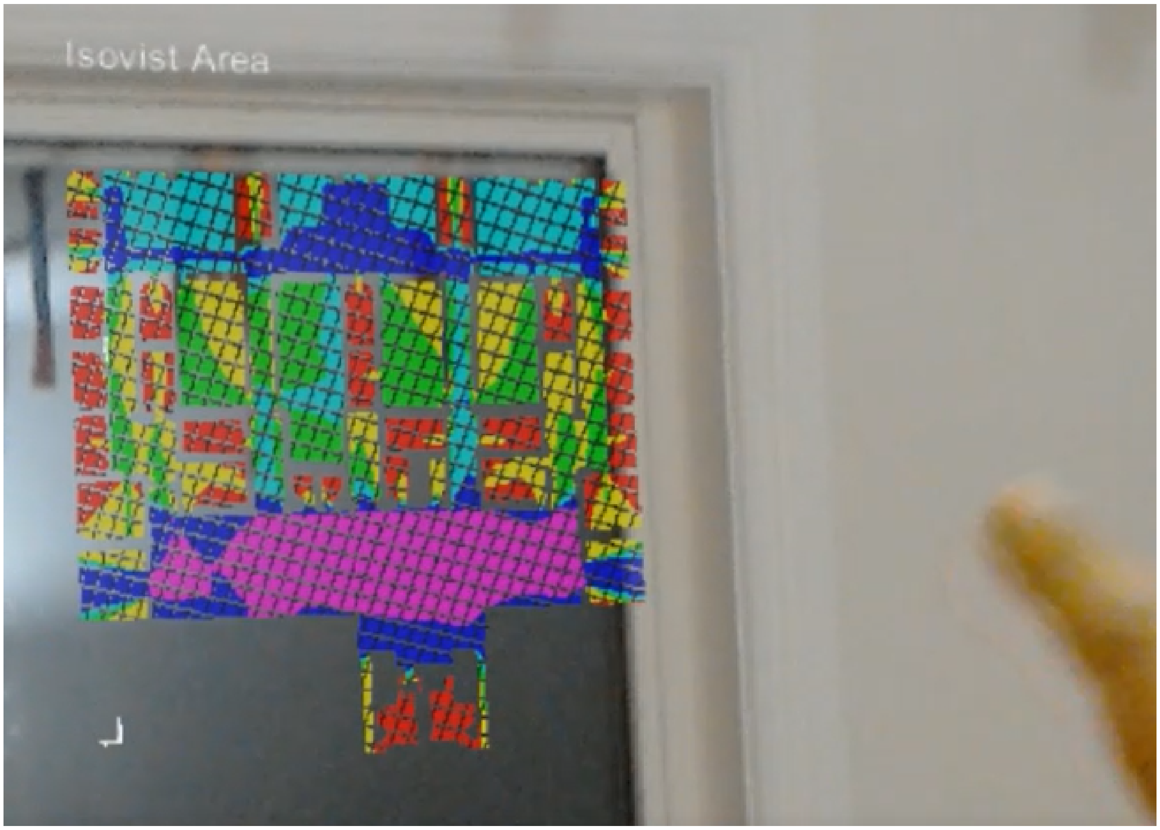


Figure 5.6: Proof of concept in AR using Unity: Mona Campbell floorplan model of isovist area projected in AR

D3.js for Information Visualizations

2D displays were created using a powerful library called D3.js [19] in combination with Node.js. D3.js is open-source and provides a fast and effective way to work around large databases for creating data visualizations. Immense research has already been done in the field of Machine learning, data mining, and big data to visualize the data in web browsers using D3.js [58]. Existing literature [67, 86, 74] supports web visualizations in AR through D3.js as it provides quick and easy to create visualizations from scratch with desired interactions over the data such as filtering, panning, and zooming.

Interactions Supported in 2D displays Only

Existing literature indicates that interactions in 2D displays are easy to perform as compared to the in-air interactions in AR content owing to the learning curve [100, 77].

Moreover, the interactions in 2D display are more accurate and less tiring [55, 39, 77]. In VizSSTA, all interactions occur on the tablet's touchscreen display while content is presented on the tablet and in AR.

Using QRCodes for Anchoring

Tracking devices in a cross-device configuration is integral to establishing a synchronous spatial distributed display among the devices. Existing literature [25, 60] supports the use of the inside-out technique of detecting devices in the environment through markers, which are cost-efficient. VizSSTA detects a QRcode attached to the tablet to calibrate the placement of AR content with respect to the tablet's position and orientation. This is done in Unity by placing a "spatial anchor" (a software object used for scene calibration) at the QRcode's location.

Color Selection

Colours used in AR For ARD, the rainbow color gradient similar to the one implemented in DepthMapX was used during the initial implementation. Prior research indicates that rainbow colour scales represent strong colour variations and are perceptually more error-prone and much slower than single-hue colour scales [18, 92]. Hence as per the recommendations, [18, 92], single-hue colour was used to represent data for ABD. A Multi-hue colour display was used to represent data for ARD. The single colour hue range for blue and red colour was carefully selected as lighter shades appear to be closer to white shade in HoloLens 2, and very dark shades of a colour appear to be black in HoloLens 2. Thus colours were carefully chosen through multiple tests with fellow researchers.

Colours Used on the Tablet Legends for AR content were presented on the tablet display: these were carefully matched with the colour scales in AR. A black background was used on the tablet screen so that AR content would be clearly visible. A research study [71] also establishes that the background color affects how well the holograms are perceived in AR. The white color or light shaded [65] background on the tablet hinders the color and contrast perception, and the colors appear less salient [71] in AR.

5.2 Implementation

The design process helped make decisions related to the implementation and development of the prototype. It enabled me to arrive at the stage where I had the low fidelity prototype ready for the initial implementation. The implementation process was followed as per the below steps.

5.2.1 Preparing the Floorplan Images

The primary stage comprised of preparing the data for DepthMapX. I used a floorplan of the Dalhousie University, Mona campbell building's fourth floor, and another image of a maze floorplan from the wikipedia source [8]. DepthMapX supports images to be exported in the dxf (Data Exchange Format). Hence, I used the Inkscape tool [56] to trace the bitmap from the images and saved the floorplans into dxf format compatible with DepthMapX.

5.2.2 Floorplan Spatial analysis in DepthMapX

Once the floorplans were in the compatible dxf format, they were imported in the DepthMapX. Floorplan analysis begins with selecting the grid size and the region in the floorplan for which we want to do the analyze. This data is saved in the graph format to be used in the command line interface. The grid size selection plays a critical role in how the visualizations appear. A smaller grid size means the visualizations will have finer details included, and increasing the grid size loses the finer details of the space. To ensure the visualizations appeared faster and there was no lag or delay while interacting with the visualizations in AR, the grid size used for the visualizations in ABD was 1, and for ARD was 10. The grid size for both the displays was selected as a high value as a tradeoff between visualization resolution and rendering cost to reduce perceptible lag in the interactive visualizations. Multiple iterations were run in DepthMapX to ensure that there was not much loss in information due to increasing the grid size. DepthMapX's command line interface (CLI) was used to perform the visibility graph analysis over the graph file of the floorplan. Command line interface is used as it provides the flexibility of running multiple analyses over the same file in comparably less time than GUI. Once the analysis was completed, the DepthMapX graph file was exported in the CSV format and was used to create data visualizations. The exported data is comprised of x and y coordinates of the locations in the floorplan and the values of the spatial attributes corresponding to that location. 18 VGA spatial attributes were exported in the CSV as shown in Table:5.1. DepthMapX supports other kinds of analysis, convex analysis, axial analysis, and agent analysis. Due to my preliminary work primarily focused on VGA, I am focusing on representing the same through this work.

Space Syntax analysis	Attributes
VGA	1. Isovist area. 2. Isovist perimeter. 3. Point first moment. 4. Point second moment. 5. Visual integration[HH]. 6. Visual integration[Tekl]. 7. Visual integration[P-value]. 8. Connectivity. 9. Isovist min radial. 10. Isovist max radial. 11. Isovist occlusivity. 12. Isovist compactness. 13. Visual mean depth. 14. Visual node count. 15. Visual entropy. 16. iIsovist drift magnitude. 17. Isovist drift angle. 18. Visual relativised entropy.

Table 5.1: DepthMapX attribues exported in CSV

5.2.3 Data Visualizations through D3.js

Information visualization guidelines [30] were followed while creating the visualizations:*overview of information by presenting an overview of the data in normal view, zoom enabled by touch on the tablet, details on demand were available by clicking on the grid points on the tablet, which displayed detail about that point.* Resetting to the previous state was provided by a reset button. *Filtering* was enabled for the users

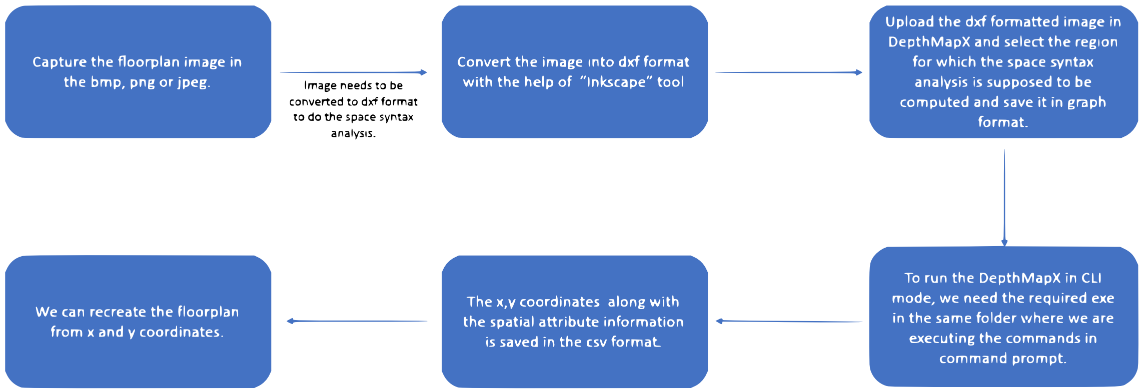


Figure 5.7: Flowchart depicting the process of preparing the data for visualization

by clicking on color scales in the legend for both ARD and ABD. Different floorplan colour maps were used to visualize different space syntax attributes.

Above the Display Implementation in AR

For ABD, three layers of data were projected: two layers were presented in AR and one layer on the tablet. Each layer in AR visualizes the spatial attributes selected by the user through the tablet interface like isovist area, isovist perimeter, visual integration[HH], and others. Two different color spectrums were used for each layer in AR -one in red color gradient and the other in blue color gradient. The color gradients vary from light colors representing the high values and dark colors representing the low values of a given spatial attribute. The operations supported by each layer- toggling the layers ON and OFF and filtering in AR layer was achieved with the help of third layer in tablet, also called the Isovist Layer. This layer created using ray tracing provides a full 360-degree isovist at any given point in the floorplan that the user touches. The Isovist Layer includes buttons that help coordinate selection operations in AR layers, namely Reset Layer 1 and Reset Layer 2. A side panel displays the X and Y coordinates and the value and range of the spatial attribute at a specific selected point.

The implementation of the two layers in AR was written in javascript [58] with the help of D3.js library. X and Y coordinates were plotted in the scatterplot and colored as per the sorted bins. The two layers were projected in AR using Canvas

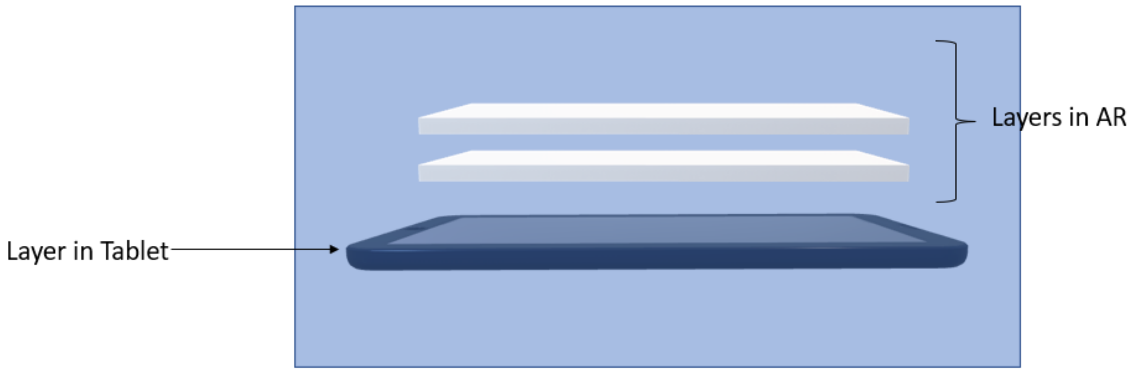


Figure 5.8: ABD layered visualization concept presented through the process of sketching

Webview [76] in Unity due to its ability to visualize web data in AR and to adjust transparency among the virtual layers.

The composite view type was used to represent data in the ABD information visualization. Transparency between each layer was achieved by adjusting the alpha values in unity to see the layers beneath and create a blended effect. Viewing the AR layers from above gives a combined view of both the layers while viewing from the side allows the user to see individual layers. The distance between each layer was chosen so that the user can see the individual layers in a seated position, and the layers appear to be merged from the top view. Multiple iterations and pilot studies were done to ensure the gap size between each virtual layer on the tablet was appropriate which was (0,0.04,0) for (X,Y,Z) as set in unity. The gap was made to ensure that the participants could see from the two layers overlapping and still see the individual layers clearly while in seated position. The connection between each layer (AR and tablet both) was established through the WebSockets (NodeJS Express edition). Figure 5.9 shows the layers and Figure 5.10 illustrates the filter selection in layers.

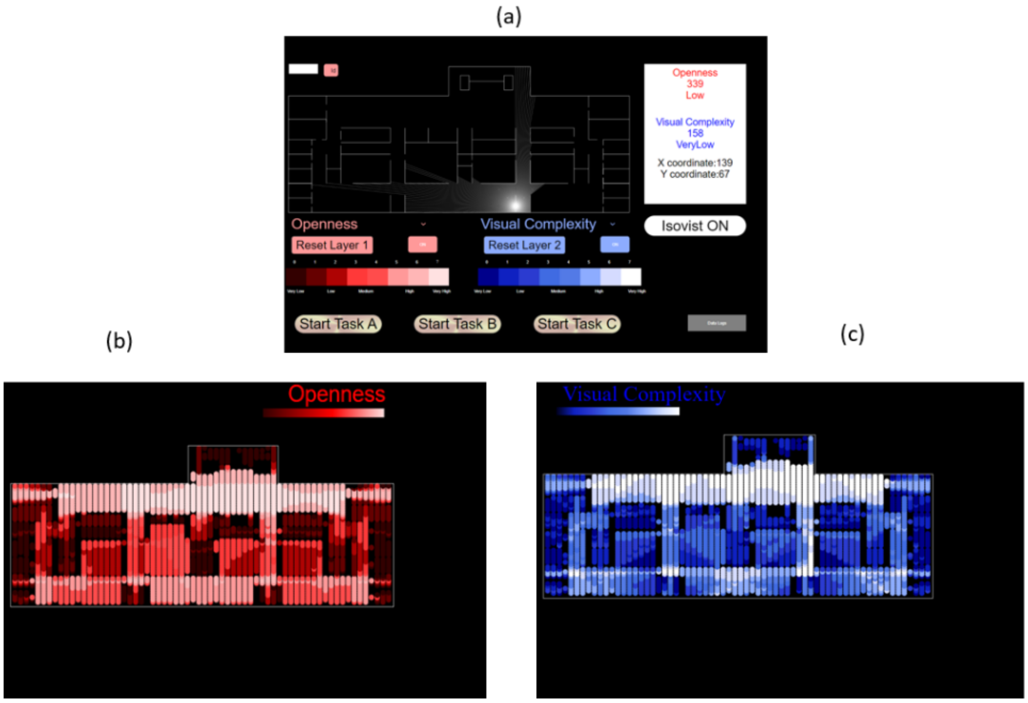


Figure 5.9: ABD: (a) This represents the Isovist Layer in the tablet. (b) and (c) represents the two layers on top of the tablet in AR with (b) on top and (c) below the layer displayed in (b)

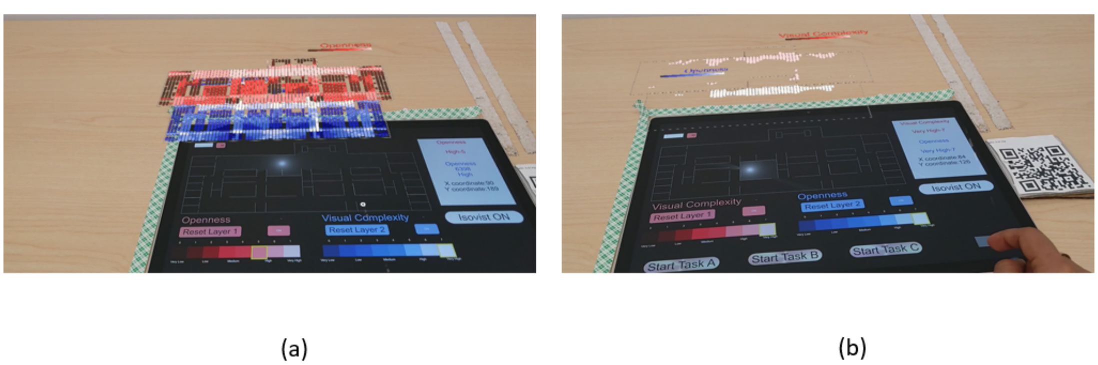


Figure 5.10: ABD in AR (a) This represents the Isovist Layer in the tablet, enabling interaction in AR layers. (b) represents the filter selection in two layers on top of the tablet in AR

Around the Display Implementation in AR

For ARD, implementation required extending the visualization around the tablet display. This was achieved by distributing the floorplan visualization across two javascript pages. D3.js was used to create the visualizations for this implementation.

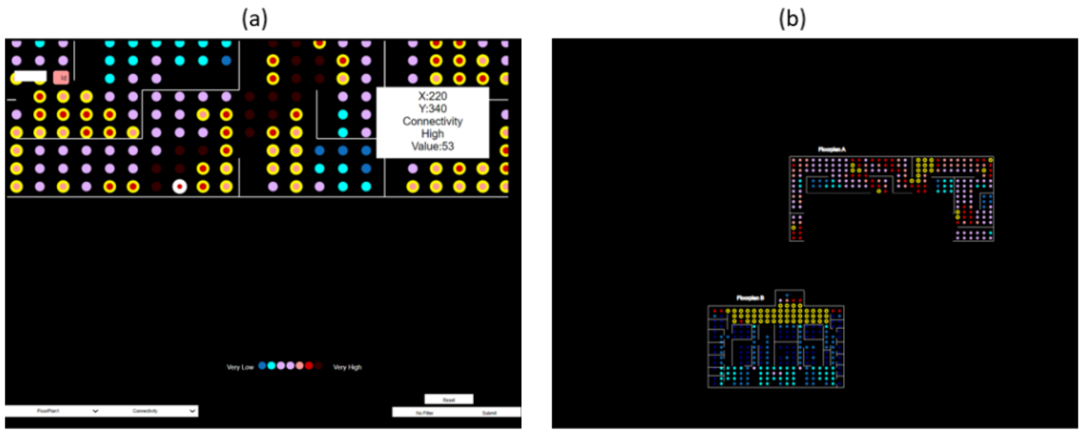


Figure 5.11: ARD in AR (a) This represents the the interface, which enables interaction in AR layers. (b) represents the rest of the floorplan in alignment with AR.

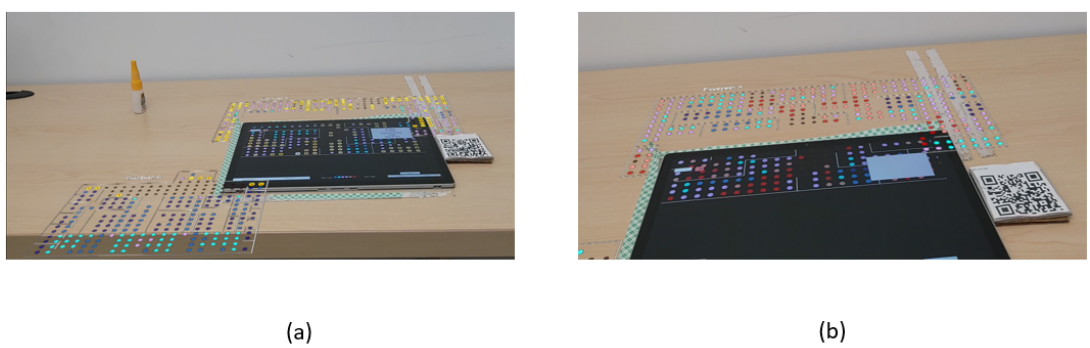


Figure 5.12: ARD in AR (a) This represents the interface which displays both floorplan A and floorplan B (focus+context region) in AR and tablet. (b) represents the focused region in tablet.

Tablet visualization represents the floorplan layout coloured as per the selected spatial attribute. The red and blue colour gradient is used to colour the values. The red gradient represents very high and high values, the blue gradient represents low and very low values, and purple represents medium values. Figure: 5.11 shows the implementation in AR and Figure:5.12 shows how the implementation appears in the hybrid interface. Once the participants zoom into the floorplan on tablet, the zoomed-in area appears on the tablet, and out-of-focus area is visualized in AR surrounding the tablet. The implementation supports filtering the values by clicking on a point in the tablet and highlighting the points with the exact same range. A Canvas Webview represented the data extending out of the tablet in AR. Reset Buttons and changing to other spatial attribute was provided in the interface.

5.2.4 Displaying visualizations

I used Microsoft Surface Pro to run the web visualizations on the tablet. For projecting the data in AR, I used Microsoft HoloLens 2 [99]. I used the unity platform and 3D WebView [75], a paid asset from vuplex. Considering that tablet is the center of the data visualizations, and pointing device, a connection between the tablet visualizations and visualizations in AR was needed. Websocket with NodeJS express edition helped us establish WebSocket client and server connection. This connection enabled us to send a continuous stream of messages among web pages on the Tablet and AR. Figure 5.13 demonstrates the flow of implementation.

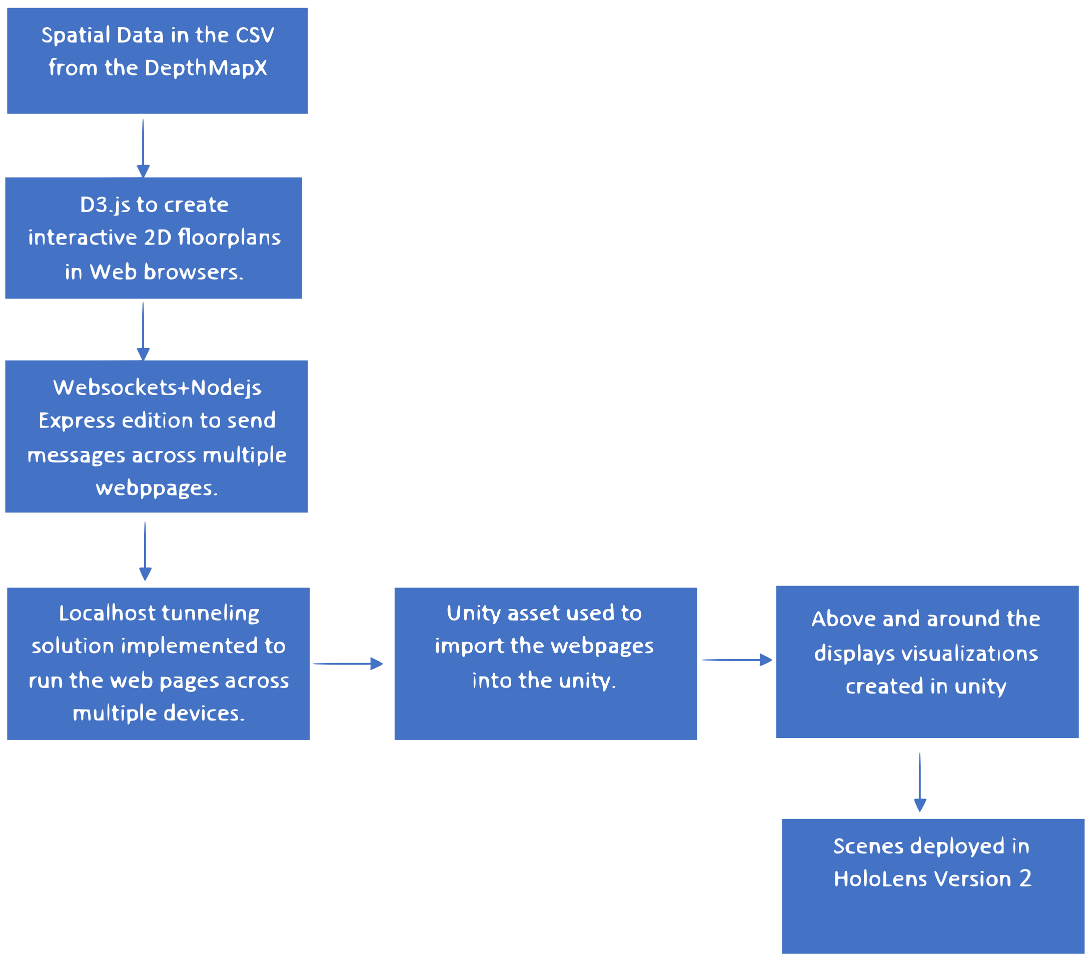


Figure 5.13: High Level Implementation in Unity

Chapter 6

VizSSTA evaluation through a study

6.1 Study Design Overview

This Chapter focuses on study design and regarding the participant recruitment. I ran a within-subjects study with 48 participants comprising two experiments - one for each BCI and space syntax domain- ABD and ARD tasks separately. Three researchers, Hariprashanth Devigasmini and I, were part of the study, and Hubert Hu, a fellow Ph.D. researcher, was part of the data analysis process. This study evaluated the effectiveness of the ABD and ARD in AR techniques for data comprehension and analysis in the space syntax and BCI domain. The participants were recruited through convenience sampling, i.e., students at Dalhousie University comprising computer science, architecture, and neuroscience. We recruited participants with and without prior experience using HMD (AR/VR). I shared the study notice through Dalhousie's internal email server and posters and advertising to groups on social media. The decision to recruit a combination of naïve and experienced users of HMDs was to mitigate selection bias in our study and to assess whether prior experience with HMDs impacts our outcomes. As per the recommendation by experts method [28], we recruited 6 participants for each group as suggested by the domain experts from the GEM lab.

When the participant expressed their interest through email, we asked them about their availability for the study session and familiarity with HMD displays to assign them to the groups- naïve or familiar. I have set a threshold value for the questionnaires; if the participant's cumulative response value falls below 40 percent, we consider the participant a novice, otherwise an experienced participant. The participants filled out the contact tracing form containing information such as name, contact number, and date and time they arrived at study due to Covid-19 protocols in case some one feels they are infected we know how to reach out to other participants. Participants provided their consent through the consent form when they arrived at

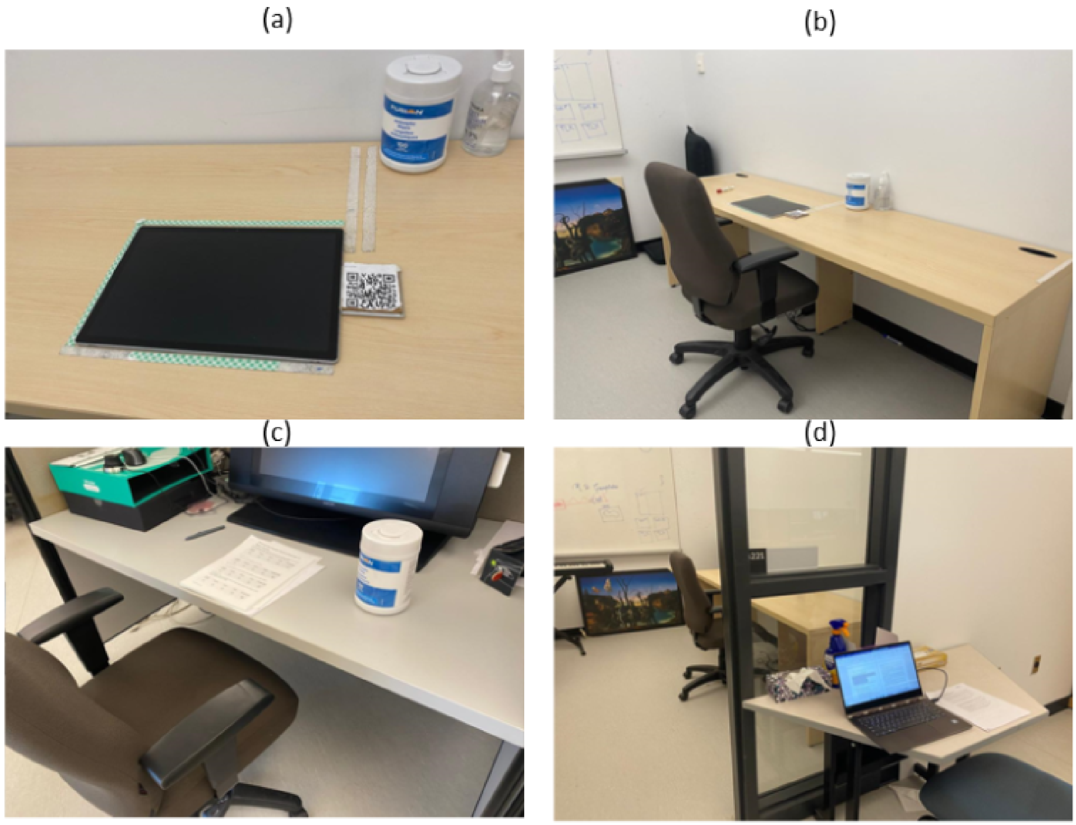


Figure 6.1: (a) represents the tablet with QRcode (b) represents the setup of the tablet (c) represents the setup where the participants did the questionnaire (d) represents from where the researcher asked the participants to do the tasks

the location. Once the participants gave consent, we scheduled them for two sessions (90 minutes each) at the Mona Campbell building 4th Floor VR and Graphics Lab.

Both the sessions took place on the same day. Upon arriving at the study location, the participants were introduced briefly to the purpose of the study and space syntax, and BCI domain through an introductory video for each domain. Each researcher made an introductory video for their specific domain, which helped the users get familiarized with the basic terminologies used during the study. I conducted two within-subjects experiments in the process of evaluating the prototype. Each experiment comprised three evaluation factors- Data domain, different visualization techniques, and interface. Domains were Space Syntax and Brain-Computer Interface(BCI), the interface was tablet+HMD(AR setup), and the tablet-only interface without AR was referred to as physical monitors throughout the study.

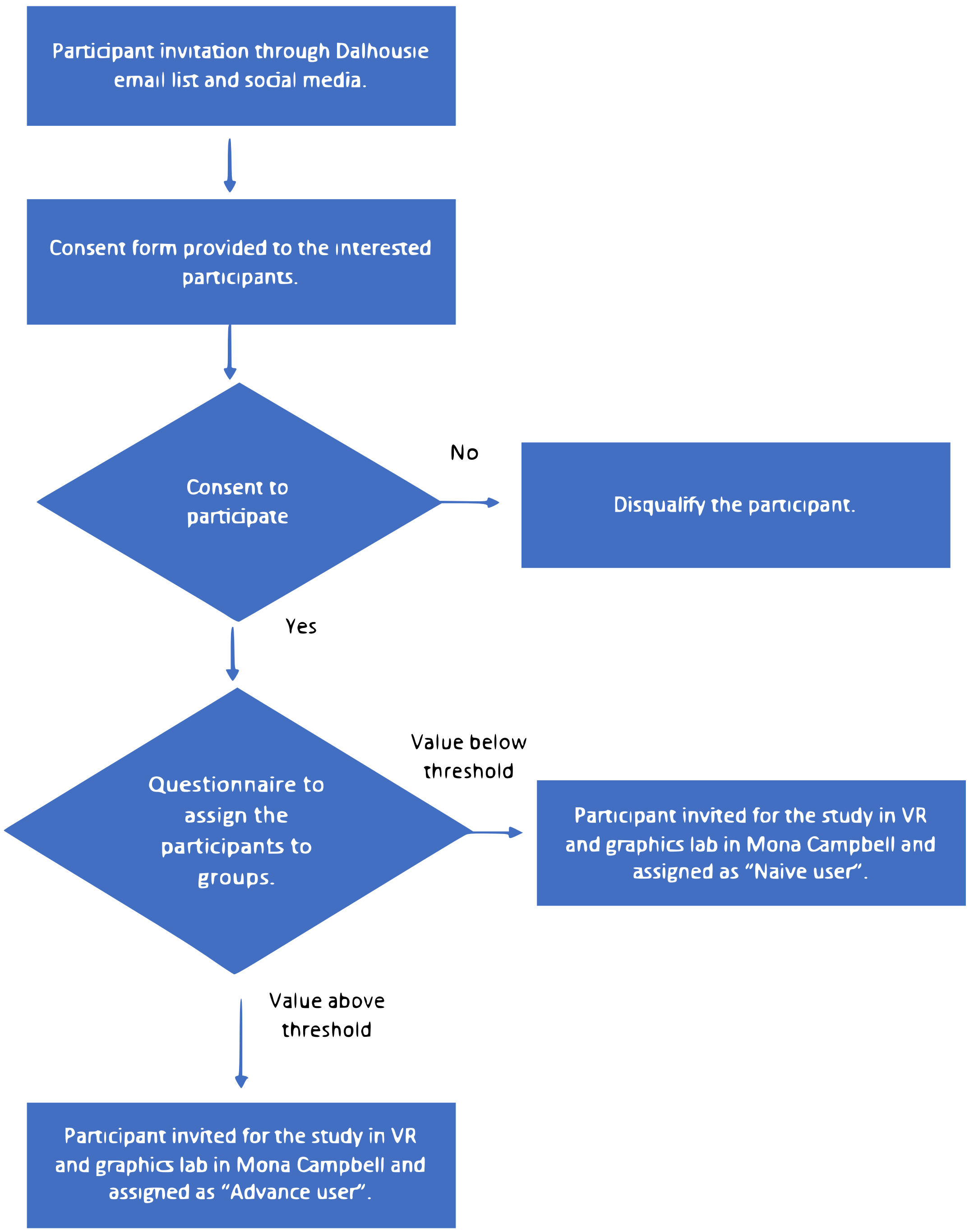


Figure 6.2: Process of recruiting the participants for the study

Tablet only version (ABD Physical monitors)

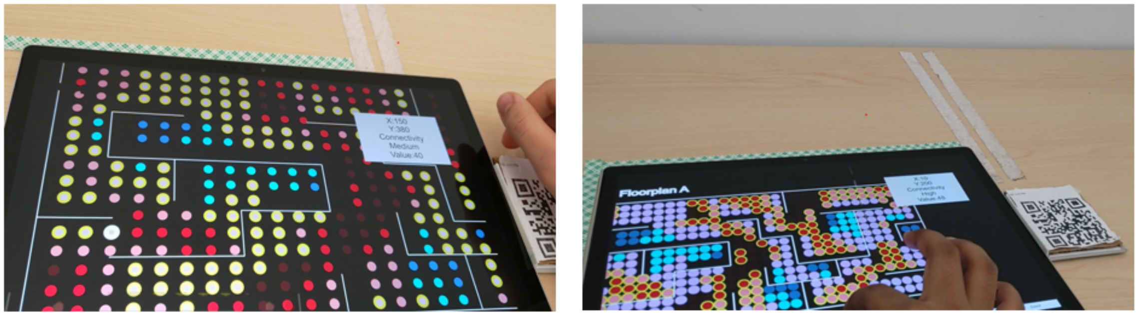
For ABD for the baseline tasks, all the three data layers -Isovist Layer, Layer 1 with a spatial attribute, and Layer 2 with a spatial attribute, were superimposed upon each other in tablet as shown in 6.3. The implementation supports selection, filtering, cues, and resetting of the information visualizations. Canvas in HTML was used to draw all three layers for the implementation. All the three layers were superimposed on each other in the canvas implementation. The Isovist Layer and the functionality were the same as those implemented for AR implementation. The floorplans in canvas HTML were drawn using dots, and the x and y values from the CSV were normalized as per the dimensions of the Isovist Layer.

(a) (b)

Figure 6.3: Tablet-only visualization implementation used as ABD baseline

Tablet only version (ARD physical monitor)

ARD implementation in Tablet used the exact implementation as in ARD implementation in AR as shown in 6.4. This implementation provided the same information guidelines for zooming, filtering, resetting, and Cues as per the Information visualization guidelines. The only difference was with respect to the out of focus region that could not be seen.



(a) (b)

Figure 6.4: Tablet-only visualization implementation used as ARD baseline

After each condition, the participants filled out a questionnaire AppendixD, and a post-condition questionnaire AppendixD was followed after completing each condition for both interfaces. At the end of each experiment, we recorded a short semi-structured interview with the participant's Appendix F to get feedback for the setup(ABD or ARD).

6.1.1 Experiment A of the study testing hypothesis HA

For this experiment, our hypothesis HA is projecting raw data and higher-level data in separate layers above the display to enhance data analysis (comprehension and exploration of space syntax) over a physical display configuration. This is a within-subjects experiment with two factors (Data Domain, Interface), each with two levels (BCI and space syntax, Tablet+HMD and Tablet Only, respectively), giving four conditions. The Data Domain factor will be nested within the interface, and with counterbalancing, this gives the following four orderings:

Tablet+HMD (Space syntax, BCI), Tablet (Space syntax, BCI)

Tablet+HMD (BCI, Space syntax), Tablet (BCI, Space syntax)

Tablet (Space syntax, BCI), Tablet+HMD (Space syntax, BCI)

Tablet (BCI, Space syntax), Tablet+HMD (BCI, Space syntax)

The participants were initially briefed about the experiment, including the tasks they needed to perform. Participants were asked to explore data and interact with the visualizations projected on display and in virtual layers above the display for BCI and space syntax during the study. They carried out UI operations to complete the tasks described in the Task sheet. Participants were asked to "think aloud" as they completed the tasks in Appendix A. Each task set contains a subset of five training tasks, which are completed first and in the same order across all conditions for all participants. These tasks were used to familiarize the participants with the interface, the data set, and its visualization and to get used to the think-aloud protocol. The training tasks were also used to mitigate the learning effect.

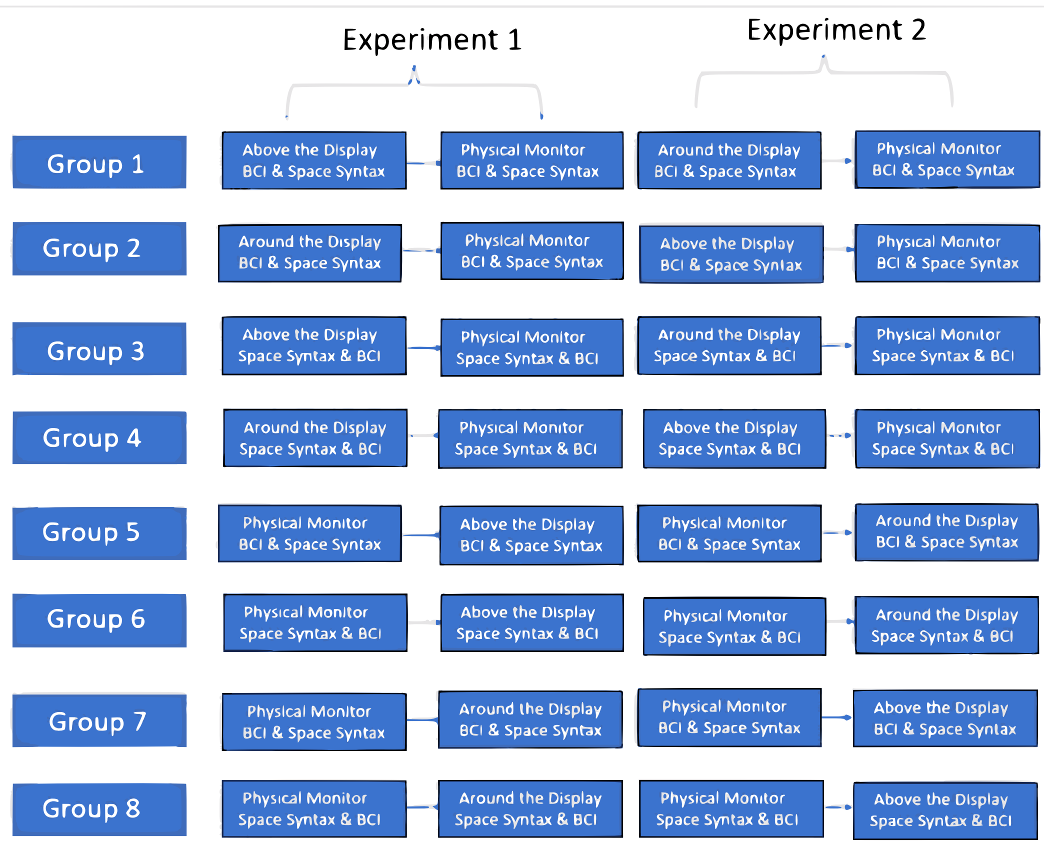


Figure 6.5: Latin square to counter balance learning bias in the study

The remaining ten ARD tasks and seventeen ABD tasks were used in our analysis, and the set of these tasks is randomized across all conditions for all participants. Each non-training task has a maximum possible time of 1 minute, after which it was abandoned if not completed, and the participant will move on to the next task. If participants expressed concern that they could not complete a task, they were asked to continue trying until the maximum time had been reached. Once all tasks were completed (or abandoned/timed out) for a given condition, a post-condition questionnaire (Appendix D) was administered. After the two conditions were completed in the given experiment, a final questionnaire (Appendix D) was administered, and a semi-structured interview (Appendix F) was administered at the end of each experiment.

S.No	Activity	Duration
1	Study overview/review, answer questions	5 minutes
2	Describe experiment	5 minutes
3	For each condition	X4 (72 mins total)
	(i) Complete training tasks	5 minutes
	(ii) Complete task set	10 minutes
	(iii) Post-condition questionnaire	3 minutes
4	Final semi-structured interview	8 minutes
5	*Total time taken in first experiment*	*90 minutes*

Table 6.1: Experiment 1 Structure

6.1.2 Experiment B of the study testing hypothesis HB

For this experiment, our hypothesis HB is that when presenting contextual data around a focus display, displaying elements above the 2D context plane enhances data analysis of multivariate data over a strictly 2D focus+context configuration. Experiment B follows the same format as Experiment A, differing only in interface and task sets and will require the same amount of time. It is a within-subjects experiment with two factors (Data Domain, Interface), each with two levels (BCI and space syntax, Planar and Planar+3D Highlighting, respectively), giving four conditions. The Data Domain factor will be nested within Interface, and with counterbalancing, this gives the following four orderings:

Planar+3D (Space syntax, BCI), Planar (Space syntax, BCI)

Planar+3D (BCI, Space syntax), Planar (BCI, Space syntax)

Planar (Space syntax, BCI), Planar+3D (Space syntax, BCI)

Planar (BCI, Space syntax), Planar+3D (BCI, Space syntax)

6.2 Data Collection

Both qualitative and quantitative data were collected from the study.

Qualitative data comprised software Logs from both HoloLens 2 and the tablet. The logs were kept anonymous by using participant ID to save the data. It comprised video data from HoloLens, recorded through an in-built video recorder and system logs from the tablet. HoloLens recorded the video of the participants performing the tasks and their voices. For this reason, participants were asked to wear the headset when completing tasks throughout both experiments (even for those conditions in Experiment A and Experiment B that do not include AR content). Gaze and eye-tracking data were collected in the CSV format to get the head position and orientation of the participant. This was captured to identify where the participants were looking. System Logs were also collected from the tablet interface in the form of CSV data which included the timestamp and button clicked information, toggle information of the layers, the filter used, space syntax attribute used, and X-Y coordinate information of the floorplan. A button was made in both ARD and ABD interfaces, which enabled downloading the system log file. Video recording of the participant's perspective through the HoloLens was recorded, showing both AR content and the tablet display, and audio capture of participants as they think aloud while completing tasks in both the experiments. Audio recording of each participant for post-condition semi-structured interview was done at the end of each experiment.

Quantitative data was collected for each participant through a custom system-related Likert scale questionnaire for each condition (AppendixD)and the final post-experiment questionnaire (Appendix E), system usability (Appendix [69]), and TLX (Appendix [50]) questions for each condition, sample questions are shown in table 6.2 and 6.3. Consent forms (Appendix B) and Questionnaire (AppendixD,E) data were collected in the form of paper documents.

6.3 Preparing data for Data Analysis

This section of thesis will discuss the process of preparing the data for data analysis.

Display	Questions
ARD	1. I could see the entire floorplan in the augmented reality (AR) configuration. 2. It was straightforward to zoom and pan on the tablet to control what is shown in AR. 3. Highlighting the different zones of the plotted data present in the entire floorplan.
ABD	1.The space syntax features presented as multiple floorplans in the tablet are appropriate for performing the data analysis tasks in space syntax. 2. I can isolate one or more layers using the toggle feature from the tablet and control what is shown in the tablet 3. Completing the tasks helped me understand how isovist size and shape contribute to the calculation of openness and visual complexity.

Table 6.2: Questions after each condition for ARD and ABD

Video Data I collected video data for both sessions of ABD and ARD for both AR and physical monitor through the HoloLens 2. In the video, I recorded the participants interacting with the interface/looking at it from the participant's perspective and the dialogue exchange between the researchers and participants. I extracted the audio file from the video file with the help of an audio extractor. The transcribing of the audio was done with the help of Microsoft Cognitive services[4] speech to text.

Post automatic transcribing, manual transcribing was done to ensure no misinterpretations and identify what was said by the researcher and what was said by the participant. From the transcriptions, I noted what was asked from the participants and what they responded to. I performed a top-down deductive coding method as discussed by Braun and Clarke [20] to understand participants' behavior as I wanted to identify how the participants interacted and whether the interface helped or not. I began with the coding: *confusion*(the participant was confused about where to look at whether in AR/tablet), *looking in the tablet*(using the tablet to perform the tasks), *looking in the AR*(using AR to perform the tasks), *giving up*(could not complete the task), I also added *physical strain to the list*(since the participants felt physical strain while doing the task) as shown in the Table 6.4. One other researcher

Display	Questions
ARD	1. Visualizing the entire floorplan data. 2. Zooming into the floorplan. 3. It was easy to highlight the different zones of the plotted data present in the entire floorplan.
ABD	1. Visually distinguishing different layers. 2. Toggling layers on and off. 3. Viewing multiple layers together.

Table 6.3: Post Study Questionnaire for ARD and ABD on the scale of AR clearly better, AR slightly better, AR and Tablet are equal, Tablet slightly better, Tablet clearly better

and I reviewed the videos and did the coding until they met acceptable inter-rater reliability(IRR)(greater than 0.7); when met, we could divide the remaining videos. I calculated the inter-rater reliability by dividing the total number of similar codes assigned by each researcher within the same time frame with the total number of codes assigned by each researcher for a participant's video.
Video data helped determine why the participants did the task the way they did, why accuracy was more for tasks, and why the time taken was more for tasks.

I have used excel again for video analysis to report how many participants did what and what they did at a given time.

Interview Data Interview data was auto transcribed with the help of Microsoft Azure cognitive services, which helps convert speech to text through a script. Later on, the data was transcribed manually to remove any errors and discrepancies. Affinity Diagramming [72] was used to create themes out of the data. Interview data give insights into why they preferred an interface over another interface.

Questionnaire Data I have used excel to enter the data from the paper data Questionnaire. Questionnaire data will help us to analyze the user perspective, what they prefer, and for what tasks. I have used a one-sample t-test to identify whether there was any significant difference in the results for the post questionnaire. I have used one-way Anova for TLX, SUS, time taken, and accuracy data for each interface ARD and ABD in physical monitor and AR.

Codes	Code Description
Technical confusion of where to look	Confusion where the participant needs to look whether in AR or Tablet
Looking at the tablet	Participant looking in the tablet
Looking at AR content	Participant looking in AR
Giving up	Participant giving up on completing the task
Asking the researcher	Participant asking the researcher for guidance.
Logical confusion	Participant confused about the task.
Inefficient or incorrect operation UI operations	Participant not using the interface adequately for the task or doing extra operations.
Physical strain	Participants were adjusting their headset or moving their head due to physical strain on the neck.

Table 6.4: A top-down approach was used to define codes which were applied to the video analysis for each participant.

Software Logs The software logs did not require any data preparation as the data was collected in the form of excel data as shown in the snapshot of Figure 6.6 and 6.7. The accuracy of the tasks and time taken by the participants was extracted by going through the software logs in tandem with the HoloLens video captures and transcripts for a given time frame. Videos were also used with software logs to identify what tasks the participants performed at a specific time frame, how long it took them to complete the tasks and their vocal responses to the tasks.

Timestamp		Map	Operation	Parameter1	Xvalue	Yvalue	SelectedPoint	NewXaxis-max	NewYaxis-max	NewXaxis-	NewYaxis-	Parameter	Zoom
1/27/2022	7:26:08PM		Plotcreation										
1/27/2022	7:26:10PM	MazeUpd	ParamterChange	Connectivity									
1/27/2022	7:26:10PM		Plotcreation										
1/27/2022	7:26:51PM	MazeUpd	mouseClick	Connectivity	220	340			High				
1/27/2022	7:26:54PM	MazeUpd	ParamterChange	Connectivity									
1/27/2022	7:26:54PM		Plotcreation										
1/27/2022	7:29:19PM	MazeUpd	mouseClick	Connectivity	220	350			VeryHigh				
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity									3
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity				374.4814516	430.05	159.4815	250.05		3
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity				374.4814516	430.05	159.4815	250.05		3
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity				374.1	429.78	159.1	249.78		3
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity				374.1	429.78	159.1	249.78		3
1/27/2022	7:29:24PM	MazeUpd	Zoom	Connectivity				373.6145161	429.51	158.6145	249.51		3

Figure 6.6: Snapshot of how the data is collected in form of software logs for ARD and baseline(ARD)

1. Accuracy: accuracy was measured from the Software logs where the participants clicked and was mapped with the videos where the participants performed that

Timestamp		Operation	Parameter	Parameter	Parameter1value	Parameter	Parameter2	Parameter2To	Parameter2value	Parameter2f	X-coordina	Y-coordina	Parame	Parameter2Legen
########	11:05:51A	ToggleLayer2					IsovistPerimet	OFF						
########	11:06:00A	FilterLayer1	IsovistArea										VeryHigh-7	
########	11:06:09A	mouseMove	IsovistArea		6469	High	IsovistPerimeter		652	VeryHigh	128	185		
########	11:06:09A	mouseMove	IsovistArea		6469	High	IsovistPerimeter		652	VeryHigh	128	185		
########	11:06:15A	Layer1Reset	IsovistArea											
########	11:06:15A	ToggleLayer1	IsovistArea											
########	11:06:16A	Layer2Reset				IsovistPerimeter								
########	11:06:16A	ToggleLayer1	IsovistArea											
########	11:06:20A	ToggleLayer2					IsovistPerimet	OFF						

Figure 6.7: Snapshot of how the data is collected in form of software logs for ABD and baseline(ABD)

task and what they responded to. For some tasks, there was more than one correct answer, such as "Identify a point in the floor plan A where the range is high" there were multiple points regarding this. Some tasks have one correct answer, such as how many points in Floor plan A have a high range. Is it 0-20,20-40,40-60 or 60-80.

2. Time taken: time taken was measured through the video and software logs as well where the participants stopped interacting with the tablet for that specific task and gave a response for the task in the video.

Chapter 7

Data Analysis

The data analysis process was initiated by transferring the Questionnaire data from the papers to CSV format with only identifier associated with each row being the participant ID. Each response was given a number from 1 strongly agreeing to 5 strongly disagree. The summation of responses was made and projected in bar charts by the researcher.

7.1 Study Population

As part of the analysis, the study population consisted of 20 female and 28 male participants. The recruited population comprised 25 Master's students, 14 Bachelor's students, and 3 Ph.D. students with their current degree status as 6 participants were either employed or recent graduates with their last completed degree as a Master's. 22 participants classified themselves as somewhat familiar with Augmented Reality/Virtual Reality/ Mixed Reality. None of the participants felt they were highly familiar with AR/VR/MR, as shown in Figure 7.1. 33 participants had used AR applications like PokemonGo, while 23 participants had experience with VR. Fifteen participants had some experience with Microsoft HoloLens or other AR HMD before.

Based on this information, the students were classified as naive or experienced users, allocating 24 participants to both categories.

Response	Score
Extremely Familiar	15
Moderately Familiar	10
Somewhat Familiar	5
Slightly Familiar	-10
Unfamiliar	-15
Yes	5
No	-5

Table 7.1: Score applied to each question based upon responses from each participant

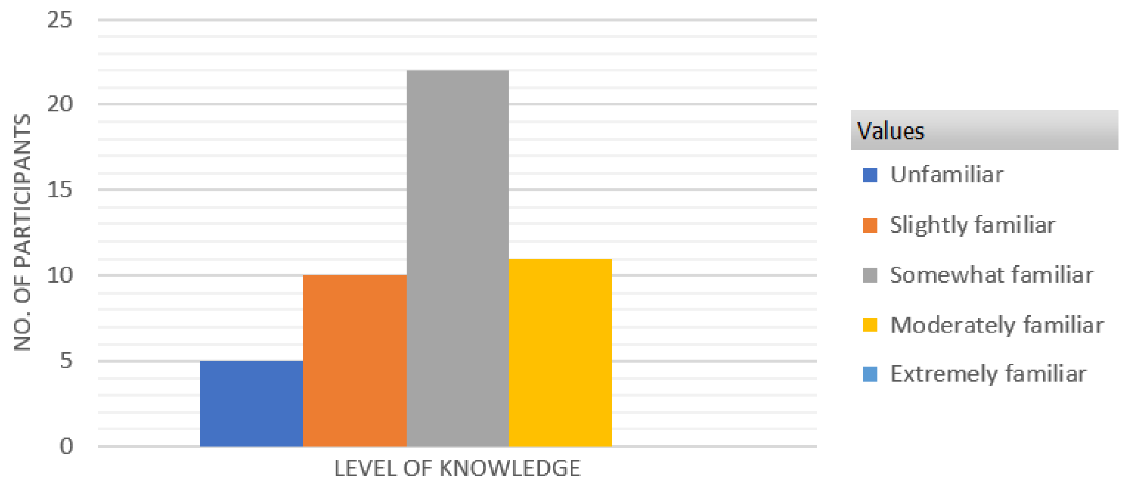


Figure 7.1: AR/VR Level of knowledge of the participants

7.2 Around the Display

As part of the ARD, I evaluated how spreading the floorplan data around the display with the tablet at the center helps the user identify regions with similar properties in the 2D floorplan better than the physical screen. This was evaluated through the tasks to identify the similar regions in the floorplans and understand how the connectivity and isovist perimeter are related. The section below elaborates on how I answered my research question using parameters like TLX, SUS, time taken to complete the tasks, and accuracy for the same tasks.

7.2.1 Post Study Questionnaire Data

Post-study for each interface ARD questionnaire helped identify various trends for each interface. Each question was ranked on 5-likert scale: AR clearly better, AR slightly better, AR and tablet are equal, tablet slightly better and tablet clearly better. Figure 7.2, 7.3, 7.4 represents the data in the form of bar charts. For the ARD interface, the following significant differences were observed through a one-sample t-test(α=0.05):

1. Keeping track of the entire floorplan (M= 2.89, SD= 1.5) t(47)=2.62, p<0.001, Cohen's D=0.37. 27 participants preferred AR versus 14 participants for physical monitor.

2. Determining x and y values and space syntax attribute value at a given point (M=1.7, SD= 0.87) , t(47)=-8.25, p<0.001, Cohen's D=1.19. 33 participants preferred physical monitor versus 1 participants for AR.

3. Zooming into the floorplan (M= 1.9, SD= 1.08) over AR for , t(47)=-5.18, p<0.001, Cohen's D=0.74. 33 participants preferred physical monitor versus 6 participants for AR. Through software logs for each participant, a significant difference was calculated through one-way ANOVA using zoom operation for all the tasks in both ARD and physical monitor (F(1,94) = 75.24, p<0.001), participants used zoom operation more in physical monitors(M=144,SD=149.5) than ARD(M=8,SD=0.5).

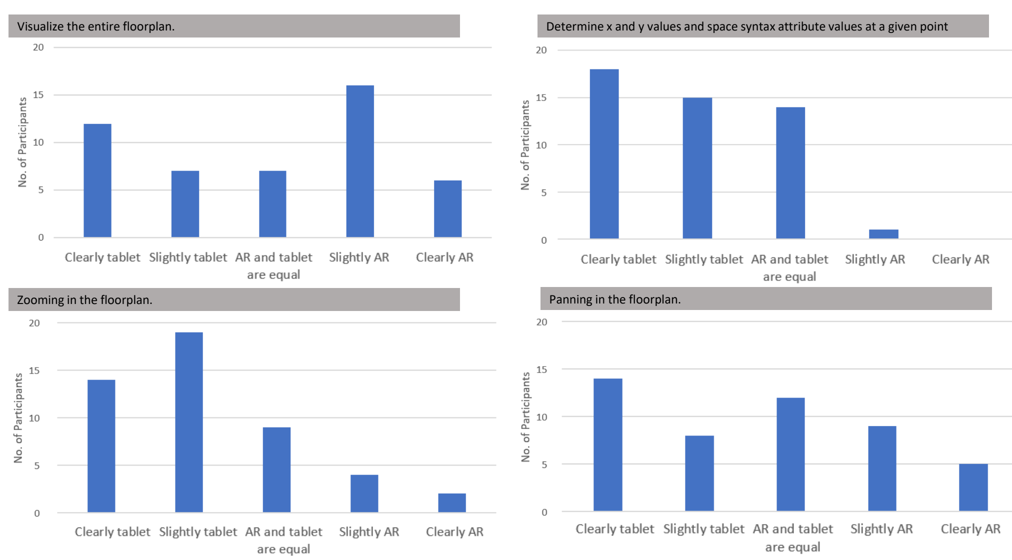


Figure 7.2: Around the Display Post Study Questions for AR and physical monitor interface

4. Panning in the floorplan (M= 2.25, SD= 1.36), t(47)=-1.80, p=0.03, Cohen's D=0.37. 22 participants preferred physical monitor versus 14 participants for AR. Through software logs for each participant, a significant difference was calculated through one-way ANOVA using pan operation for all the tasks in both ARD and physical monitor (F(1,94) = 75.24, p<0.001), participants used zoom operation more in physical monitor (M=433,SD=598) than ARD(M=12,SD=4.1).

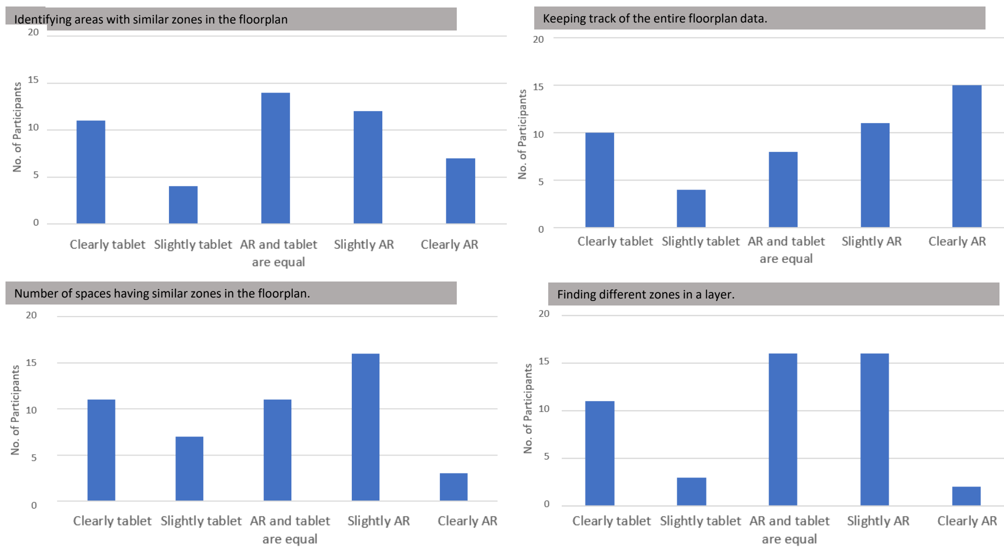


Figure 7.3: Around the Display Post Study Questions for AR and physical monitor interface

5. Completing tasks efficiently(M= 2.19, SD= 1.2), t(47)=-2.88, p=0.002, Cohen's D=0.41. 23 participants preferred physical monitor versus 9 participants for ARD. A detailed comparison of the time taken to complete the tasks in ARD and physical monitor is described in section 7.2.5 and 7.2.4

6. Completing tasks accurately(M= 1.91, SD= 1.04), t(47)=-5.38, p<0.001, Cohen's D=0.77. 32 participants preferred physical monitor versus 6 participants for ARD. A detailed comparison for the accuracy of the tasks in ARD and physical monitor is described in section 7.2.5

No significant difference was observed for the following custom questions in questionnaire: visualizing the entire floorplan data(t(47)=-0.30, p=0.61, Cohen's D=0.04, identifying areas with similar zones in the entire floorplan(t(47)=0, p=0.5, Cohen's D=0),counting the number of spaces having similar zones for entire floorplan(t(47)=-0.78, p=0.7, Cohen's D=0.11) and finding different zones in a layer(t(47)=-0.58, p=0.72, Cohen's D=0.08). Behavioral differences were observed from the participant with respect to the question counting the number of spaces having similar zones for entire floorplan as described in the section7.2.5 and 7.2.4.

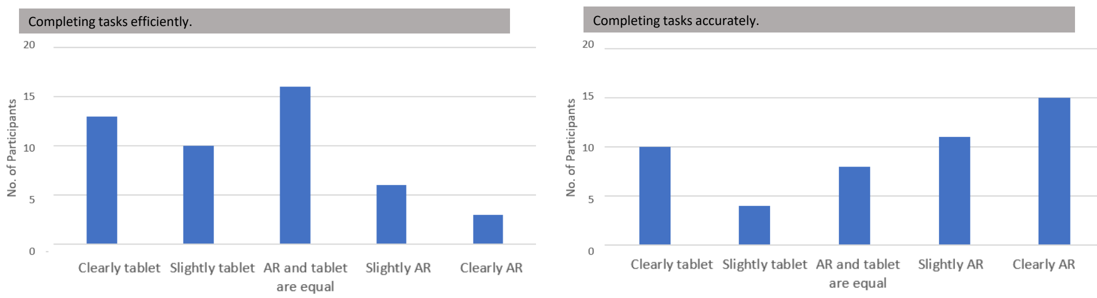


Figure 7.4: Around the Display Post Study Questions for AR and physical monitor interface

7.2.2 TLX Questionnaire

Figure:7.5 represents the NASA-TLX questionnaire responses. Normality distribution was determined with the help of Shapiro-Wilk normality test(α=0.05) as shown in Table 7.2. Through Kruskall-Wallis I computed the statistical differences (α=0.05), it was identified that platform(AR or physical monitor) used has no significant impact on the TLX of the interfaces for mental demand $\chi^2 = 1.01$, $p = 0.31$),df=1,physical demand $\chi^2 = 0.36$, $p = 0.5$),df=1, time pressure $\chi^2 = 0.01$, $p = 0.89$),df=1, successful$\chi^2 = 0.56$, $p = 0.45$),df=1, performance $\chi^2 = 0.89$, $p = 0.34$),df=1, and frustration $\chi^2 = 0.23$, $p = 0.63$),df=1.

Through the video observational data, not much physical effort was observed for tasks in AR as the participants were performing the tasks in seated position.

NASA-TLX	Shapiro-Wilk Normality Test(α=0.05)		
	Test Statistic(W)	p-value	Conclusion
Mental Demand	0.94	0.00	Non-parametric
Physical Demand	0.88	< 0.001	Non-parametric
Temporal Demand	0.92	< 0.001	Non-parametric
Performance	0.92	< 0.001	Non-parametric
Effort	0.88	< 0.001	Non-parametric
Mental Frustration	0.94	0.00	Non-parametric

Table 7.2: Normality of Test ratings

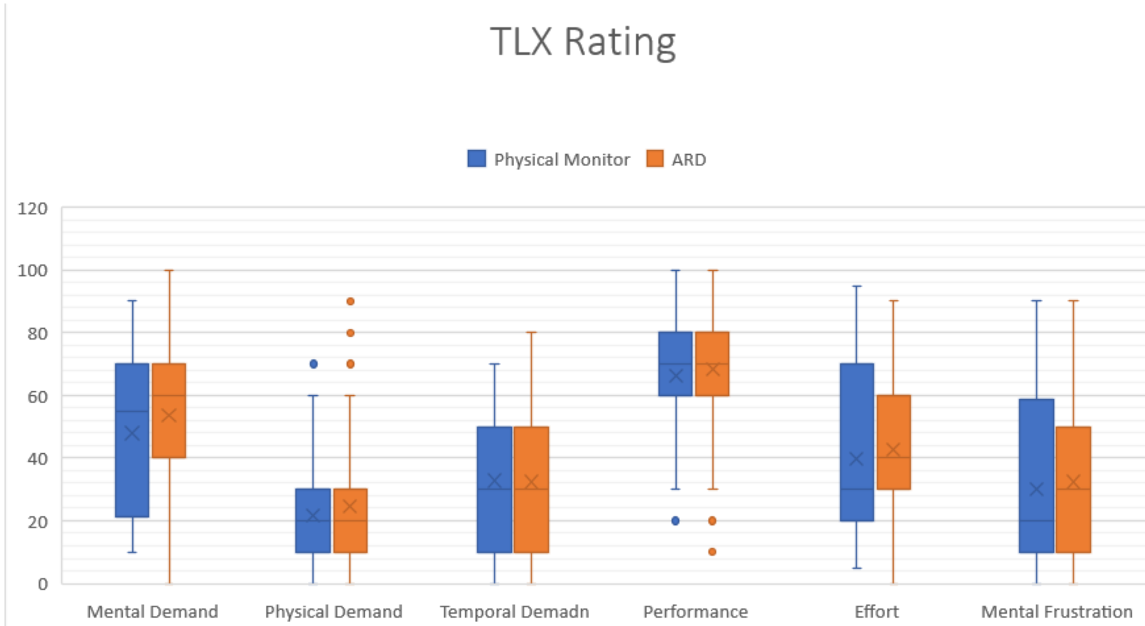


Figure 7.5: TLX score comparison for around the display interfaces

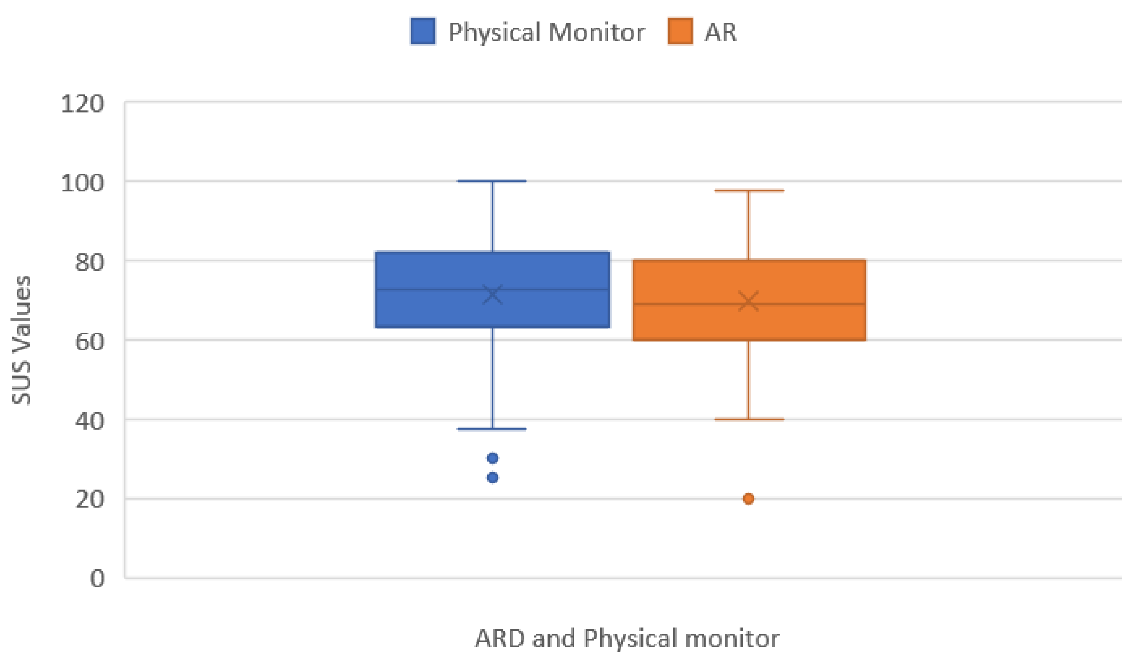


Figure 7.6: Average SUS score comparison for around the display interfaces

7.2.3 System Usability

The system usability score for the ARD was 69.9 which is right above average of 68 [21, 22], and for the physical monitor/tablet was 73 which is good rating. The normality for each condition was calculated and the data is not normally distributed as per Shapiro-Wilk test,W(98)=0.96, p=0.01.

No significant difference were observed among the SUS scores for ARD and physical monitor interface through the Kruskall-Wallis test(α=0.05), $\chi^2 = 0.22$, $p = 0.63$),df=1 .

7.2.4 Time taken to complete the tasks

The normality of the overall time taken to complete the tasks was assessed across ARD and physical monitor. The Shapiro-Wilk test(α=0.05) indicated that the scores were not normally distributed,W(96) =0.93, p=0.00. It was identified through Kruskall Wallis test(α=0.05) that the system used ARD or physical monitor significantly impacts the time taken to complete specific tasks, $\chi^2 = 14.35$, $p = 0.00$),df=1 ARD (M=16.72 minutes, SD=3.72 minutes) and physical monitor (M=14.06 minutes, SD=4.45 minutes).

A significant difference was observed for the following tasks.

1. Identifying points within a specific zone(zone with highs and lows) with zooming and panning.A significant difference was observed, $\chi^2 = 70.50$, $p< 0.001$,df=1 with ARD(M= 1.38, SD= 0.34) and physical monitor (M= 1.15, SD= 0.47).

2. Understanding relationship between isovist area and isovist perimeter. A significant difference was observed, $\chi^2 = 44.76$, $p < 0.001$,df=1 with ARD(M= 0.95, SD= 0.20) and physical monitor (M= 1.37, SD= 0.26).

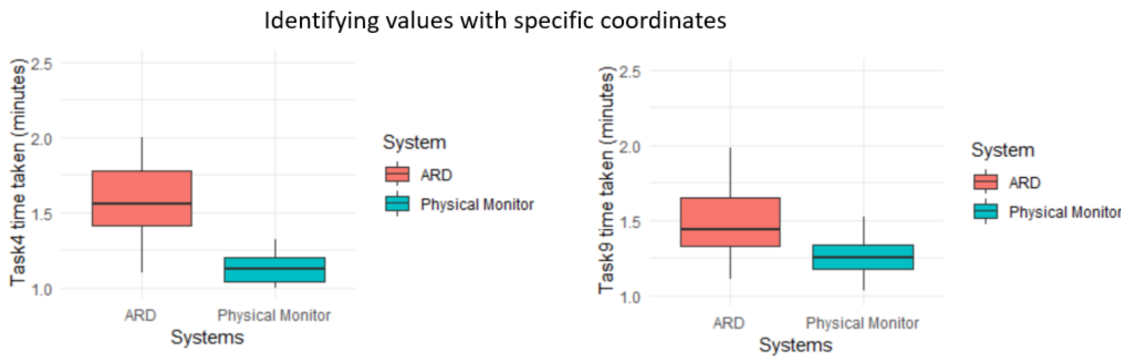


Figure 7.7: Time taken to identify points with specific X and Y coordinates

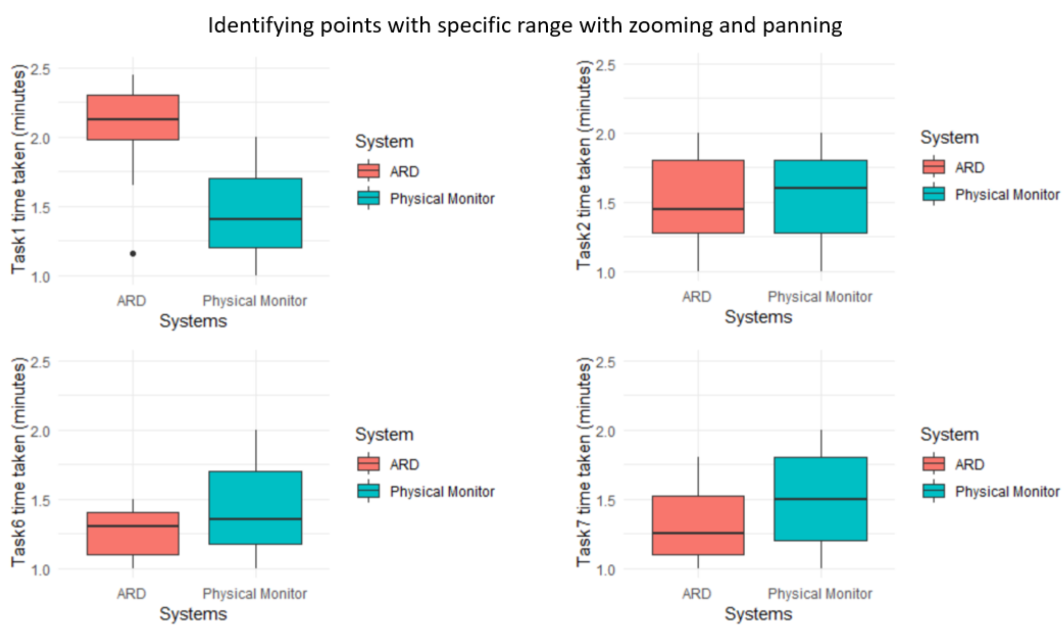


Figure 7.8: Time taken to identifying points with specific zone/range with zooming and panning in Floorplan A and Floorplan B

Identifying points with specific zone/range with zooming and panning

The following tasks comprised of identifying with specific zone/range and significant differences were observed for each task:

1. Task1: For Connectivity spatial attribute:

   (a) Click on a point with "High" values, in the bottom left of the floorplan A.

   (b) How many points have similar range in the floorplan A.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.

   (c) How many points have similar range in the floorplan B.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.

2. Task2: The above tasks were repeated for another value like low/very low.

3. Task 6: For isovist perimeter attribute:

   (a) Click on a point with "High" values, in the bottom left of floorplan A.

   (b) How many points have a similar range in floorplan A? Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.

   (c) How many points have a similar range in the floorplan B? Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.

4. Task 7: The above tasks were repeated for another value like low/very low.

5. Task 4: Find the point X=290, Y=390 in floorplan A and click on that point. What is the range and connectivity value.

6. Task 9: Similar to Task 4 was performed for isovist perimeter.

Task	Kruskall Wallis(α=0.05)		
	χ^2	p	df
Task1	15.54	< 0.001	1
Task 2	17.12	< 0.001	1
Task 6	22.47	< 0.001	1
Task 7	22.82	< 0.001	1

Table 7.3: Significant differences for the tasks involving Identifying points with specific zone/range with zooming and panning

A significant difference was observed in time taken to do the tasks for connectivity(M=13.5, SD=0.1) and isovist perimeter(M=5, SD=0.2) in ARD, $\chi^2 = 64.07$, $p < 0.001, df$=1. Learning effect was observed for the tasks in ARD since the time was reduced as the participants proceeded to do the tasks for spatial attributes from connectivity to isovist perimeter as similar tasks were performed for both the spatial attribute. While performing the tasks for spatial attribute: Isovist perimeter, participants got familiar with observing the floorplan B in AR layer and took less time as shown in Figure: 7.8. Also the participants performed the tasks using less zoom and pan operations in ARD((freq of operations calculated by overall time taken = 0.18 for isovist perimeter) than the physical monitor (freq=15).

Transfer error was also observed as the participants were trying to click on the points in AR, while the AR interface did not have any interactions. 18 participants tried to do the same thing(Technical confusion, M=0.37 SD=0.48). Habituation period and transfer error added up to more time taken to complete the tasks in AR for initial tasks with connectivity spatial attribute, which decreased as the participants moved towards the isovist perimeter attribute, as shown in 7.8.

Participants performed more zoom and pan operations for the tasks and took extra time in physical monitor as the participants had to switch between floorplan A and floorplan B by zooming and panning. A significant difference was observed between operations(zoom and pan) performed in physical monitor (M=30,SD=0.7) and ARD(M=3.1, SD=1.1) for these tasks:$\chi^2 = 71.393$, $p = < 0.001$,df=1. This resulted in participants losing track of where they were looking and taking more time to accomplish the tasks and making an error in identifying the zones mentioned in section: 7.2.5. 31 participants in physical monitor lost track of the point they clicked due to switching back and forth between floorplan A and floorplan B which was marked as logical confusion.

Understanding the relationship between Isovist Perimeter and Isovist Area

The time taken for the tasks in ARD (M=0.95, SD=0.20) for understanding the relationship between isovist perimeter and isovist area was less than in physical monitor (M=1.34, SD=0.26). A significant difference was observed between operations(zoom and pan) performed in physical monitor (M=70, SD=6.3) and AR (M=28.3, SD=6.2) for these tasks:$\chi^2 = 71.393$, $p = < 0.001$, df=1. This was observed through the video analysis that participants could look at the bigger picture all at once and did not require multiple zoom and pan operations in ARD, which lead to less time taken in

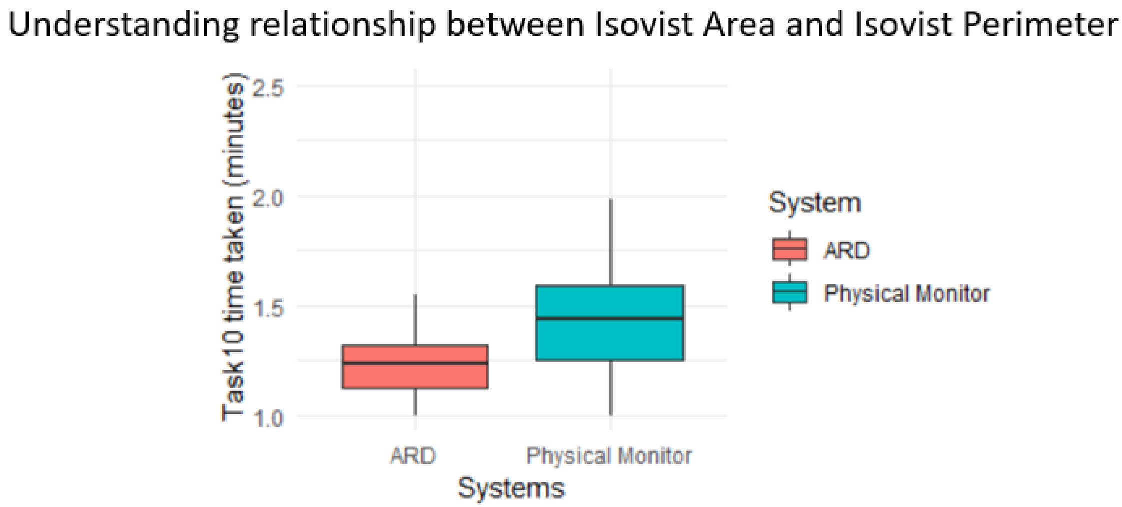


Figure 7.9: Understanding relationship between isovist area and isovist perimeter

ARD.

7.2.5 Accuracy

The overall accuracy of the AR platform appears to be more than physical monitor platform. Accuracy for the tasks was measure with the help of software logs and video recording from the HoloLens 2. If the participant clicked at the correct place and reported the correct answer, the accuracy was given as 1. Each task had sub-tasks in it and the accuracy value was assigned as per each sub-task. The accuracy was measured on the scale of 0 to 1 for each tasks. Accuracy for all the tasks in AR is 0.90 and in physical monitor is 0.87. A significant difference was observed for ARD and physical monitor, F(1,94) = 49.95, p= $2.73 * e^{-10}$,.

Normality for the tasks was determined with the help of Shapiro-Wilk Normality Test(α=0.05) and non-parametric test was used for each tasks. Significant difference was observed as shown in the Table: 7.3

Identifying points with specific zone/range with zooming and panning

Accuracy for these tasks was less in physical monitor (Accuracy rate=0.80) than ARD(Accuracy rate=0.84). Participants panned to and fro between Floorplan A and Floorplan B in the physical monitor interface. This operation was overhead for the participants and made them forget where the selected point in Floorplan A and

Task	Kruskall Wallis(α=0.05)		
	χ^2	p	df
Task1	32.19	$1.39 * e^{-08}$	1
Task 2	15.54	$7.93 * e^{-05}$	1
Task 6	22.47	$2.13 * e^{-06}$	1
Task 7	22.82	$1.77 * e^{-06}$	1

Table 7.4: Significant differences for the Accuracy of tasks involving identifying points with specific zone/range with zooming and panning

Floorplan B was. For ARD, participants performed less zoom and pan operations as they could complete the task by looking at focus+context regions simultaneously.

Understanding the relationship between Isovist Perimeter and Isovist Area

The final task of an understanding relationship between isovist perimeter and isovist area, participants performed better in AR than physical monitor for the same reason as for the above task. The operations(zoom and pan) were less in ARD(M=15.3, SD=3.1) than physical monitor (M=5.1, SD=2.6).

Tasks	Accuracy rate ARD	Accuracy Rate Physical Monitor
Identifying similar regions in Floorplan A	1	1
Identifying similar regions in Floorplan B	0.93	0.86
Identifying coordinates in Floorplan A.	0.98	0.83
Understanding relationship between isovist perimeter and isovist area	0.90	0.87
Identify regions next to a certain region in Floorplan A	0.90	0.82
Identify regions next to a certain region in Floorplan B	0.99	0.91

Table 7.5: Around the Display Accuracy of the tasks data

7.3 Above the Display

As part of the ABD, I evaluated how the layered approach of projecting data above the display interface using tablet + HMD helps the user understand how two spatial attributes (openness and visual complexity) are related to each other and the raw isovist data. This was evaluated through tasks where the participants were supposed to tell how the isovist shape and size correlate with openness and visual complexity values.

7.3.1 Post Study Questionnaire Data

A statistical analysis of data from the post-study questionnaire indicates that participants ranked the tablet interface above the ABD interface across a range of measures:

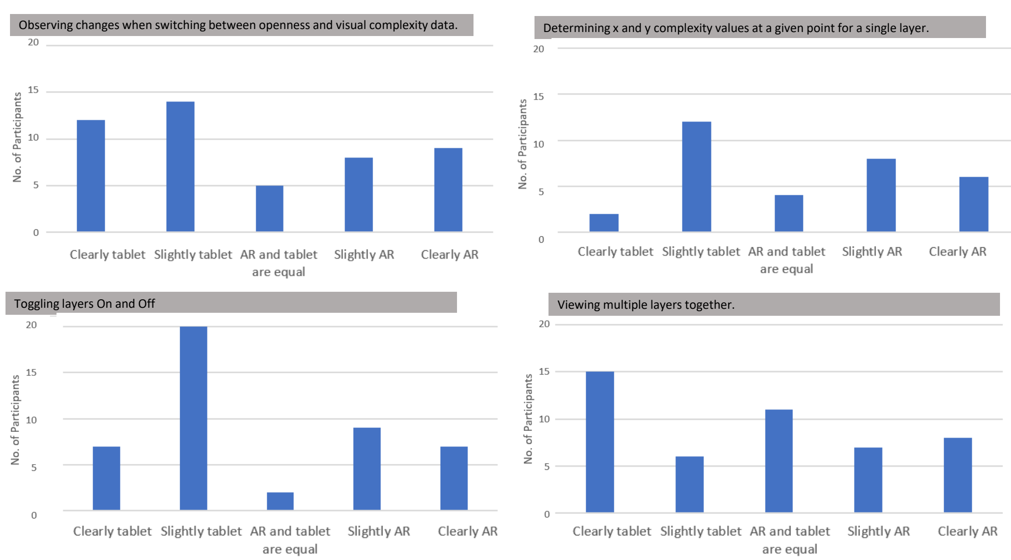


Figure 7.10: ABD Post Study Questions for AR and physical monitor interface.

1. Determining x and y complexity values at a given point for a single layer, t(47)=-5.78,p=2.82e-07, Cohen's D=0.83. 32 participants expressed that tablet is better than AR for this task, while 10 participants ranked AR and tablet as equal.

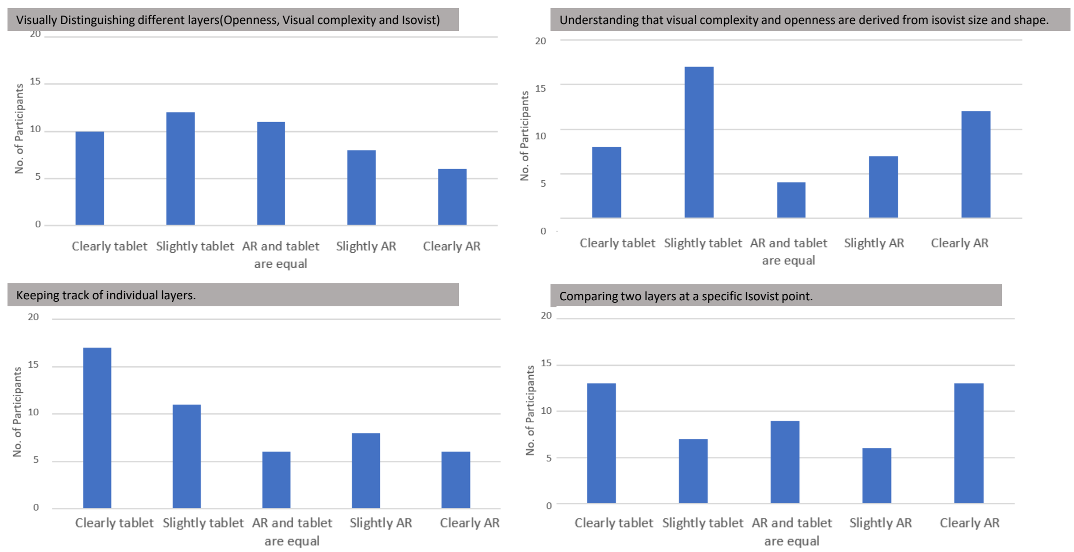


Figure 7.11: ABD Post Study Questions for AR and physical monitor interface continued.

2. Understand that visual complexity and openness are derived from isovist size and shape better in a tablet than AR, t(47)=-2.29,p=0.0131, Cohen's D=0.33. 19 Participants preferred tablet followed by 17 participants reporting that tablet and AR are equal. Observational data from video analysis is described in the section 7.3.5.

3. Completing the tasks efficiently, t(47)=-2.67,p=0.005, Cohen's D=0.38. 21 participants reported that tablet is better, followed by 14 participants ranking that AR and tablet are equal. Observational data from video analysis is described in the section 7.3.4.

4. Completing the tasks accurately, t(47)=-4.8003,p=8.236e-06, Cohen's D=0.69. 29 participants reported that tablet is more accurate, followed by 10 participants expressing that AR and tablet are equal. Observational data from video analysis is described in the section 7.3.5.

   For the rest of the questions, no significant difference was observed. Through the detailed observational data from video analysis and software logs discussed in section 7.3.5, some disparities were observed in terms of accuracy which were contradicting to the self reported data for tasks involving understanding that visual complexity and openness are derived from isovist size and shape.

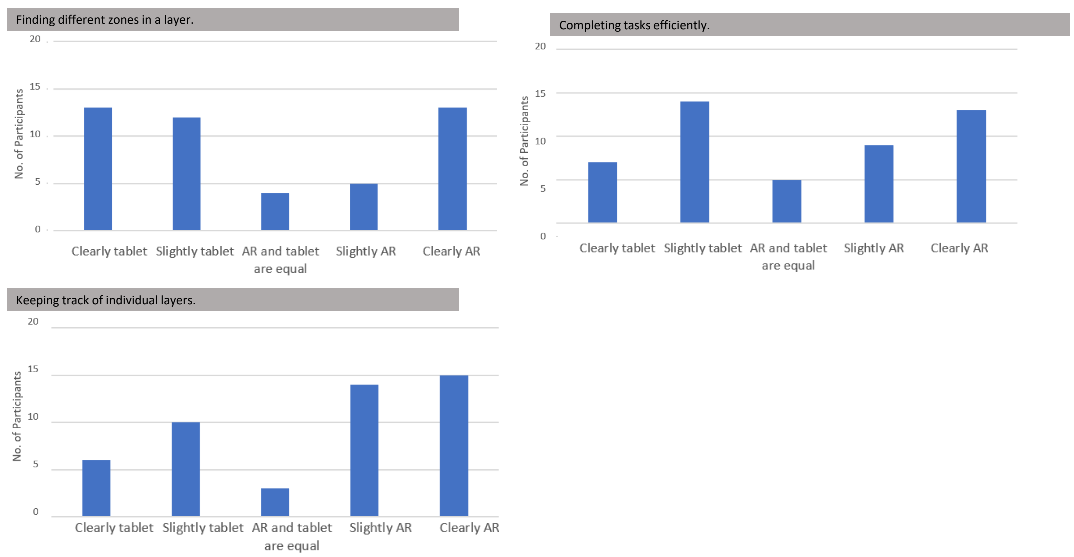


Figure 7.12: ABD Post Study Questions for AR and physical monitor interface continued.

7.3.2 TLX Questionnaire

Figure: 7.5 represents the NASA-TLX questionnaire responses. Normality distribution was determined with the help of Shapiro-Wilk normality test(α=0.05) as shown in Table 7.6. Through Kruskall-Wallis I computed the statistical differences (α=0.05), significant difference was computed for the physical activity required to perform the tasks in AR and physical monitor interface , $\chi^2 = 0.14$, $p = 0.02$, df=1. For ABD, physical stress(M=34.5,SD=29.12) required to perform the tasks in AR while physical stress reported for physical monitor (M=20, SD=22.12).

It was identified that platform(AR or physical monitor) used had no significant impact on the TLX of the interfaces for mental demand $\chi^2 = 0.14$, $p = 0.69$),df=1, time pressure $\chi^2 = 0.03$, $p = 0.86$),df=1, successful$\chi^2 = 2.27$, $p = 0.13$),df=1, performance $\chi^2 = 0.32$, $p = 0.56$),df=1, and frustration $\chi^2 = 0.71$, $p = 0.39$),df=1.

Through video analysis, the time taken to complete the tasks was calculated and observation notes were made for each participant. It was determined that participants took time(M=0.13, SD=3.2) to align the layers with the tablet for ABD. While the participants were asked to do the tasks such as identify the overlapping zones for two layers and determining the Isovist property at that point, participants stood up and with their head position oriented down aligned layers perceptually such that the two layers in ABD overlap with the data in tablet. Since the tablet was lying flat and the participants wearing HoloLens had to look down at the ABD interface for a longer period of time(M=17.63 minutes, SD=0.88) at the standing position, the participants expressed through the interview that the headset's weight added to the physical constraint since the participants were always looking down to see. All the participants wished they could change the alignment of the tablet with respect to them as compared to tablet always lying flat on the surface. P39 also said that "It would have been better if the visuals were placed on the screen on the wall because in that case you can see like a whole view which is like cinema". P31 also stated, "I felt my neck was definitely strained the whole time. I think it would have been easier if the visuals were in front of me. Instead of looking down, I could see in front."

NASA-TLX	Shapiro-Wilk Normality Test(α=0.05)		
	Test Statistic(W)	p-value	Conclusion
Mental Demand	0.95	0.00	Non-parametric
Physical Demand	0.83	< 0.001	Non-parametric
Temporal Demand	0.92	< 0.001	Non-parametric
Performance	0.88	< 0.001	Non-parametric
Effort	0.94	< 0.001	Non-parametric
Mental Frustration	0.88	< 0.001	Non-parametric

Table 7.6: Normality of Test ratings for ARD

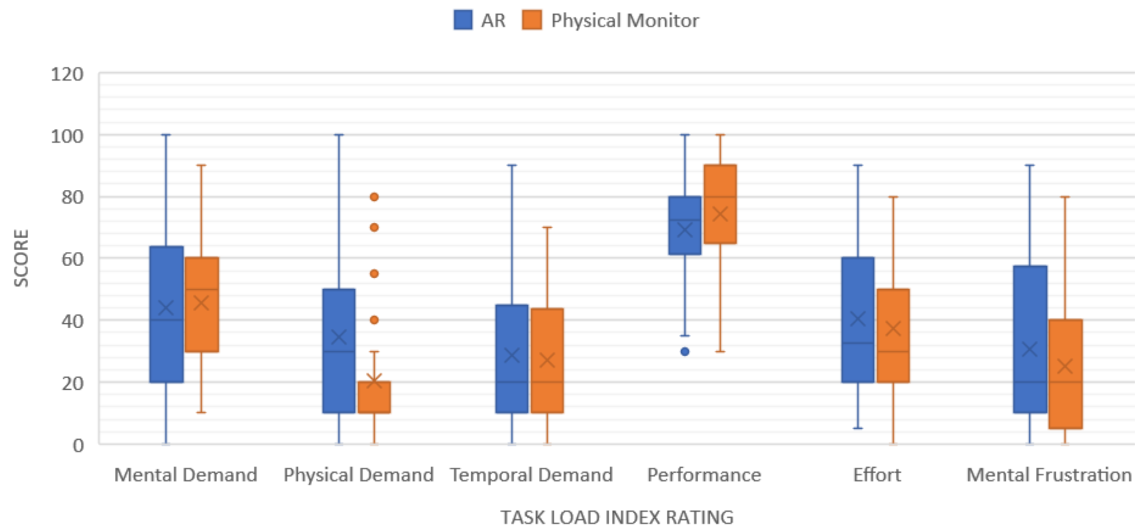


Figure 7.13: TLX score comparison for above the display interface

7.3.3 System Usability

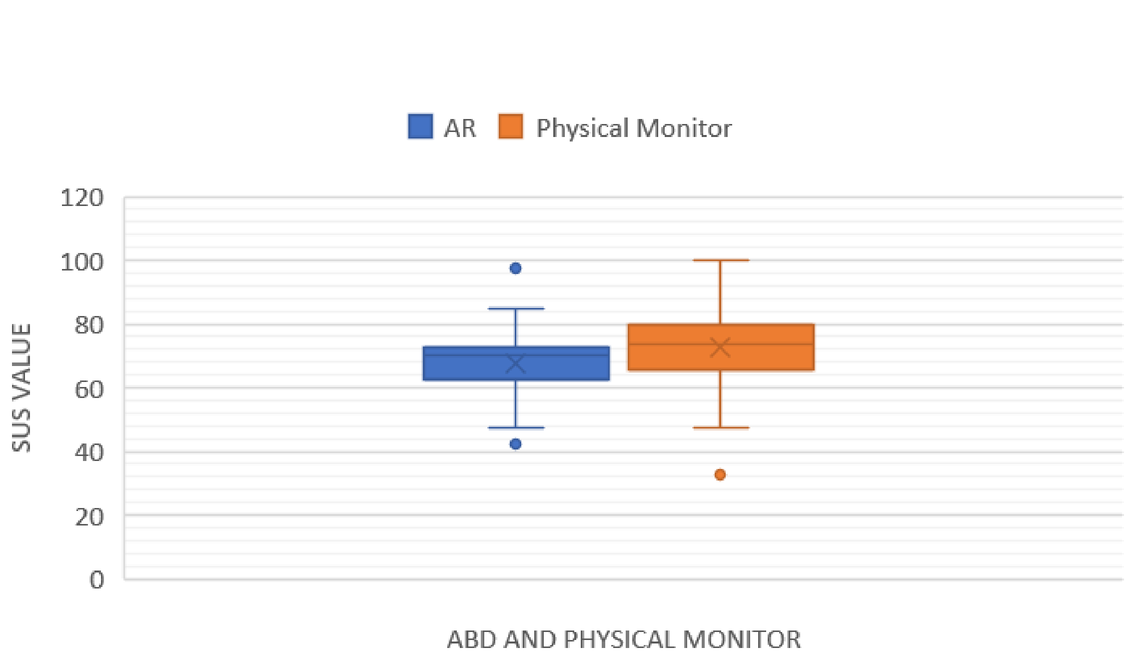


Figure 7.14: SUS score for Above the display interfaces

The system usability score for the ABD and physical monitor was 70 and 75, respectively, which is a good rating [21, 22]. The normality for each condition was calculated, and the data is not normally distributed as per Shapiro-Wilk test, W(98)=0.97,

p=0.07. No significant difference were observed among the SUS scores for ABD and physical monitor interface through the Kruskall-Wallis test(α=0.05), $\chi^2 = 0.97$, $p = 0.07$),df=1 .

7.3.4 Time taken to complete the tasks

The normality of the overall time taken to complete the tasks was assessed across ABD and physical monitor. The Shapiro-Wilk test indicated that the scores were not normally distributed,W(96) = 0.86, $p = 5.04 * e^{-08}$. It was identified through Kruskall Wallis test(α= 0.05) that the platform significantly impacts the time taken to complete specific tasks for both around the display, $\chi^2 = 5.53$, $p = 0.01$),df=1 with ARD (M = 20.47, SD = 6.49) and physical monitor (M=18.13, SD=4.59).

The participants performed 17 tasks for ABD and Baseline (ABD):

1. Four initial tasks are working with a single layer on the tablet to identify the zones.

2. Four tasks to identify zones on a single layer and determine isovist property at that point.

3. Four tasks to identify the overlapping zones for two layers and determine the Isovist property.

4. Five tasks for the participants to use their own approach to identify points with specific isovist properties in the floorplan.

No significant difference was observed for the any of the tasks.Shapiro-Wilk test indicated that the scores were not normally distributed. Kruskall-Wallis test(α=0.05) was used to calculate the differences as shown in the table: 7.7

Some interesting observations were made during the video analysis.

NASA-TLX	Kruskall-Wallis (α=0.05)		
	χ^2	p-value	df
Task 1	0.07	0.78	1
Task 2	5.93	0.11	1
Task 3	0.97	0.32	1
Task 4	3.54	0.08	1
Task5	0.01	0.12	1
Task 6	1.4	0.23	1
Task 7	1.1	0.29	1
Task 8	0.007	0.93	1
Task 9	0.22	0.63	1
Task 10	2.23	0.13	1
Task 11	2.23	0.13	1
Task 12	0.86	0.35	1
Task 13	2.03	1.533	1
Task 14	0.27	0.59	1
Task 15	2.69	0.10	1
Task 16	0.30	0.85	1
Task 17	3.38	0.18	1

Table 7.7: Kruskall-Wallis for ABD tasks Time taken

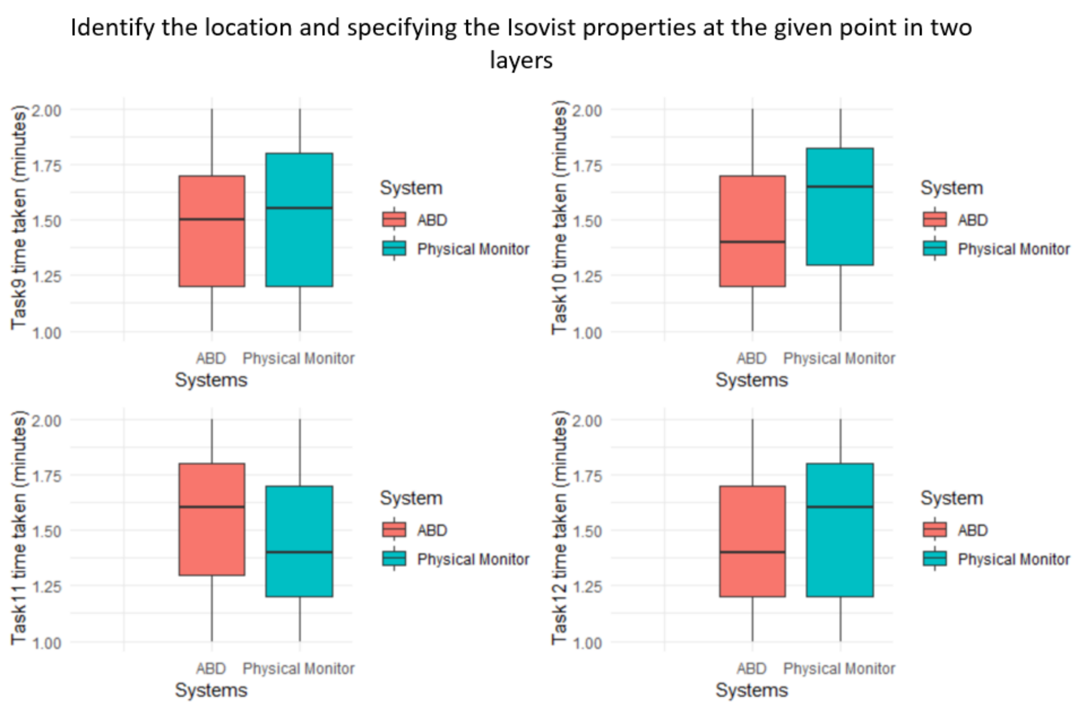


Figure 7.17: Box Plot for time taken in minutes for Above the display tasks 9-12

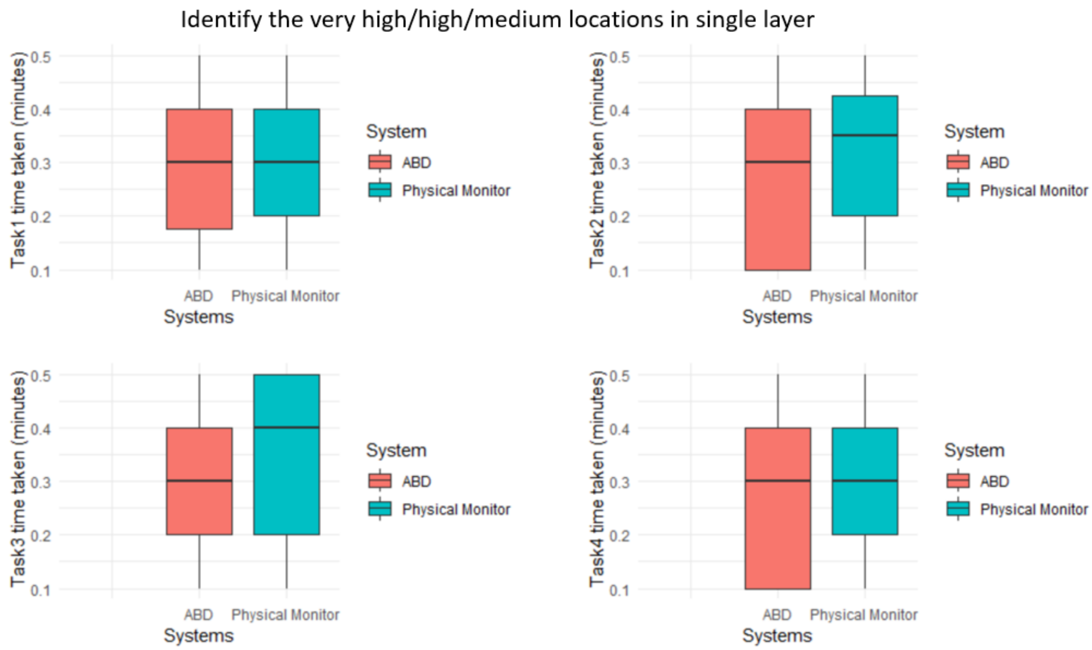


Figure 7.15: Box Plot for time taken in minutes for Above the display tasks 1-4

Choosing own way to identify isovist properties

Task 13 to Task 17 allowed the participants to choose their own way to complete the tasks. Task 13 involved identifying the isovist properties and how the visual complexity and openness values change across a specific path, time taken to complete this task in ABD(M=0.56, SD=2.6) and physical monitor(M=0.47, SD=0.26). The participants spent some time (M=0.1, SD=1.2) in physical monitor to remove (through toggling Off the layer) the merged openness and visual complexity layer to better see the isovist layer in the physical monitor interface. 20 participants removed the layers by toggling the layers "OFF." All the other 28 participants had some challenges in identifying the isovist shape and size with merged layers in physical monitor, and the accuracy rate was calculated for these tasks in the next section 7.3.5 which conveyed that toggle On/Off affects the accuracy rate in physical monitor. No significant difference was observed for the toggle/no toggle condition with time taken across the ABD/physical monitor, Task13 $\chi^2 = 2.31$, $p = 0.50$),df=3.

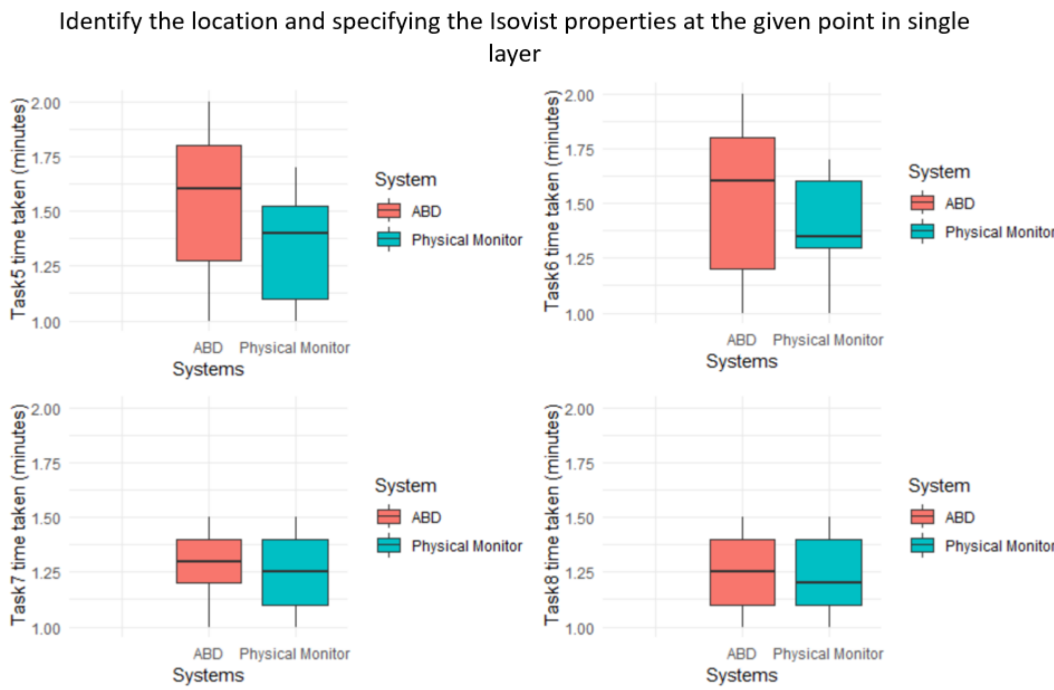


Figure 7.16: Box Plot for time taken in minutes for Above the display tasks 5-8

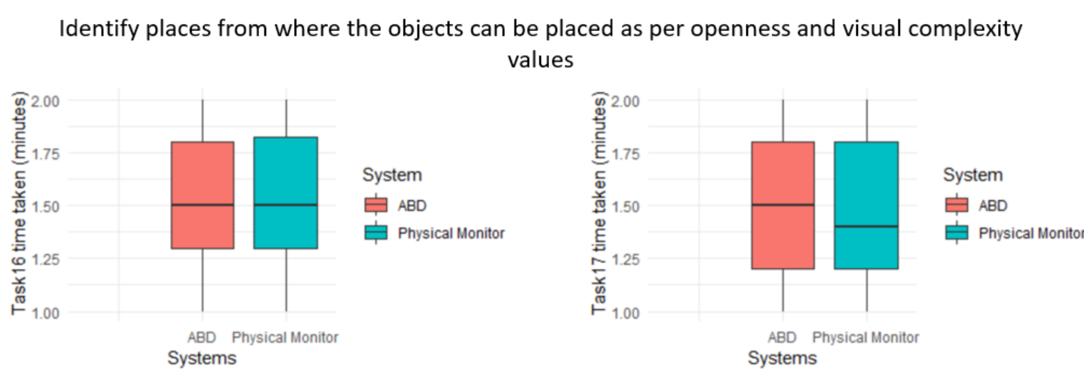


Figure 7.19: Box Plot for time taken in minutes for Above the display tasks 16-17

Identify object placement coordinates

Task16 and Task17 involved identifying the regions with specific properties for the placement of objects. E.g., one task involved identifying two places for the placement of Object A and object B in the floorplan where the openness and visual complexity are very high, and isovist is big. The time taken to achieve these tasks in physical

Figure 7.18: Box Plot for time taken in minutes for Above the display tasks 13-15

monitor (M=1.49, SD=0.32) and AR interface (M=1.51, SD=0.31). 25 participants among these did not make use of any filters provided to identify such regions both in AR and physical monitor interface, this resulted in taking more time to complete the task in ABD (M=1.8, SD=0.25)and physical monitor (M=1.55, SD=0.27) than participants using the filters to identify regions in ABD (M=0.39, SD=0.11) and physical monitor (M=0.44, SD=0.35). No significant difference was observed for the filter/no filter condition with time taken in ABD/physical monitor.Task16 $\chi^2 = 0.80$, $p = 0.84$),df=3 Task17 $\chi^2 = 3.5$, $p = 0.4$),df=4.

From the qualitative analysis of the interview data, it was determined that once the participants grasped how the openness and visual complexity are distributed, they felt confident that they could determine the values by themselves without using any filter. P7 quoted that, “I didn’t use filter since I knew the openness is less in the corners since isovist is small there.”

7.3.5 Accuracy

Overall ABD platform appeared to be more accurate than the physical monitor platform. The Shapiro-Wilk test indicated that the scores were not normally distributed,W(96) = 0.96, p = 0.02. It was identified through Kruskall Wallis test(α= 0.05) that there was no significantly impact of accuracy to complete all the tasks for ABD and physical monitor, χ^2 = 1.38, p = 0.23),df=1 with ARD (M = 0.86, SD = 0.08) and physical monitor (M=0.83, SD=0.09). Some careful observations with respect to the accuracy of the tasks were made while the participants used toggle and filter operations. Tasks 9 to 12 in Group 4, comprising of identifying the isovist properties as per the openness and visual complexity across two layers, showed some significant difference.

No significant difference was observed for the any of the tasks.Shapiro-Wilk test indicated that the scores were not normally distributed. Kruskall-Wallis test(α=0.05) was used to calculate the differences as shown in Table:7.8.

NASA-TLX	Kruskall-Wallis (α=0.05)		
	χ^2	p-value	df
Task 1	0.1.41	0.22	1
Task 2	2.11	2.11	1
Task 3	1.56	0.32	1
Task 4	0.54	0.6	1
Task5	2.12	0.15	1
Task 6	0.05	0.80	1
Task 7	0.21	0.70	1
Task 8	1.54	0.93	1
Task 15	2.69	0.10	1
Task 16	0.30	0.85	1
Task 17	3.38	0.18	1

Table 7.8: Kruskall-Wallis for ABD tasks

Identifying the isovist size and shape and how the visual complexity and openness is changing across the path.

For these task, significant difference was observed with, Task9 χ^2 = 11.51, p = 0.00),df=1, Task10 χ^2 = 16.03, $p < 0.001$,df=1, , Task11 χ^2 = 16.33, $p< 0.001$,df=1,

Interface	Task 9	Task 10	Task 11	Task 12	Task 13
Toggle in ABD	0.89	0.92	0.91	0.92	1
No Toggle in ABD	0.89	0.93	0.91	0.97	1
Toggle in physical monitor	0.8	0.84	0.74	0.79	0.89
No Toggle in physical monitor	0.74	0.75	0.73	0.77	0.78

Table 7.9: Accuracy comparison with toggle/No toggle across ABD and Physical monitor

Task12 χ^2 = 0.86, $p<$ 0.001,df=1, Task13 χ^2 = 22.02, $p<$ 0.001,df=1, Task14 χ^2 = 47.77, $p <$ 0.001,df=1.

The participants performed better in AR while identifying isovist characteristics at a given point for isovist area/isovist perimeter in two layers. This occurred as participants had difficulty identifying the isovist shape and size since the two overlapping layers in the physical monitor hinder the visibility of the isovist layer. The accuracy was less in physical monitor and "No toggle" reduced the accuracy furthermore as shown in Table: 7.9. Significant difference was also observed for these tasks of using the Toggle/No Toggle with ABD/Physical monitor, Task9 χ^2 = 11.54, p = 0.00),df=3, Task10 χ^2 = 20.51, p = 0.00,df=3, , Task11 χ^2 = 16.69, p = 0.00,df=3, Task12 χ^2 = 22.80, $p<$ 0.001,df=3, Task13 χ^2 = 48.49, $p<$ 0.001,df=3.

1. 28 participants had difficulty in identifying the exact isovist shape and size(logical confusion) in physical monitor interface due to the overlapping layers(merged layer) in the physical monitor interface.

7.4 Post study Interview Data

Short notes were created from the transcribed interview data in the Miro, and 60 notes were distributed to each participant. One 2-hour session of the Affinity Diagramming technique was used to make themes out of the short notes in the Miro. This two-hour session helped organize the feedback into three themes and 17 subthemes as shown in Figure 7.20. The three themes were focused on user experience, user implementation, and Issues. User Experience comprised of the comments about the layered interface, advantages of AR interface, task difficulty, first-time AR users, tablet bias, how visual

Tasks	Accuracy ABD AR	Accuracy Physical Monitor
Identifying regions for isovist area/isovist perimeter	0.89	0.84
Identifying overlapping regions for isovist area and isovist perimeter	0.83	0.75
Identifying isovist characteristics at a given point for isovist Area/isovist perimeter in Single layer	0.89	0.89
Identifying isovist characteristics at a given point for isovist area/isovist perimeter in Two layer	0.82	0.74
Explain how the isovist values are distributed across the floorplan	0.8	0.7
Identify the regions for the object placement	0.91	0.9

Table 7.10: Above the Display Accuracy of all the tasks

distinction of SS data was engaging in AR, applications of the interface, and some miscellaneous comments about the interface issues.

Tablet Bias: Ten participants expressed that their past experience with the tablet favored using the physical tablet interface more than the AR interface. P28 quoted that "I was filling out the form(Post Study Questionnaire), and at times I thought like is it because I am more used to using iPad."

Advantages of AR(big picture view): 20 participants expressed that they preferred AR over the tablet. The main emphasis was that the AR gave a more comprehensive 360-degree picture with relatively fewer operations like scrolling, dragging, and zooming in and out. P10 also expressed that "I would get bored of looking at Tablet all the time, but like that was very interactive ".P23 quoted that "I can see the entire range of the graph in a single shot that is very useful to compare different values, and I can see both floorplans with zoom display the single time.".

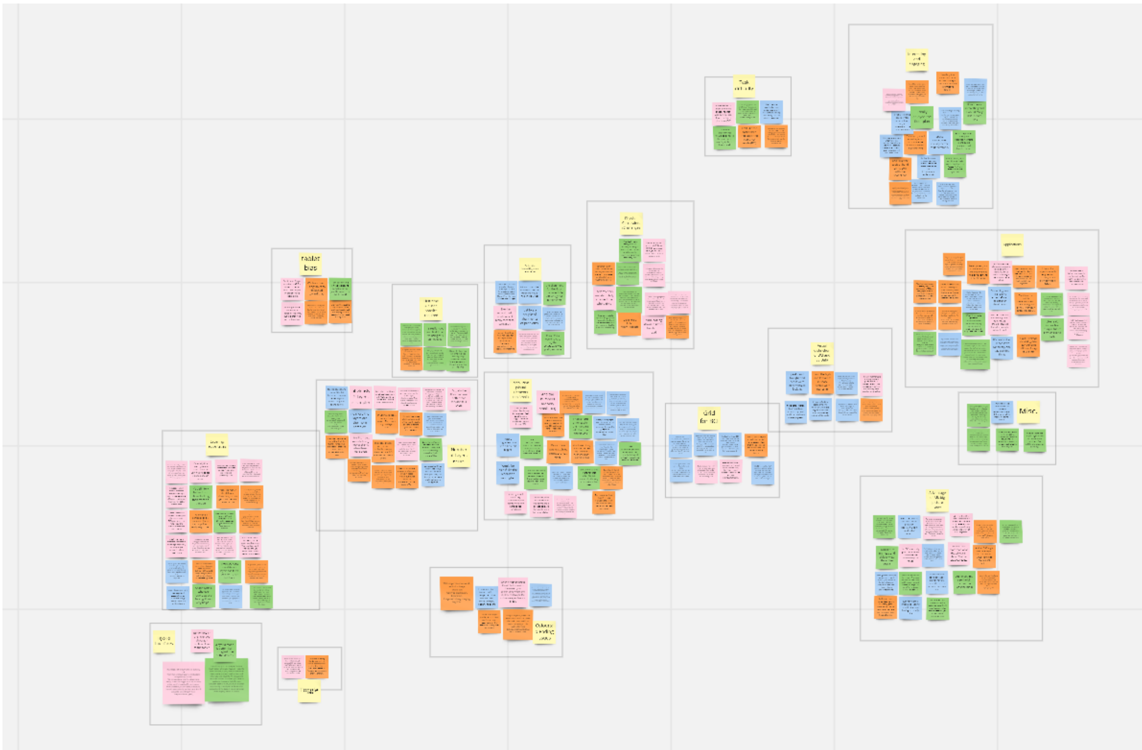


Figure 7.20: Affinity Diagram notes arranged by the researchers into themes

Interesting and Engaging: 35 participants expressed the implementation aspects that they discovered more exciting and engaging. P20 said that the space syntax was visually better to understand, and P13 said, "I liked the topic in hand space syntax and also enjoyed it".P15 also expressed that "I really liked the space syntax because it was easy to understand. The tasks were fun". P7 expressed that"I could differentiate them better with AR like the dark places or the light places."

Task Difficulty: The comments did not mention any difficulty with respect to tasks. P11 said that "Space syntax tasks were fun and were easy to understand since the application of space syntax was helpful and quite good."

First time AR user, practice required: 5 participants expressed that the some time is needed to get familiar with the AR. Participants were more comfortable in the second part of the study(Experiment B). P26 expressed that "Honestly, from the last time, this was like very, very convenient to use for someone who is like using it for the second time".

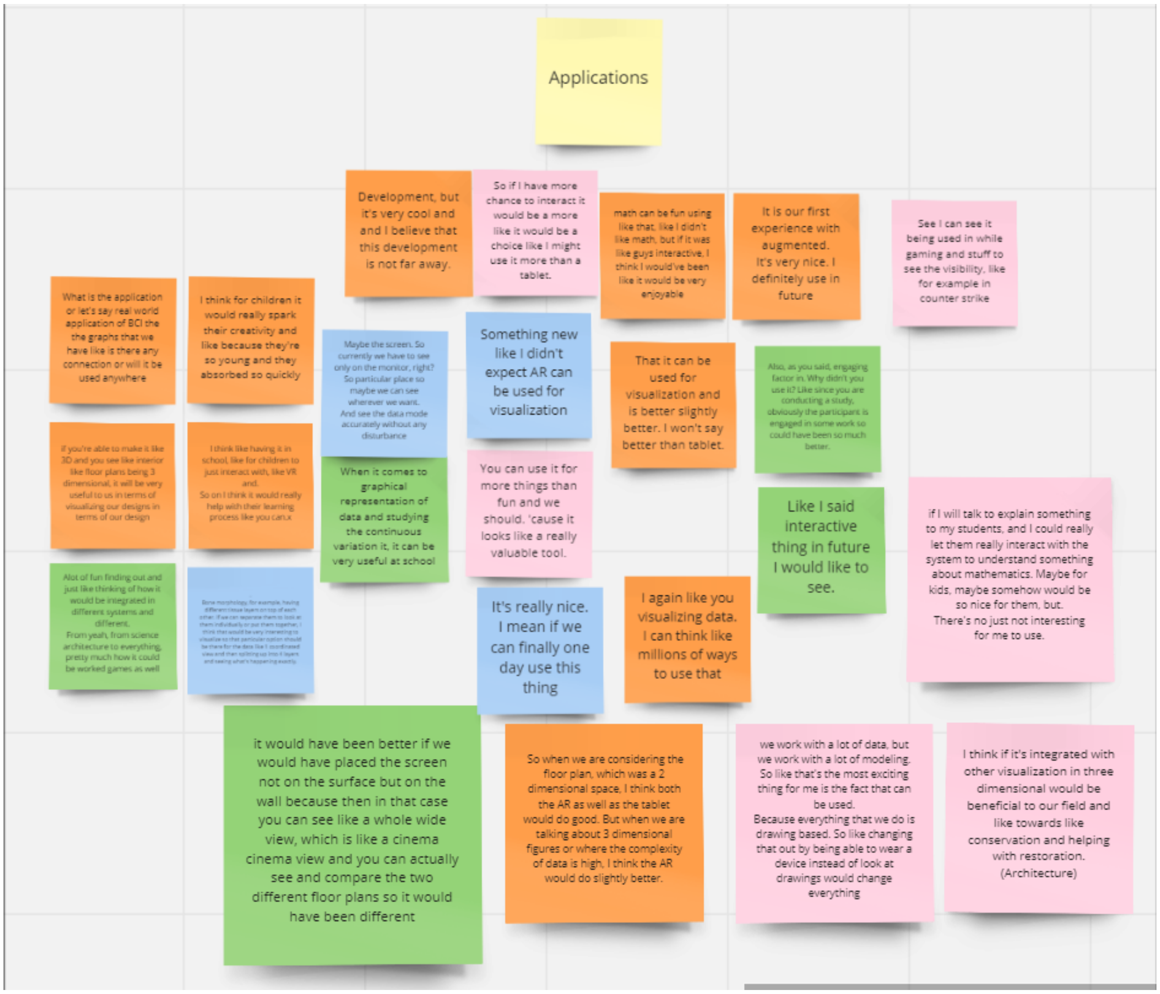


Figure 7.21: Affinity Diagram notes under one of the theme Applications

Applications: The participants expressed that the space syntax can be used across various domains, and the participants could think of million ways it can be used. Two Domain experts from architectural backgrounds said they could see displaying space syntax visualization implementation in their field, especially in the form of 3D floorplans depicting which room will have more openness. P23 expressed that "I work with a lot of data, but we work with a lot of modeling. So like that's the most exciting thing for me is the fact that it can be used. Because everything that we do is drawing-based. So like changing that out by being able to wear a device instead of look at drawings would change everything."

Visual Distinction of the features in SS: "The entire sort of like a heat map in the study was helpful when I had to complete the task." P28 expressed this. As per the participants, the floorplan was aesthetically pleasing, and it was good to compare peaks in it.

Issues

Implementation Issues:

Toggle : As part of the implementation, 36 participants felt that it was helpful to toggle the layers and the toggle feature helps to give accurate value to the data. P10 expressed that "Toggle feature which was actually helpful whenever you ask me to find a specific value. I use a toggle function because it gives me the accurate data I want".

Color, Calibration, and Resolution Issue : As part of the space syntax, AR has some colour issues. The users identified that dark colours are difficult to differentiate, and the users also felt a problem with the alignment and wished they could calibrate while studying. P15 quoted that "There's an issue that it is difficult to see the dark colors in AR."

Number of Layers : According to 41 participants, the number of layers also contributes to the tasks' simplicity and performance. The more the number of layers, the more is the complexity. The complexity arises because of the density of the information. P25 expressed that "it was easier, since there were only two layers," conveying complexity increases as the number of layers increases.

Hardware Issues: These issues comprised of physical constraints mentioned by the participants due to HoloLens. Almost all participants complained about ergonomic issues like neck strain due to the headset's weight. Participant31 expressed that "I felt my neck was definitely strained the whole time."

7.5 Study summary

Our study comprised 48 participants who examined ABD and ARD interfaces across two different AR and physical monitor platforms in the space syntax domain. I analyzed self-reported data collected through TLX, System usability scale, post condition questionnaire, and interview data. Further, I also analyzed the videos and system logs to identify behavioral patterns, the time taken, and the accuracy of the platforms across the two interfaces. The findings are summarized in table 7.10.

For ABD, our research question was how can the layered approach of projecting raw and high-level data above the display interface using tablet + HMD enhance data analysis of multivariate data superior to physical screens for space syntax. I can conclude that for the ABD in the AR interface, the participants were able to understand isovist properties like shape and size and how these are distributed throughout the floorplan, and how the openness and visual complexity values vary from corners towards the more centralized areas of the floorplan. While using the physical monitor the participants had difficulty looking the isovist size and shape as the openness and visual complexity data hinders the visibility of isovist. It was also observed that the participants faced physical challenges while looking at the layers since the tablet was lying flat and weight of the HoloLens added as a constraint.

For ARD, our research question was how can spreading the floorplan data around the display with the tablet at the center help the user identify regions with similar properties in 2D floorplan superior to physical screen. I can conclude that the participants could identify similar regions in floorplans and better understand the relationship between the isovist area and isovist perimeter in AR with less zoom and pan operations. The participants could see both focus+ context region at the same time. Learning effect and transfer error was observed. The accuracy was significantly high for the tasks used for the assessment of the research questions: identify regions with similar space syntax attributes across the entire floorplan and understand how connectivity and isovist perimeter correlates.

Considering the SUS, TLX scores, and video analysis, much work needs to be done to reduce physical and mental stress. The participants expressed through the interview that the resolution of AR content was not as good as physical monitor, and the headset's weight was also added as overhead. Because of tablet bias, some participants felt more confident and successful in the physical monitor while doing the tasks. A significant number of participants also reported it would have been better if they could do the tasks without standing and looking from the top to see the layers for the above display, as it adds to the physical overload on their neck. Various other behavioral observations were made from the interview and video data, which will help future research.

Interface	Tested variable	Outcome
Above	Accuracy	AR platform provides more accuracy in the tasks which involve identifying isovist properties and understanding how the isovist values are distributed throughout the floorplan along with the space syntax attributes
Above	Time taken	For tasks involving two layers, participants took some time to adjust their view to see the two layers on top of the tablet. Participants took a significant amount of time between the tasks since they felt a bit heavy on the neck while performing the tasks due to the HoloLens weight.
Above	System Usability	Through the SUS scale, it was analyzed that the participants felt the system was complex and needed to learn a lot of things before using the system. The participants also felt that they would not use the system frequently.
Above	TLX	Overall, the participants felt more encouraged and successful while doing the tasks with physical monitors with less mental and physical activity required.
Around	Accuracy	AR platform provides more accuracy in the tasks which involves understanding the relationship between isovist perimeter and isovist area. Further, participants were more accurate in identifying the similar regions in Floorplan B and Floorplan A in AR.
Around	Time taken	For initial tasks, participants took some time to get familiar with the initial tasks in AR as they performed tablet interactions in AR.
Around	System Usability	Through the SUS scale, it was analyzed that the participants felt the system was complex and needed to learn a lot of things before using the system.
Around	TLX	No significant difference for any of the parameters for any tasks.

Table 7.11: Study summary for ABD and ARD interface.

Chapter 8

Discussion

This chapter reflects upon the results and their implications on space syntax and hybrid interfaces. I also propose directions for future work and the current limitations, and how the researchers can work on them.

8.1 Implications of the results

This section discusses the implications of the results for ABD and ARD visualizations towards the space syntax domain and hybrid interfaces.

8.1.1 Projecting Space Syntax data in AR

ABD

The post-study questionnaire, TLX, and SUS indicated that the participants preferred the tablet over the hybrid tablet+AR interfaces. A significant difference was observed in post study questionnaire where the participants expressed they felt they were more accurate and efficient in the tablet-only interface. Additionally, through TLX, participants felt more mental and physical load while performing the tasks in the AR interface. A similar observation was made through the video analysis. The participants spent a fair amount of time adjusting the HMD owing to adjusting their perspective view of the layers above the tablet. Participants also reported in the interviews that more layers above the tablets lead to more complexity, increasing the mental load to understand the data. No significant difference was observed for SUS. No significant differences were observed in the time taken to do various tasks. However, some careful observations were made while analyzing the video data: participants had trouble looking at the layers in AR and took some time to adjust themselves to see the adequately aligned data. Some participants reported that it would have been better if the participants were not supposed to stand and look from the top to see the overlapping layers. Regarding the accuracy of the tasks, participants performed better in AR as they could distinguish the data spread across the individual layers. This made it easier to identify the correct isovist shape and size distributed throughout the floorplan, and participants made fewer errors. Currently, with two layers (openness and visual complexity), participants had challenges looking at the merged data. If the data layers are increased, participants will have more difficulty.

ARD

A similar observation was observed for the ARD study through the post study questionnaire, that the participants preferred a tablet-ony over a hybrid Tablet+AR interface. A significant difference was observed in post study questionnaire where the participants expressed they felt they were more accurate and efficient in the physical monitor interface. Participants reported that it was helpful for two floorplans at the same time with the help of AR. No significant difference was observed for TLX. Although a significant difference was observed for SUS, the participants felt the AR system was complex and required learning many things to operate it. A significant difference was observed in the time taken to identify points with specific zone/range and understanding how isovist perimeter and connectivity are related.AR interface took less time than physical monitors. This was because participants could see a bigger picture of the floorplans without panning/zooming in on the AR interface. Multiple operations in physical monitors like dragging/panning/zooming led the participants to lose track of the floorplan in the physical monitor and hence took more time. A significant difference was observed in the accuracy of the tasks for the same tasks as mentioned for the time taken. Through video analysis, a similar thing was observed: participants had trouble looking at both the floorplans simultaneously. Multiple UI operations such as zoom and pan led to losing track of the floorplan in the physical monitor. Both observations affected the accuracy of the interface.

8.2 Implications for Space Syntax domain

VizSSTA helped understand the VGA space syntax terminologies- openness, visual complexity, connectivity, and isovist, which addresses the limitations mentioned by

Singh et al. [88, 68, 51]. The tool was used by participants who did not have any prior knowledge of space syntax. This could also help the authors to efficiently use the space syntax attributes for placement of story elements in the Story CreatAR tool [89] as it will help the authors know how the spatial attribute is distribute throughout the floorplan and will allow to compare the space syntax attributes. This could open new pathways to understand the space syntax terminologies along with the work of Behbahani et al. [14] which works on existing resources(manuals, documentation) to provide a better understanding of the space syntax domain. Moreover, VizSSTA could also reduce dependency on the DepthMapx tool and similarly complex alternatives. Hence the user can understand the space syntax terminologies without any prior knowledge of space syntax tools, and this was one of the challenges mentioned by Behbahani et al. [14].This research also identified that participants felt that space syntax tasks were fun and easy to understand.

8.3 Implications for Hybrid Systems

VizSSTA provides feedback from the user study that was a gap in the recent research [67, 36, 54, 66], these could be adopted and will be helpful to improve hybrid systems such as more habituation period to mitigate transfer error and learning effect. Through VizSSTA, I identified that hybrid systems can provide an understanding of space syntax, as Zhu et al. [104] identified for generalized tasks. An attempt was made to build a lightweight system with internal tracking through QRcodes to mitigate the challenge of heavy devices and lab equipment required to run hybrid systems as faced across various research [104, 46, 55, 67]. QR anchoring will help with the weight of the hybrid systems. Despite using HoloLens 2, I found similar results with respect to the physical load as with HoloLens 1 observed in previous research as well [55, 46].

8.4 Limitations

The study's main limitation while doing the study for both the above and around the display study was that the tablet was placed flat on the surface. The participants were not allowed to move the tablet in any other position. Through the interview process, participants mentioned that they would like to see the implementation where the tablet can be placed as per their preference. P39 quoted that "It would have been better if we would have placed the screen not on the surface but the wall because then, in that case, you can see like a whole wide view, which is like a cinema view, and you can actually see and compare the two different floor plans so it would have been different." For future work, the participants should be allowed to move the tablet screen as per their preference. The implementation of the QRcode already allows the information visualizations to be adjusted as per the tablet screen position. Conducting a user study will allow identifying what tablet position works best. As part of the analysis, I explored only three space syntax attributes of VGA- isovist area, isovist perimeter, and connectivity. Other space syntax attributes further need to be explored through a hybrid system. I need to explore whether ABD and ARD hybrid systems help to understand the space syntax attributes other than isovist area, isovist perimeter, and connectivity.

Other limitations were the weight and resolution limitations of the device. As technology advances, the limitations will be mitigated.

8.5 VizSSTA Design

This chapter reflects upon the contributions towards the space syntax and hybrid systems in AR.

Aim of the hybrid interface: Tool to display space syntax visualizations : The main aim of the interface is to provide an immersive experience for the users to understand the isovist properties better. [81, 45] represents that the users find it difficult to understand due to the workflow(setting radius for VGA analysis and following the steps to run the VGA analysis) of the tasks to perform while doing the analysis. VizSSTA provides an interface where the users can visualize the space syntax attributes without going through the steps to interact with the space syntax tool. VizSSTA can also visualize the isovist at a given point and related space syntax attributes. The tasks in the study involved the participants deducing how the openness was distributed throughout the floorplan as per the isovist characteristics-big/small and spiky/compact.

Provide focus+context view of the space syntax attributes : VizSSTA provides a focus+context view of space syntax attribute in an immersive environment. VizSSTA extends the tablet display in AR providing the ability to visualize and interact with large floorplans without zooming in and out.

Composite Comparative view of the space syntax attributes : VizSSTA provides a display to compare data spread across multiple layers without hindering the visibility of any of the layers. This provides a way to view the isovist at a given point and space syntax attribute value without toggling between views.

Prototype evaluation through study : Hubenschmid et al. [55], and a case study by Havard et al. [49] helped determine that the information visualizations in AR help the users understand better through AR as the AR systems provide an extensive view and bigger picture of the information. Through the literature review, [67] presents the interface implemented and presents the expert feedback. [67, 36, 54, 66] these prototypes were not evaluated through user studies. Our study of VizSSTA sheds light on the complexities and unique challenges that such hybrid systems impose on usability.

Responsive space syntax visualizations : VizSSTA provides responsive floorplans in Augmented Reality. The space syntax visualizations change in AR as the users interact with the tablet. This is achieved through a careful selection of webview visualizations, socket communications and data resolution.

Support visualization of 18 space syntax attributes : VizSSTA supports visualization of 18 attributes for both above and around the display interface. During the study, participants used two parameters- isovist area and isovist perimeter.

Color Legend : During the prototyping process, careful design decisions were made to select the colors for the legend. This was done to make sure that the users are able to perceive the colors accurately.

Color blending through transparency : The prototype offers transparency so that the users can see through the holograms. To support the visibility of multiple parallel layers on top of the tablet, transparency helped by looking through the layers while creating a composite view.

Toggle Layers ON and OFF : The prototype offers a toggle feature that allows the users to remove the data which they do not want to look at, which improves the clarity of the data.

8.6 Future Work

Through this user study, I identified that much work is required with the current implementation by analyzing the participants' behavior through the videos and SUS, TLX, and interviews. As part of the current work, the system was evaluated with the tablet lying flat on the surface, adding to the head strain. Further analysis needs to be done to identify which tablet position works best for the setup without adding any strain on the neck. Moreover, two architectural domain participants expressed that 3D floorplans will give a better picture of the space. They would like to see the spaces and their space syntax properties in a 3D perspective. A learning effect was observed, which can be mitigated by giving the participants some more habituation time to get familiar with the AR interface. Further, Participants also expressed that they would like to see the implementation in a hybrid system where the participants have the freedom to switch to AR and physical monitor as and when required. Further research needs to be done with respect to this that will help to identify whether such hybrid systems will help the user. As part of the current research, I used HoloLens 2, which provides the best resolution and is lighter in weight than the HoloLens 1. Future HMDs may provide better resolution and come with relatively less weight which will favor the AR platform with respect to the user's perspective and hence may require less physical demand. Also, work needs to be done to make sure that the users feel confident in working with AR systems as they perform the tasks accurately through AR. As part of the current research, I have presented only one part of space syntax analysis, i.e., visibility graph analysis. Other analyses like axial analysis, convex, and agent analysis, need to be explored as part of the space syntax domain.

There are still a few unanswered questions that appeared through this study:

1. How can we motivate the users to use the functionalities provided in the interfaces like toggle feature and filter functionality to do their tasks efficiently. Our study determined that many participants did not use these functionalities.

   The user could be motivated to use toggle and filter functionality by increasing the habituation period and including training tasks which highlight the usage of filter and toggle features. Our study concluded that participants displayed that participants required more habituation period.

2. How the tablet should be aligned with respect to user and what alignment will work best for hybrid systems.

   A study which allows the user to place the tablet as per their convenience will help to determine this.

3. Will this setup help in other types of space syntax analysis like convex analysis, and agent analysis, among others.

   Implementing the usage of convex and agent analysis and also displaying the relative isovist in the system and evaluating the system with a user study will help answer this question.

4. How will 3D models of urban floorplans across this setup affect the usability and user understanding of the space syntax domain.

   Displaying the space syntax distribution across 3D representation of floorplan in AR and conducting a user study to evaluate this prototype will help identify whether 3D models affect usability and user understanding.

5. How can we mitigate the transfer error?

   Increasing the habituation time during the study so that the users get accustomed to the AR interface might help mitigate transfer error.

Future research will help to shed some light on these questions.

Chapter 9

Conclusion

In this thesis, I identified the gaps in understanding the space syntax domain through preliminary work and existing literature. I identified space syntax visualization use-cases inspired by our experiences designing the Story CreatAR toolkit and working with authors who used the toolkit. Two primary use-cases were comparing two space syntax attributes and identifying regions in the floorplan with similar properties. This motivated us to develop VizSSTA around the two use cases. Existing literature supported that displaying data in AR has been proven effective in sensemaking by offloading the data into the large space. Two display paradigms in AR and physical monitor was developed, representing the focus+context data around the tablet and a composite comparative view above the tablet. Using a within the subjects user study, I explored two research questions that compare the AR and physical monitor display paradigms. One research question: how does spreading the floorplan data around the display with the tablet at the center helps the user identify regions with similar properties in 2D floorplan better than the physical screen, and other how does the layered approach of projecting raw and high-level data above the display interface using tablet + HMD enhance data analysis of multivariate data better than physical screens for space syntax. Through the study, I found that the AR display provides a better understanding of the isovist properties for both ARD and ABD by displaying both focus+context regions in ARD and representing a composite view of isovist attributes with isovist without hindering the visibility in ABD. However, due to familiarity, participants faced some challenges due to the device's weight and expressed bias towards the tablet. Much work is required towards the hybrid systems and space syntax domain to mitigate transfer error and learning effect and identify which tablet placement works better.

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Appendices

Appendix A

Letter of Approval

DALHOUSIE UNIVERSITY
Research Services

Social Sciences & Humanities Research Ethics Board
Letter of Approval

July 22, 2021

Ramanpreet Kaur
Computer Science\Computer Science

Dear Ramanpreet,

REB #: 2021-5754
Project Title: Above and Around the tablet Information Visualizations in AR for BCI and Space Syntax

Effective Date: July 22, 2021
Expiry Date: July 22, 2022

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Effective March 16, 2020: Notwithstanding this approval, any research conducted during the COVID-19 public health emergency must comply with federal and provincial public health advice as well as directives from Dalhousie University (and/or other facilities or jurisdictions where the research will occur) regarding preventing the spread of COVID-19.

Sincerely,

Dr. Karen Foster, Chair

FUNDED
MITACS - No Award Number Given

Appendix B

Consent Form

Project title: Above and Around the tablet Information Visualizations in AR for BCI and Space Syntax.

Lead researchers: Ramanpreet Kaur, Faculty of Computer Science Hariprashanth Deivasigamani, Faculty of Computer Science Other researchers Hubert (Sathaporn) Hu, Faculty of Computer Science Dr. Derek Reilly, Faculty of Computer Science

Funding provided by: MITACS / Ericsson

Introduction

I invite you to take part in a research study conducted by Hariprashanth Deivasigamani and Ramanpreet Kaur, who are students at Dalhousie University. Your participation is voluntary and you may withdraw from the study at any time. Your academic (or employment) performance evaluation will not be affected by whether you participate. The study is described below.

The purpose of this study is to evaluate two types of tablet display enhancements made possible using an augmented reality (AR) headset—around the display, where contextual information is presented around a tablet's screen, and above the display, where layers of related data float above a tablet's screen. You will use these techniques to explore floorplan analysis(space syntax) data and brain-computer interface (BCI) data. Participants with Architectural, Neuroscience, Psychology and computer science preferred. No prior experience with augmented reality, BCI, or floorplan analysis is required to participate. Your participation will help us to better understand how to combine AR and tablet displays for data analysis.

If you decide to participate in this research, you will be asked to visit the visual and graphics Lab (Mona Campbell building, 4th floor) for two sessions. Each session will take 60-90 minutes. Sessions will begin with an overview of the study, this will include addressing any questions you may have. You will then be asked to perform a set of pre-defined tasks with BCI and floorplan datasets using two different interfaces, and to answer a brief questionnaire after each set of tasks. After all tasks are done, you will complete another brief questionnaire and answer a few interview questions.

There are no direct benefits for participating, but we might learn new things about interface design that may benefit others. There are no risks for participating in this research beyond feeling a bit of discomfort wearing the augmented reality headset. Unlike virtual reality headsets, augmented reality headsets are not known to trigger feelings of nausea. Participants will receive an honorarium of 30 dollars as a token of appreciation. Participation in this research will be known only to the members of the research team. The identity of each participant will be kept confidential: no video or audio will be used in publication or stored in public data repositories, and any quotes used in publication will be identified only by participant ID. The informed consent form and all identifying research data (audio, video) will be kept in a secure location under confidentiality in accordance with University policy for three years post publication and then destroyed. Non-identifying data (task times, software logs, and questionnaire data) will be stored in a public data repository to support the integrity of our research findings. In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance at (902) 494-3423, or email: ethics@dal.ca.

Signature Page

Project Title: Above and Around the tablet Information Visualizations in AR for BCI and Space Syntax.

Lead Researcher: Hariprashanth Deivasigamani ,Faculty of Computer Science, hr533370@dal.ca

Ramanpreet Kaur, Faculty of Computer Science, rm216536@dal.ca

I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I understand that a video recording of my interactions with the interface is necessary to participate in the study, but that this video will only be viewed by the researchers. I understand direct quotes of things I say may be used without identifying me. I agree to take part in this study. My participation is voluntary and I understand that I am free to withdraw from the study at any time.

Name ______________________ Signature ______________________ Date ____________

Please provide an email address below if you would like to be sent a summary of the study results.

Email address: ____________________

Note: The signature of a researcher or a witness is not required. Getting participants to sign two copies is not required, and in fact may compromise privacy if the participant copy is not stored securely.

Appendix C

Task Lists

Sets of Tasks to be performed by the participants.

Training Tasks: Around Display, Space Syntax AR

Remember to "think aloud" as you complete each task.

1. Notice that the legend presentation in the bottom of the screen below the floorplan in the tablet.
2. What range of values are presented for Connectivity and how is it represented?
3. Select the highlighted point with white color in the floorplan and touch two fingers on the tablet screen, and move them apart to zoom in.
4. Select any point in the tablet. Look in the panel to identify X and Y coordinates and Value for the point.
5. Do you see other points with similar range i.e. Low/High connectivity highlighted in the AR.
6. Use two fingers on the tablet and swipe right to pan the map to its left edge.
7. Click on "No Filter" to remove the selection filter of range of values.
8. Click on Reset button to remove the zoom of the floorplan.

Training Tasks: Around Display, Space Syntax Physical monitor

Remember to "think aloud" as you complete each task.

1. Notice that the legend presentation in the bottom of the screen below the floorplan in the tablet.
2. What range of values are presented for Connectivity and how is it represented?
3. Select any location on the tablet. Do you see other points with similar value i.e. Low/High connectivity highlighted in the AR.

5\. Look in the panel to identify X and Y coordinates and Value for the point.

5\. Touch two fingers on the touch screen, and move them apart to zoom into above floorplan together to zoom out.

6\. Use two fingers on the tablet and swipe right to pan the map to its left edge.

7\. Click on "No Filter" to remove the selection filter of range of values.

8\. Click on Reset button to remove the zoom of the floorplan.

Task Set 1 Around the Display for Space Syntax:

1. Select the highlighted point with white color in the floorplan and touch two fingers on the tablet screen, and move them apart to zoom in.
2. Click on a point with "Medium" values, in the bottom left of the floorplan A.
   - How many points have similar zone in the floorplan A. Is it 0-20, 20-40, 40-60 or more than 60?
   - How many points have similar zone in the floorplan B. Is it 0-20, 20-40, 40-60 or more than 60? Also point out the regions where the points are.
   - What is the zone for the point in the immediate right and left of the selected point, whether it is Medium, Low, etc.
   - What are the X and Y coordinates for the points in the immediate right and left of the selected point.
3. Select a different point in the floorplan which has zone- Low , in the bottom center of the floorplan A.
   - How many points have similar range in the floorplan A. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
   - How many points have similar range in the floorplan B. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
   - What is the zone for the point in the immediate right and left of the selected point, whether it is Medium, Low, etc.
   - What are the X and Y coordinates for the point in the immediate right and left of the selected point.

No Guidance
In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

4. Find the point "X:290 Y:390 in the floorplan A and click on that point in the floorplan. What is zone for that point and connectivity value for that point.
5. Given a scenario where you want to place an object in a highly connected place which is right next to a low connected place, what are the two places tell by pointing out in the floorplan B and mentioning the X and Y coordinates for the floorplan A where you can keep it and also tell what is the value at that point.

Guided Tasks
In all the next tasks the participant will be guided to perform the tasks by the researcher.

6. Change the value of the spatial attribute by clicking on the second dropdown. Click on "Isovist Perimeter" from the second dropdown.
   - Select the highlighted point with white color in the floorplan and double tap to zoom.
7. Click on any point with "Medium" values in the floorplan A, in the bottom center of the floorplan A.
   - How many points have similar range in the floorplan A. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.

- How many points have similar range in the floorplan B. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
- What is the zone for the point in the immediate right and left of the selected point, whether it is Medium, Low, etc.
- What are the X and Y coordinates for the point in the immediate right and left of the selected point?

8. Select a different point in the floorplan which has zone- Low , in the bottom center of the floorplan A.
    - How many points have similar range in the floorplan A. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - How many points have similar range in the floorplan B. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are. Tell the researcher zone whether it is Medium, Low, etc. for the point in the immediate right and left of the selected point.
    - What is the zone for the point in the immediate right and left of the selected point, whether it is Medium, Low, etc.
    - What are the X and Y coordinates for the point in the immediate right and left of the selected point?

No Guidance
In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

9. Find the point “X:290 Y:390 in the floorplan A and click on that point in the floorplan. . What is zone for that point and Isovist Perimeter value for that point.
10. Given a scenario where you want to place an object in a high Isovist Perimeter place which is right next to a low Isovist Perimeter place the low Isovist Perimeter place should be at right, what are the two places tell by pointing out in the floorplan B and mentioning the X and Y coordinates for the floorplan A where you can keep it.
11. Is there any relationship between the low values for Isovist Perimeter and connectivity?

Task Set 2 for Around the Display:

Guided Tasks

In all the next tasks the participant will be guided to perform the tasks by the researcher.

1. Select the highlighted point with white color in the floorplan and touch two fingers on the tablet screen, and move them apart to zoom in.
2. Click on a point with “High” values, in the bottom left of the floorplan A.
    - How many points have similar range in the floorplan A.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - How many points have similar range in the floorplan B.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.
    - What is the zone whether it is Medium, Low, etc. for the point in the immediate right and left of the selected point?
    - What are the X and Y coordinates for the point in the immediate right and left of the selected point?

3. Click on a point with “Medium” values, in the bottom center of the floorplan A.
    - How many points have similar range in the floorplan A. Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - How many points have similar range in the floorplan B. Is it 0-20, 20-40, 40-60 or more than 60? Also point out two regions where the points are.
    - Tell the researcher zone whether it is Medium, Low, etc. for the point in the immediate right and left of the selected point.
    - Tell the X and Y coordinates for the point in the immediate right and left of the selected point from the panel.

No Guidance

In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

4. Find the point “X:160 Y:400 in the floorplan A and click on that point in the floorplan What is the zone for that point and connectivity value.
5. Given a scenario where you want to place an object in a medium connected place which is right next to a low connected place, tell researcher about two places by pointing out in the floorplan B and mentioning the X and Y coordinates for the floorplan A where you can keep it and also tell what the value at that point is.

Guided Tasks

In all the next tasks the participant will be guided to perform the tasks by the researcher.

6. Click on the second dropdown and select “Isovist Perimeter”.
7. Click on the highlighted point with white color in the floorplan and touch two fingers on the tablet screen, and move them apart to zoom in.
    - Click on a point with “High” values in the floorplan A in the bottom left region.
    - How many points have similar range in the floorplan A.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - How many points have similar range in the floorplan B.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - What is the zone whether it is Medium, Low, etc. for the point in the immediate right and left of the selected point?
    - What are the X and Y coordinates for the point in the immediate right and left of the selected point?
8. Click on a point which has zone- Medium in the bottom center region of floorplan A.
    - How many points have similar range in the floorplan A.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - How many points have similar range in the floorplan B.? Is it 0-20, 20-40, 40-60 or more than 60? Also point out any two regions where the points are.
    - What is the zone whether it is Medium, Low, etc. for the point in the immediate right and left of the selected point?
    - What are the X and Y coordinates for the point in the immediate right and left of the selected point.

No Guidance

In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

9. Find the point “X:340 Y:340 in the floorplan and click on that point in the floorplan. Tell researcher about the zone for that point.
10. Given a scenario where you want to place an object in a low Isovist Perimeter place which is right next to a high Isovist Perimeter place, tell researcher about two places by pointing out in the below floorplan and mentioning the X and Y coordinates for the selected above floorplan where you can keep it and also tell what the value at that point is.
11. Is there any relationship between the high values for Isovist Perimeter and connectivity.

Training Tasks: Above Display, Space Syntax AR

Remember to "think aloud" as you complete each task. I will keep on prompting if the participant forgets this.

1. Notice that different types of data are presented in separate layers. How many layers do you see including the tablet layer, and what data is presented on each layer?
2. Notice that the legend presentation below the button "Reset Layer 1" and "Reset Layer 2".
3. What is the range of values "Very High" to "Very Low" presented for Openness and how is it represented through the colors?
4. What is the range of values "Very High" to "Very Low" presented for Visual Complexity and how is it represented through the colors?
5. Click on colored button between the text High and number 5 from Layer 1 and Layer 2 gradients. This will highlight the other points with similar range i.e., High-5 openness and visual complexity in the tablet.
6. Toggle OFF the visual complexity layer by clicking on the "OFF" button for Layer 2.
7. Click on any point in the floorplan to see the Isovist. Panel in the right shows the X, Y coordinates and openness and visual complexity values for that given point.
8. Reset the Layer 1 by clicking on Reset Layer 1 in the openness layer.
9. Stand and look from the top to observe the layers and see the overlapping region and point out the overlapping regions for both very high visual complexity and openness.

Training Tasks: Above Display, Space Syntax Physical Monitor

Remember to "think aloud" as you complete each task.

1. Notice that different types of data presented on floorplan by looking above the button Reset Layer 1 and Reset Layer 2. How many layers do you see, and what data is presented on each layer?
2. Notice that the legend presentation below the button "Reset Layer 1" and "Reset Layer 2".
3. What is the range of values "Very High" to "Very Low" presented for Openness and how is it represented through the colors?
4. What is the range of values "Very High" to "Very Low" presented for Visual Complexity and how is it represented through the colors?
5. Click on colored button between the text High and number 5 from Layer 1 and Layer 2 gradients. This will highlight the other points with similar range i.e., High-5 openness and visual complexity in the tablet.
6. Toggle OFF the openness layer by clicking on the "OFF" button right next to Reset Layer 1 for Layer 1.
7. Click on any point in the floorplan to see the Isovist. Panel in the right shows the X, Y coordinates and openness and visual complexity values for that given point.
8. Reset the Layer 1 by clicking on Reset Layer 1 in the openness layer.

Task Set 1 Above the Display Tasks for Space Syntax:

Note: for the Above Display Condition, we will follow this protocol: Task group 1 will be done while seated, group 2 will be done while seated and looking at the layers from an angle in which layers are non-overlapping, group 3 will be done while standing and looking down at the layers, and group 4 will be done using the participant's own preferred set of approaches.

I will guide you in the tasks below by mentioning where and what to click. There will be as set of tasks where I will not guide you and you will be free to do what and how you want to do. For AR below tasks might require standing position.

Group 1:

1. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on the "Very High" for Layer 1.
   - Point out one region with "Very High" value in the top central middle region
2. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on "High" with number 5 for Layer 1.
   - Point out one region with high value in the bottom center region of the floorplan.
3. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1. Click on "High" with number 5 in layer 2 .
   - Point out one region with high value in the bottom center region of the floorplan in the tablet.
4. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1.
   - Click on "Medium" with number 4 in layer 2 for Visual complexity.
   - Point out one region with value Medium-4 in the bottom region second space from the right of the floorplan in the tablet.

Group 3:

1. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on the "Very High" for Layer 1.
   - Click on any point with "Very High" value in the top central middle region
   - What is the corresponding numerical value for Openness and X and Y coordinates from the panel.
   - Describe the size of the Isovist with respect to floorplan, Is it big, small or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count and tell me how many rooms can be seen from this point.
2. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on "High" with number 5 for Layer 1.
   - Click on any point with high value in the bottom center region of the floorplan.
   - What is the corresponding numerical value for Openness and X and Y coordinates from the panel.
   - Describe the size of the Isovist for clicked point.Is it big, small or medium with respect to the floorplan.

- Describe the shape of the Isovist whether it is compact or spiky.
- Count how many rooms can be seen from this point.

3. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1. Click on "High" with number 5 in layer 2 .
   - Click on any point with high value in the bottom center region of the floorplan in the tablet.
   - What is the corresponding numerical value for visual complexity and X and Y coordinates from the panel.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.
4. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1.
   - Click on "Medium" with number 4 in layer 2 for Visual complexity.
   - Click on any point with value Medium-4 in the bottom region second space from the right of the floorplan in the tablet.
   - What is the corresponding numerical value for visual complexity and X and Y coordinates from the panel.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.

5. Reset the Layer1 and Layer2 and click on "Medium-3" gradient for both layers.
   - Circle out an overlapping region in the air. (For the Tablet +AR display ask the participants to stand and see to identify the overlapping regions)
   - Click on any overlapping point such that both the openness and visual complexity is "Medium-3". Tell me the X and Y coordinate for the selected point.
   - Tell me the openness and visual complexity values at the given point from the panel.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan?
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.
6. Click on the color gradient representing Very Low-0 for Layer 1 and "Very Low-0 " Layer 2.
   - Circle out an overlapping region in the air. (For the Tablet +AR display ask the participants to stand and see to identify the overlapping regions)
   - Click on any overlapping point such that both the openness and visual complexity is "Very Low -0". Tell me the X and Y coordinate for the selected point.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.
7. Reset both the Layer 1 and Layer by clicking on Reset Layer 1 and Reset Layer 2.
   - Select any point in the top left room of the floorplan in the Isovist Layer.
   - Identify the color gradient for both layers of that clicked point and click on the color from the legend to select the points with similar property distributed throughout the floorplan.

- o Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan.
- o Describe the shape of the Isovist whether it is compact or spiky.
- o Count how many rooms can be seen from this point.
- o Tell researcher numerical value for openness and visual complexity. Also tell researcher X and Y coordinate.

8. Reset both the Layer 1 and Layer by clicking on Reset Layer 1 and Reset Layer 2.
   - o Select any point in the top right room of the floorplan in the Isovist Layer.
   - o Identify the color gradient of that clicked point for both layers and click on the color from the legend to select the points with similar property distributed throughout the floorplan.
   - o Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan.
   - o Describe the shape of the Isovist whether it is compact or spiky.
   - o Count how many rooms can be seen from this point.
   - o Tell researcher numerical value for openness and visual complexity. Also tell researcher X and Y coordinate.
   - o Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.

Group 4:

In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

9. Click on Start Task C button and touch and move in the Isovist Layer starting from top left corners following the yellow path and tell how the Isovist shape and size changes throughout the floorplan.
   - o Describe the shape and size of the Isovist in the corners as you move through the path . Tell how the Isovist values for Openness and Visual complexity are changing as you move from top left starting to the bottom end of the path.
10. Click on Start Task A
    - o Identify a point in the floorplan from where all the rooms with yellow points in it can be seen. The identified point should point to a place with high-5/high-6 openness and high-5/high-6 visual complexity.
11. Click on Start Task B
    - o Identify a point in the floorplan from where the room or space with yellow point in it cannot be seen. The identified point should point to a high-5/high-6 openness and high-5/high-6 visual complexity.
12. Consider a scenario where a person wants to place two objects- object A and object B where visual complexity is very high-7 and openness is very high-7 and the Isovist is big.
    - o What are the X and Y coordinates for object A and object B.
13. Consider a scenario where a person wants to place two objects- object A and object B where visual complexity is very high-7 and openness is very high-7 and the Isovist is big.
    - o What are the X and Y coordinates for object A and object B.

Task Set 2 for Above the Display:

Group 1:

1. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on the "High" with number 6 color from the gradient for Layer 1.
   - Point out one region with "High" value in the top central middle region
2. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 2. Click on "Medium -4" with number 1" color from the gradient for Layer 1
   - Point out one region with high value in the bottom center region of the floorplan.
3. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1. Click on "Very High" with number 7 in layer 2 for Visual complexity color from the gradient for Layer 2.
   - Point out one region with high value in the bottom center region of the floorplan in the tablet.
4. Reset the Layer1 and Layer2.
   - Toggle "OFF" the Layer 1. Click on "Medium" with number-3 in layer 2 for Visual complexity.
   - Point out one region with value Medium-4 in the bottom region second space from the right of the floorplan in the tablet.

Group 3:

1. Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.
   - Toggle "OFF" the Layer 2. Click on the "High" with number 6 color from the gradient for Layer 1.
   - Select one of the "High-6" point in the Layer1 floorplan in the top central middle region .
   - Click on the floorplan in the tablet to see the Isovist at the selected point and tell me the corresponding numerical value for Openness and X and Y coordinates from the panel.
   - Describe the size of the Isovist with respect to floorplan, Is it big, small, or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count and tell me how many rooms can be seen from this point
2. Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.
   - Toggle "OFF" the Layer 2. Click on "Medium -4" with number 1" color from the gradient for Layer 1.
   - Click on any point with Low-1 value in the bottom central left region of the floorplan. Click on the floorplan in the tablet to see the Isovist at the selected point and tell me the corresponding numerical value for Openness and X and Y coordinates from the panel.
   - Describe the size of the Isovist with respect to floorplan, Is it big, small, or medium with respect to the floorplan.
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count and tell me how many rooms can be seen from this point
3. Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.

- Toggle "OFF" the Layer 1.
- Click on "Very High" with number 7 in layer 2 for Visual complexity color from the gradient for Layer 2.
- Click on any point with very high value in the top central middle region of the floorplan in the tablet. Tell the X and Y coordinate for the selected point and the visual complexity value from the panel.
- Describe the size of the Isovist for clicked point in the bottom center region of the floorplans. Is it big, small or medium with respect to the floorplan?
- Describe the shape of the Isovist whether it is compact or spiky.
- Count how many rooms can be seen from this point.

4. Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.
   - Toggle "OFF" the Layer 1.
   - Click on "Medium" with number-3 in layer 2 for Visual complexity.
   - Click on any point with value Medium-3 in the bottom central middle region of the floorplan in the tablet.
   - Tell the X and Y coordinate for the selected point and the visual complexity value from the panel.
   - Describe the size of the Isovist for clicked point in the bottom center region of the floorplans. Is it big, small or medium with respect to the floorplan?
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.

Stand to look the merged layers in the interface for the AR display.

5. Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2 and click on "Very High-7" gradient.
   - Observe the two layers and circle out an overlapping region in the air.(For the Tablet +AR display ask the participants to stand and see to identify the overlapping regions)
   - Click on any overlapping point such that both the openness and visual complexity is "Very High-7". Look at the values in the panel. Tell me the X and Y coordinate for the selected point.
   - Tell me the openness and visual complexity values at the given point from the panel.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan?
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.
6. Click on the color gradient representing Low-2 for Layer 1 and "Low-1" Layer 2.
   - Notice all the points that are highlighted. Observe the two layers and tell how the two values "openness" and "visual complexity" are distributed. (For the Tablet +AR display ask the participants to stand and see to identify the overlapping regions)
   - Circle out an overlapping region in the air.
   - Click on any overlapping point.
   - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan?
   - Describe the shape of the Isovist whether it is compact or spiky.
   - Count how many rooms can be seen from this point.
   - Tell researcher numerical value for openness and visual complexity. Also tell researcher X and Y coordinate.
7. Reset both the Layer 1 and Layer by clicking on Reset Layer 1 and Reset Layer 2.
   - Select any point in the bottom right room of the floorplan in the Isovist Layer.
   - Identify the color gradient of that clicked point and click on the color from the legend to select the points with similar property distributed throughout the floorplan.

- Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan?
- Describe the shape of the Isovist whether it is compact or spiky.
- Count how many rooms can be seen from this point.
- Tell researcher numerical value for openness and visual complexity. Also tell researcher X and Y coordinate.

8. Reset both the Layer 1 and Layer by clicking on Reset Layer 1 and Reset Layer 2.
    - Select any point in the bottom left room of the floorplan in the Isovist Layer.
    - Identify the color gradient of that clicked point and click on the color from the legend to select the points with similar property distributed throughout the floorplan.
    - Describe the size of the Isovist for clicked point. Is it big, small or medium with respect to the floorplan?
    - Describe the shape of the Isovist whether it is compact or spiky.
    - Count how many rooms can be seen from this point.
    - Tell researcher numerical value for openness and visual complexity. Also tell researcher X and Y coordinate.
    - Reset the Layer1 and Layer2 by clicking on Reset Layer 1 and Reset Layer 2.

Group 4:
In all the next tasks the participant can do the tasks as they want to do. The researcher will not tell the participant what to do.

9. Click on Start Task C button and touch and move in the Isovist Layer starting from top corners following the yellow path and tell how the Isovist shape and size changes throughout the floorplan.
    - Describe the shape and size of the Isovist in the corners as you move through the path . Tell me about how the Isovist values for Openness and Visual complexity are changing as you move from top left starting to the bottom end of the path.
10. Click on Start Task A
    - Identify a point in the floorplan from where all the rooms with yellow points in it cannot be seen. The identified point should point to a place with high-6 openness and high-6 visual complexity.
11. Click on Start Task B
    - Identify a point in the floorplan from where the room or space with yellow point in it can be seen. The identified point should point to a high-6 openness and high-6 visual complexity.
12. Consider a scenario where a person wants to place two objects- object A and object B where visual complexity is medium-4 and openness is medium-3.
    - Tell researcher the X and Y coordinates for object A and object B.
13. Consider a scenario where a person wants to place two objects- object A and object B where visual complexity is low-1/2 and openness is low-1/2.
    - Tell researcher the X and Y coordinates for object A and object B.

Appendix D

Questionnaires

Appendix D: Full Questionnaire

Questionnaire to decide whether participant is naïve or experienced using HoloLens shared over email.

Familiarity with the HoloLens

Study Questionnaire

1. I classify my level of knowledge in Augmented Reality/Virtual Reality/Mixed Realityas:

   Mark only one oval.

Extremely Familiar	Moderately Familiar	Somewhat Familiar	Slightly Familiar	Unfamiliar
○	○	○	○	○

2. I have experience with Virtual Reality games or other VR apps using a headset(Oculus, HTC Vive etc).

   Mark only one oval.

   ○ Yes
   ○ No

3. I have used some augmented reality applications before e.g Pokemon Go

   Mark only one oval.

   ○ Yes

No

4. Have you used Microsoft Hololens or another AR HMD before ?

Mark only one oval.

Yes

No

Questionnaire for Above the Display and Physical Monitors for Space Syntax:

Above and Around the Display AR data visualization of BCI and Space Syntax

Study Questionnaire

1. What is your gender:

   Mark only one oval.

Female	Male	Other
○	○	○

Other: ____________________

2. Gender: How do you identify yourself?

   Mark only one oval.

Man	Woman	Non-Binary	Prefer to Describe	Other
○	○	○	○	○

Prefer to describe yourself as below

Other: ______________________

3. Your level of education

Mark only one oval.

High School	Bachelors	Masters	PhD/PDF	Other
◯	◯	◯	◯	◯

◯ Other: ______________________

4. Your current designation

Mark only one oval.

Student	Professor	Other
◯	◯	◯

◯ Other: ______________________

Above the Display AR data visualization of Space Syntax

For all statements below mark the circle that most closely matches your level of agreement/disagreement. Mark only one circle for each statement.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

1. I could see the three layers-two floorplans in AR and one layer in tablet screen clearly in the augmented reality (AR) configuration.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

2. It was straightforward to interact with tablet and see the corresponding the changes in AR.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

3. It was straightforward to isolate one or more layers using the toggle buttons on the tablet to control what is shown in AR.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

4. It was easy to determine the peaks of the plotted data using the colors present in the layers.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

5. It was useful to view layers at an angle such that each layer did not overlap.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

6. It was useful to view multiple layers in an integrated way by looking at them from above.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

7. The layout and alignment of individual AR layers above the tablet was appropriate for performing the tasks

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

8. It was useful to change my position and orientation relative to the layers to achieve different perspectives.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

9. Completing the tasks helped me understand how openness and visual complexity values are distributed in the floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

10. Completing the tasks helped me understand how Isovist shape changes as the openness and visual complexity values change in the floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

11. I can imagine using this type of visualization setup to explore data in school, at work or home.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

12. I would recommend this type of visualization setup to my peers for data exploration.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

Above the display in Physical Monitor of Space Syntax

For all statements below mark the circle that most closely matches your level of agreement/disagreement. Mark only one circle for each statement.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

1. I could see the two floorplan layer and one Isovist Layer clearly on the tablet.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

2. I can isolate one or more layers using the toggle feature from the tablet and control what is shown in the tablet

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

3. I can isolate individual floorplans and determine the peaks of the plotted data using the colors and Isovist size and shape present in the layers.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

4. From the tablet, I can identify compare the values of openness and visual complexity and size/shape of the Isovist at a specific point.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

5. The space syntax features presented as multiple floorplans in the tablet are appropriate for performing the data analysis tasks in space syntax.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

6. Completing the tasks helped me understand how isovist size and shape contribute to the calculation of openness and visual complexity.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

7. I can imagine using this type of visualization setup to explore data in school, at work or home

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

8. I would recommend this type of visualization setup to my peers for data exploration

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

Around the Tablet Display in Augmented Reality of Space Syntax

For all statements below mark the circle that most closely matches your level of agreement/disagreement. Mark only one circle for each statement.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

1. I could see the entire floorplans in the augmented reality (AR) configuration.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

2. It was straightforward to interact with tablet and see the corresponding the changes in AR.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

3. It was straightforward to zoom and pan on the tablet to control what is shown in AR.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

4. It was easy to highlight the different zones of the plotted data present in the entire floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

5. The layout and alignment of AR layer around the tablet was appropriate for performing the tasks

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

6. It was helpful to see the zoomed in (focus) region along with the other region (context region) which is spread in the AR .

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

7. Completing the tasks helped me understand how the connectivity and Isovist perimeter values are distributed in the floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

Around the Display Physical Monitor of Space Syntax

For all statements below mark the circle that most closely matches your level of agreement/disagreement. Mark only one circle for each statement.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

1. I could see the entire floorplans on the tablet.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

2. It was straightforward to zoom and pan on the tablet to control what is shown.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

3. It was helpful to see the zoomed in (focus) region along with the other region (context region) which is spread in the AR .

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

4. It was easy to highlight and identify the different zones of the plotted data present in the entire floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

5. The layout and alignment of AR layer around the tablet was appropriate for performing the tasks

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

6. Completing the tasks helped me understand how the connectivity and Isovist perimeter values are distributed in the floorplan.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle

7. The data exploration between the layers was easy in above the tablet display in Augmented Reality for space syntax.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

Mark only one circle.

System Usability and TLX Questionnaire

System usability questionnaire

1. I think that I would like to use this system frequently.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

2. I found the system unnecessarily complex.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

3. I thought the system was easy to use.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

4. I think that I would need the support of a technical person to be able to use this system.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

5. I found the various functions in this system were well integrated.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

6. I thought there was too much inconsistency in this system.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

7. I would imagine that most people would learn to use this system very quickly.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

8. I found the system very cumbersome to use.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

Mark only one circle.

9. I felt very confident using the system.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

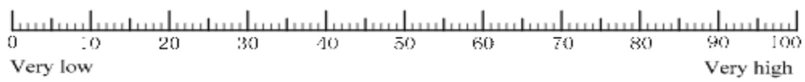
Mark only one circle.

10. I needed to learn a lot of things before I could get going with this system.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
◯	◯	◯	◯	◯

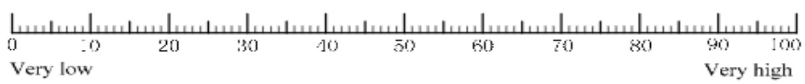
Mark only one circle.

TLX Questionnaire

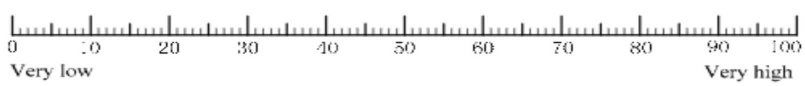


Scale used for the below questions.

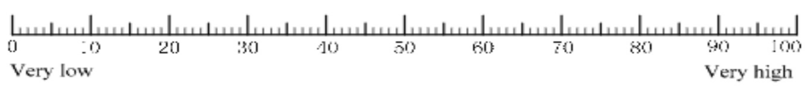
1. How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?



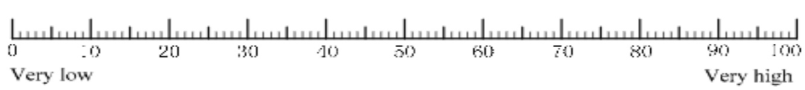
2. How much physical activity was required (e.g.. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?



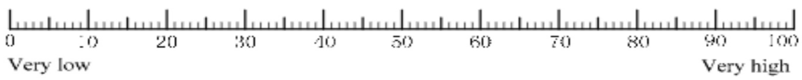
3. How much time pressure did you feel due to the rate or pace at which the tasks occurred? Was the pace slow and leisurely or rapid and frantic?



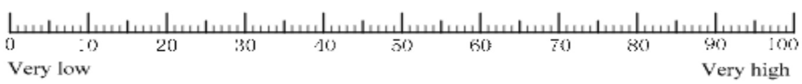
4. How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?



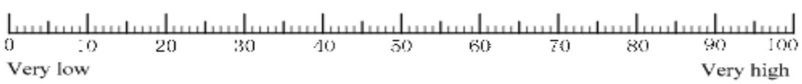
5. How hard did you have to work (mentally and physically) to accomplish your level of performance?



6. How hard did you have to work (mentally and physically) to accomplish your level of performance?



7. How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?



Appendix E: Semi Structure Interview

Debriefing and Interview

Our study involves evaluating interfaces with or without Augmented Reality by analyzing the various aspects of how the participants interact with the interfaces.
In this research through the data collected, we will analyze that how the information visualizations across different interfaces with or without AR for both BCI (Brain Computer Interface) and Space Syntax data visualization impact on data analysis from the user's perspective.
May I have your consent to record the audio for the interview?

1. How is your overall experience with the study?
2. Do you have any preference which domain works best for this setup – Space Syntax or BCI. Why?
2. Do you have any suggestions for improvement for both space syntax and BCI?
3. What were the interesting or engaging design aspects of this setup for both BCI and Space Syntax.
4. What did you learn about AR (Augmented Reality) today through our study?
5. What upgrades would you like to see in future is this setup?
6. Do you have any question for us?

Appendix F: Checklist

CheckLlist:

- ☐ Collect the consent forms from the participants.
- ☐ Brief the participants about the study "This research is conducted to evaluate the understanding of Brain Computer Interface and Space syntax across various interfaces with and without Augmented Reality. You will be performing few tasks wearing the HoloLens. We will record video and audio data for research purpose.
- ☐ Keep the HoloLens and Tablet always on charge if the participant has not arrived.
- ☐ The tablet should be on charged during the study as well.
- ☐ The HoloLens volume should be "0" and the brightness should be 80.
- ☐ As the participants fill the contact tracing form. Make sure the pens are sanitized.
- ☐ Make the participants watch video for Space syntax and BCI.
- ☐ Place the tasks list for the participants. Check the sheet to check which Group is assigned to the participant.
- ☐ Make sure these things are up and running.
  - o Video recording in the HoloLens.
  - o HoloLens application in the laptop to see what the participant is looking at.
  - o HoloLens are charged and backup HoloLens is also there.
  - o Ask the participants to think a loud.
- ☐ Make sure to collect the logs once the tasks are completed. Place the logs in the designated folder for each domain- Space Syntax and BCI.
  - o Physical Monitor Around the Display.
  - o AR Around the Display.
  - o Physical Monitor Above the Display.
  - o AR Above the Display.
- ☐ Collect logs from HoloLens and Tablet.
- ☐ Keep the questionnaires ready for the participants.

☐ Audio record the interviews.

Appendix E

Post Study Questionnaire

Above the Display comparison

In the following section are statements that asks you to compare the two display conditions you have just completed: *AR* (layers presented above the tablet display) and *tablet* (all layers presented on the tablet display). For each aspect listed below, mark the circle that most closely corresponds to your opinion.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

1. Visually distinguishing different layers(Openness, Visual Complexity and Isovist Layer).

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

2. Determining x and y complexity values at a given point for a single layer.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

3. Toggling layers on and off.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

4. Viewing multiple layers together.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

5. Observing changes when switching between openness and visual complexity data.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

6. Understanding that visual complexity and openness are derived from isovist size and shape.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

7. Keeping track of individual layers.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

8. Comparing two layers at a specific Isovist point.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better

◯	◯	◯	◯	◯

Mark only one oval.

9. Finding different zones in a layer.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

10. Completing tasks efficiently.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

11. Completing tasks accurately.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

Around the Display comparison

In the following section are statements that asks you to compare the two display conditions you have just completed: *AR* (layers presented above the tablet display) and *tablet* (all layers presented on the tablet display). For each aspect listed below, mark the circle that most closely corresponds to your opinion.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

1. Visualizing the entire floorplan data.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

2. Determining x and y values and space syntax attribute value at a given point.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

3. Zooming into the floorplan.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
○	○	○	○	○

Mark only one oval.

4. Panning in the floorplan.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

5. Identifying areas with similar zones in the entire floorplan.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

6. Keeping track of the entire floorplan data.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

7. Counting the number of spaces having similar zones for entire floorplan.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

8. Finding different zones in a layer.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

9. Completing tasks efficiently.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

10. Completing tasks accurately.

AR Clearly Better	AR Slightly Better	AR and Tablet are Equal	Tablet Slightly Better	Tablet Clearly Better
◯	◯	◯	◯	◯

Mark only one oval.

Appendix F

Interview Questions

May I have your consent to record the audio for the interview?

1. How is your overall experience with the study?
2. Do you have any suggestions for improvement?
3. What is experience with Layered visualization and around visualizations, they can engage in design aspects
4. What did you learn about AR (Augmented Reality) today through our study?
5. What upgrades would you like to see in future for ARTIV?
6. Do you have questions for us?

Appendix G

Checklist

Appendix E: Semi Structure Interview

Debriefing and Interview

Our study involves evaluating interfaces with or without Augmented Reality by analyzing the various aspects of how the participants interact with the interfaces.
In this research through the data collected, we will analyze that how the information visualizations across different interfaces with or without AR for both BCI (Brain Computer Interface) and Space Syntax data visualization impact on data analysis from the user's perspective.
May I have your consent to record the audio for the interview?

1. How is your overall experience with the study?
2. Do you have any preference which domain works best for this setup – Space Syntax or BCI. Why?
2. Do you have any suggestions for improvement for both space syntax and BCI?
3. What were the interesting or engaging design aspects of this setup for both BCI and Space Syntax.
4. What did you learn about AR (Augmented Reality) today through our study?
5. What upgrades would you like to see in future is this setup?
6. Do you have any question for us?

Appendix F: Checklist

CheckLlist:

- ☐ Collect the consent forms from the participants.
- ☐ Brief the participants about the study "This research is conducted to evaluate the understanding of Brain Computer Interface and Space syntax across various interfaces with and without Augmented Reality. You will be performing few tasks wearing the HoloLens. We will record video and audio data for research purpose.
- ☐ Keep the HoloLens and Tablet always on charge if the participant has not arrived.
- ☐ The tablet should be on charged during the study as well.
- ☐ The HoloLens volume should be "0" and the brightness should be 80.
- ☐ As the participants fill the contact tracing form. Make sure the pens are sanitized.
- ☐ Make the participants watch video for Space syntax and BCI.
- ☐ Place the tasks list for the participants. Check the sheet to check which Group is assigned to the participant.
- ☐ Make sure these things are up and running.
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    - o HoloLens application in the laptop to see what the participant is looking at.
    - o HoloLens are charged and backup HoloLens is also there.
    - o Ask the participants to think a loud.
- ☐ Make sure to collect the logs once the tasks are completed. Place the logs in the designated folder for each domain- Space Syntax and BCI.
    - o Physical Monitor Around the Display.
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- ☐ Collect logs from HoloLens and Tablet.
- ☐ Keep the questionnaires ready for the participants.

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