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ViSSTA: a Hybrid Tablet and Augmented Reality Interface for Space Syntax Data Analysis

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Abstract

A key challenge in the application of space syntax is the difficulty for researchers, practitioners, and especially non-experts face in understanding the meaning of various analytical metrics and their underlying relationships. This is particularly true for Visibility Graph Analysis (VGA), where the connection between abstract attributes like Connectivity, Openness, and Visual Complexity and the underlying isovist geometry can be difficult to intuit. Existing software tools, while powerful for analysis, often present these attributes in isolated, static visualizations, making it challenging to conduct comparative analysis or explore the correlations between multiple metrics simultaneously.

This paper presents ViSSTA (Visualizing Space Syntax with Tablet and AR), a research prototype developed to explore how novel, interactive visualization techniques can address these comprehension and communication challenges. We introduce two distinct methods for visualizing space syntax data using a hybrid system that combines a tablet for interaction with an Augmented Reality (AR) head-worn display for visualization. The first method, Above-Display (AbD) layering, presents multiple, translucent heatmaps of different VGA attributes in spatially registered layers above the floor plan. This allows users to view the data layers in an integrated, superimposed manner or examine them individually by shifting their physical viewpoint, while an interactive link on the tablet displays the raw isovist for any selected point. The second method, Around-Display (ArD) extension, uses the space around the tablet to extend the visualization of a single floor plan or to display a second floor plan for side-by-side comparison, facilitating large-scale pattern identification without constant panning and zooming.

We evaluated these visualization techniques in a controlled, within-subjects study (n=48) where participants without prior space syntax knowledge performed a range of analytical tasks. The tasks were designed to assess their ability to identify spatial properties, compare regions across plans, and understand the relationship between different VGA attributes and isovist shapes. The results show that while participants were often slower with the AR interfaces, both the AbD and ArD techniques led to modestly higher task accuracy compared to a conventional tablet-only interface. Specifically, the AR visualizations improved participants' ability to understand the relationships between spatial attributes and to identify regions with similar properties across floor plans. Participants also identified a range of ways that the AR modality helped their understanding. Still, participants preferred the tablet-only interfaces across several measures. These findings suggest that immersive and coordinated visualization approaches offer a promising direction for developing more effective tools for space syntax analysis, education, and stakeholder communication.

Keywords

Space Syntax, Information Visualization, Isovist Analysis, Augmented Reality, Hybrid Interface

1. Introduction

Space syntax (Reilly et al., 2020) is a set of methodologies used to analyze the spatial characteristics of buildings and urban areas. It has been applied most predominantly in architecture (Benedikt, 1979) and urban planning (Karlström & Mattsson, 2009; Wiener et al., 2007; Zhang et al., 2019), but increasingly in other areas, such as gaming (Choi et al., 2012) and locative interactive experiences (Bıyık & Sürer, 2020; Choi et al., 2012; Reilly et al., 2020; Singh, 2021; Singh et al., 2021). Space syntax has even helped detect crime patterns (Nubani & Wineman, 2005) through axial analysis, by correlating high levels of integration and connectivity with crime rate. A key challenge expressed by researchers and practitioners when applying space syntax analysis is understanding the meaning of space syntax attributes and their underlying mathematics and procedures (Amini Behbahani et al., 2017; Heitor & Serra, 2016; Lerman & Lebendiger, 2017; Reilly et al., 2020; Singh, 2021). It can also be very challenging to communicate relationships to non-experts (Amini Behbahani et al., 2017; Heitor & Serra, 2016; Lerman & Lebendiger 2017), and this can impact the adoption of space syntax analysis in both its traditional domains and new domains. The tools available for conducting space syntax analysis also require considerable expertise to operate (Heitor & Serra, 2016).

Space syntax analysis can be divided into three broad approaches: convex, axial, and visibility graph analysis. *Axial analysis* provides a graph-based spatial abstraction, obtained by drawing and connecting axial lines (lines of traversal) throughout a floor plan or urban region (Amini Behbahani et al., 2017). Because it is a graph, an axial representation supports common graph-based analytic approaches for properties such as centrality. *Agent-based analysis* generates predictive patterns of flow and gathering, leading to visit frequency estimators like gate count. These forms of space syntax analysis are readily presented to and understood by a wide range of non-expert stakeholders. Visibility graph analysis (VGA), by contrast, can be difficult to understand, especially as we move to 2nd and 3rd order relationships among isovist sets. Tools that assist in understanding the relationships between spatial attributes derived from isovists can yield not only a better understanding of what isovist-based analyses (including VGA) provide, but also how the various attributes overlap and are related to one another. In fact, the deep interconnectedness between and similarity of many isovist properties contribute to the difficulty in understanding them, in correctly interpreting them, and in choosing a parsimonious subset of these properties in analysis.

Information visualizations can help identify relationships, trends, and patterns in data (Siricharoen, 2013) that may be otherwise hard to find. Users can also interact with visualizations, such as by applying filters, or zooming/panning the visualization (Reipschlägeret al., 2021). Coordinating multiple views on complex datasets can help to reveal relationships between data attributes, and support for multiple views is something asked for by expert and novice users of space syntax tools (Reilly et al., 2020; Singh, 2021). Systems that use the space around conventional displays to display data date back to the early nineties (Van Krevelen & Poelman, 2010). Projecting data in augmented reality (AR) has been proven effective for sensemaking by extending data representations into the larger space around a display (Langner et al., 2021; Mahmood et al., 2018). Using AR to extend displays also eliminates the requirement of using multiple or very large physical monitors to display data visualizations, which occupy more space in a room and are not portable (Pavanatto et al., 2021). The combination of conventional displays and AR has also been shown to increase task performance (Grubert et al., 2015). While there has been a considerable amount of recent work exploring the potential of immersive visualization (Hubenschmid et al., 2018; Langner et al., 2018, Langner et al., 2021; Mahmood et al., 2018; Normand & McGuffin, 2018; Pavanatto et al., 2021) including a small amount involving space syntax data (Reilly et al., 2020; Singh et al., 2021), we still do not understand the benefits and drawbacks of specific immersive visualization approaches for visual representations of space syntax attributes.

This paper presents ViSSTA (Visualizing Space Syntax with Tablet and AR), a research prototype that explores how hybrid AR+tablet visualizations might address these comprehension and communication challenges. In a controlled within-subjects experiment with 48 participants, we ask the following research questions:

1. Does using AR to spread floor plan data beyond the boundaries of a tablet display help the user identify regions with similar properties more effectively than using swipe and zoom on the tablet?
2. Can layering data in AR above a tablet display enhance the analysis of multivariate space syntax data better than a tablet display alone?

The ViSSTA interface displays a region of a large floor plan on the tablet and the rest of the floor plan around the tablet; we call this the around-display extension technique (ArD). Participants used ArD to identify regions with similar space syntax attributes across two floor plans and explore how Isovist Connectivity and Isovist Perimeter correlate, addressing question one. The ViSSTA interface also displays space syntax attribute visualizations as layers above the tablet, while the tablet screen displays the floor plan and permits the generation of raw isovist data by touching a location on the floor plan; we call this the above-display layer technique (AbD). Participants used AbD to understand how the two spatial attribute data layers (Openness and Visual Complexity) are related to each other and the raw isovist data, addressing research question two. We compared the ArD and AbD ViSSTA interface features against baseline visualization interfaces on the tablet. Participants used traditional zoom and pan to view the larger floor plan and used the touch interface to select which layers were visible.

ViSSTA is positioned primarily as a learning and communication tool, rather than as a substitute for analytical software such as DepthMapX. Its development was guided by the needs of three primary audiences : (1) students and novice to space syntax who need to build intuition about how isovist based attributes such as Connectivity, Openness, and Visual Complexity relate to the underlying geometry; (2) practitioners (architects, urban designers, interaction designers working with spatial AR/VR content) who need to communicate the implications of analytical results to non-expert stakeholders such as clients, planners, or community members; and (3) researchers exploring how immersive, coordinated visualizations affect comprehension of multivariate spatial data. The current prototype focuses on the first two audiences; support for expert analysts is identified as future work in Section 7.2.

2. Related Work

2.1. Space Syntax Tools and Their Ease of Use

Existing digital tools for space syntax analysis, including DepthMapX (The Bartlett School of Architecture, 2025) and modules for QGIS (The QGIS Project, 2025) and Grasshopper (Davidson, 2025) are not designed with novices in mind and have a practical rather than pedagogical intent. Furthermore, VGA analysis can be resource-intensive (Raford, 2009), so a tool that provides a preliminary understanding to set values for grid size and other global metrics would be helpful. Because space syntax analysis generates many visual representations over a single floor plan or region, it is difficult to employ traditional single-display visualization approaches, especially to show relationships between space syntax attributes and to show how space syntax attributes are derived from low-level spatial data.

Other related work has explored how interactive design tools can make spatial analysis and evidence-based design more accessible to non-expert users. For example, Drawscapes (Carranza & Karimi, 2022) enables participants to create simple diagrammatic sketches of urban layouts through a web-based interface while receiving feedback on aspects of their proposals, demonstrating how alternative interaction paradigms can broaden engagement with spatial reasoning.

Attempts to incorporate space syntax analyses into domain-specific tools further motivates the need for tools that facilitate comprehension. For example, Story CreatAR (Singh et al., 2021) is a tool created for authors of immersive augmented reality narratives that uses isovist, convex, and agent-based analysis to place narrative elements and control character behaviour. During sessions with authors who used the tool (Singh et al., 2022), it was difficult for the authors to use the spatial rules, in line with findings in other applied domains (Lerman & Lebendiger, 2017). The authors often misinterpreted terminology, and similar comprehension issues are raised by Behbahani et al. (2017).

2.2. Information Visualization in AR

Information Visualization in AR often builds directly on techniques and insights from traditional displays. Overview, filtering, zoom, details on demand, extract, and relate are high-level interaction goals (Baur et al., 2012) facilitated by interactions like zooming, panning, filtering, selection, marking, and brushing (Ferreira de Oliveira & Levkowitz, 2003). Data presentations can be placed into four broad categories: overview+detail, zooming, focus+context, and cueing (Cockburn et al., 2009; Hubenschmid et al., 2018). In this research, we have used the focus+context technique to project data in ArD by keeping both the focus and context regions in place and projecting both regions- the focus region in the tablet space and the context region in the AR space. We have also used cueing to highlight the data of interest, for both the AbD and ArD interfaces. The selected data among the layers in the AbD interface is highlighted, and non-selected data among the layers is removed. In the ArD interface, the data of interest is highlighted, while the non-selected data remains as it is.

Combining AR views with tablets, smartwatches, mobile phones, and larger displays has been explored in many domains (Baur et al., 2012; Grubert et al., 2015; Langner et al., 2021; Normand & McGuffin, 2018). These hybrid interfaces permit combinations of 2D and 3D information visualizations (Irshad et al., 2020). Augmented Reality with Tablets (ARts) by Hubenschmid et al. (2018) displayed 3D scatterplots on the tablet surface and allow the users to link individual scatterplots as per the proximity of the tablets. Langner et al. (2021) arranged 2D and 3D visualizations above, around, and between the tablet surfaces. Langner et al. (2021) and Hubenschmid et al. (2018) explored how visualizations can be distributed across interfaces and correctly aligned. Numerous research projects (e.g., Dedual et al., 2011; Grubert et al., 2015; Hubenschmid et al., 2021; Normand & McGuffin, 2018; Reipschläger & Dachselt, 2019; Wu et al, 2020) have explored which interactions work best for hybrid interfaces. Expert feedback on the research prototypes by Langner et al. (2021) helped guide design decisions, such as ensuring readability of details in AR and supporting interaction on the tablet.

3. Design and Implementation of ViSSTA

Our prototyping process consisted of three stages. In the brainstorming stage, four researchers shared relevant research, discussed design ideas, considered interaction techniques, identified potential challenges and requirements for good visualizations in AR, and provided hardware and software considerations. All researchers were familiar with VGA and related tools through prior and concurrent projects. In an affinity diagramming session, the researchers reviewed and classified the ideas into themes: visual representation and layout, software and hardware, algorithms, multimodal interactions, and embodied interactions. The next stage involved iterative sketching and prototyping. This allowed the team to build a detailed understanding of visual layout and interactivity, and identify more explicit hardware and software requirements. In the final stage, a working prototype was iteratively built and refined in Unity 3D (n.d.), allowing us to validate our choices of data source, visual presentation, software libraries, and systems architecture.

3.1. Design Elements

This section lists key design and implementation decisions for ViSSTA resulting from the design process.

2D visualizations using D3.js. While 3D space syntax analysis is a topic of current research and development (Dep, 2020), space syntax traditionally treats a physical environment as a 2D plane, and resulting data visualizations are presented in 2D. We therefore chose to use D3.js (Bostock et al., 2011) with Node.js. This common toolset used by researchers such as Langner et al. (2021), Mahmood et al. (2018), and Ritsos et al. (2017) to support rapid development of custom 2D visualizations and interaction techniques such as filtering, panning, and zooming.

AbD: Data Layers. We present the results of individual space syntax analyses as distinct 2D layers in augmented reality above the tablet display, which presents the floor plan. This permits viewing multiple analyses in an integrated way by looking at the tablet head-on, and looking at individual layers by viewing from an oblique angle.

ArD: Maintaining Context. For large or zoomed-in floor plans, AR is used to extend the tablet display, such that entire floor plans are always visible. This also allows for two different floor plans to be shown side-by-side for comparison, without requiring both to be visible on the tablet.

Touch Interaction. Prior literature suggests that touch interactions are preferred over in-air interactions due to the learning curve (Normand & McGuffin, 2018; Wu et al., 2020), and issues with fatigue and accuracy (Hubenschmid et al., 2021; Normand & McGuffin, 2018; Reipschläger & Dachselt, 2019). In ViSSTA, all interactions occur on the tablet's touchscreen display while content is presented on the tablet and in AR.

Anchoring QR Codes. We chose the common and cost-efficient technique of detecting devices in the environment through markers (Bussink et al., 2022; Johnson et al., 2022). ViSSTA detects a quick response (QR) 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 QR code's location.

Colour Scales. We considered using a rainbow colour gradient similar to that used in DepthMapX (Jkwchui, 2011). 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 (Borland & Taylor, 2007; Stoelzle & Stein, 2021), and our hardware device (Microsoft HoloLens 2) was known to have issues with colour stability, particularly when viewing content near the display edge (Lang, 2020). A different single-hue colour scale was used to represent data for each AbD layer, and a two-colour scale was used to represent data for ArD. Scale values were carefully selected as the HoloLens' additive display causes lighter shades to be more opaque than very dark shades (Livingston et al., 2009). Colours used on the tablet display 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 (Kruijff et al., 2010; Livingston et al., 2009).

4. Implementation

4.1. Data Preparation

We used a floor plan of Mona Campbell Building at Dalhousie University, and a floor plan of a generic maze (Jkwchui, 2011). Inkscape (Inkscape Project, 2025) was used to produce vectorized versions, saved in dxf format. These files were then imported into DepthMapX. In DepthMapX, visibility graph analysis requires selecting a grid size, or level of resolution. In our study, we consider the AbD and ArD features separately. We wanted higher resolution for AbD to allow small differences in visualization layers to be visible, and chose a grid size of one. For ArD, we needed analysis over a large floor plan region and wanted panning interactions to be smooth, so we used a grid size of 10. Multiple iterations were run in DepthMapX to ensure that there was no marked loss of information due to increasing the grid size. DepthMapX's command line interface was used to perform visibility graph analysis, which generates a CSV file comprised of x and y coordinates and the values of the spatial attributes corresponding to that location. The visibility graph analyses were performed offline as part of the preprocessing workflow which is not dynamically integrated within ViSSTA yet. Accordingly, users interacted with pre-generated analysis outputs, and modifications to floor plans would require rerunning the external preparation pipeline.

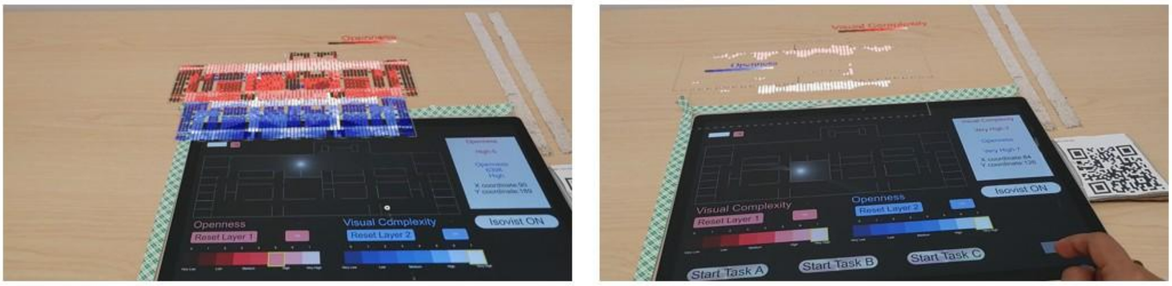
4.2. Above Display (AbD) Implementation

For AbD, three layers of data were presented: two in AR, and one on the tablet. The AR layers plot spatial attributes selected by the user through the tablet interface, including Isovist Area, Isovist Perimeter, and Visual Integration [HH], while the floor plan itself is presented on the tablet.

AR Layers plotted data on a transparent canvas and data glyphs were themselves translucent, such that viewing the AR layers from above gives an integrated view of both layers over their corresponding locations on the floor plan, while viewing from an angle allows the user to see individual layer values. The distance between each layer was determined in pilot testing such that the user could comfortably see the individual layers while seated with the tablet lying face up on a table in front of them.

Red and blue colour gradients were used for the AR layer plots, light colours representing high values and dark colours low values of a given spatial attribute. Toggling the layers ON and OFF and filtering within a layer was accomplished through touch controls on the tablet. Tapping on a point on the floor plan selected it, which generated a 360-degree isovist at that point on the tablet display. A side panel displayed the X and Y coordinates of the selected point and the corresponding numeric values of the spatial attributes plotted on the AR layers.

X and Y coordinates were plotted in the scatterplots and coloured as per the sorted bins using D3.js, and projected in AR using Canvas Webview (Vuplex, n.d.) in Unity. Layer synchronization was achieved using WebSockets (NodeJS Express edition).



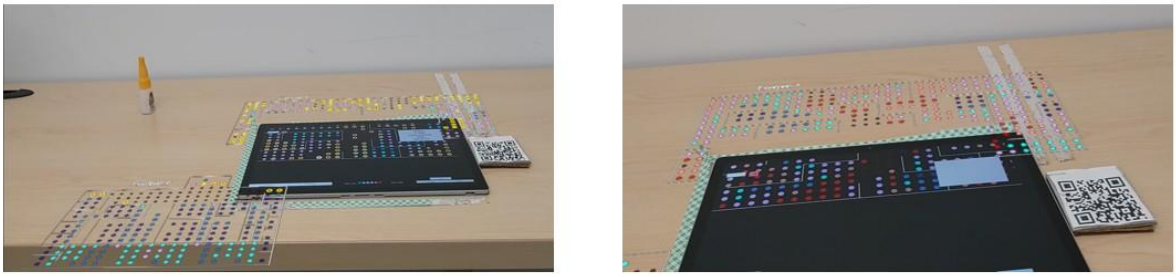
(a) (b)

Figure 1 AbD in AR (a) The tablet interface and floor plan view. (b) Demonstrating a filter selection: data points within the filter range are presented on the two AR layers

4.2. Around Display (ArD) Implementation

For ArD we plot a single space syntax attribute using coloured glyphs on the tablet display and in AR around the display, using a red-to-blue gradient to represent high-to-low attribute values, respectively. The tablet and the AR displays each show different portions of a plot of spatial attribute values and the floor plan itself. Figure 2 shows the ArD interface. The implementation supports filtering values by clicking on a point on the tablet, after which all points in the same range are highlighted on the tablet and the surrounding AR. The floor plan can be zoomed in and out using pinch gestures, or panned using swipe gestures.

Controls were presented on the tablet for resetting the zoom level and centering the position, and for selecting a different spatial attribute to visualize.

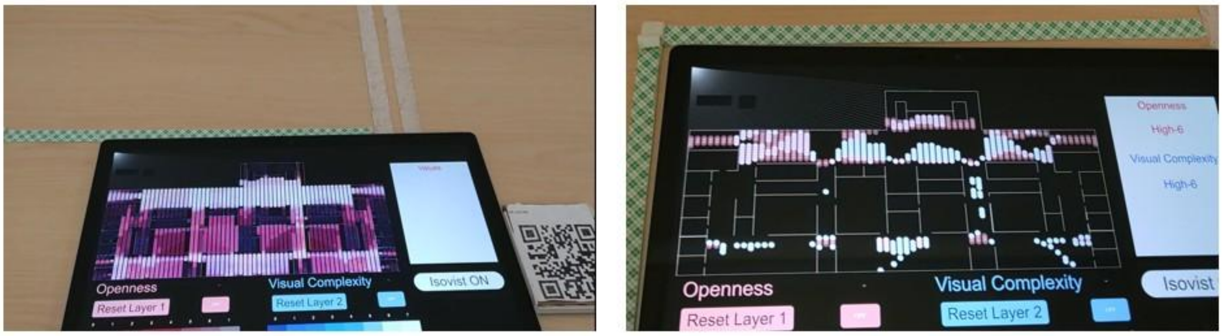


(a) (b)

Figure 2 Around the display ArD interface (a) used here to compare two floor plans. (b) used with a single floor plan.

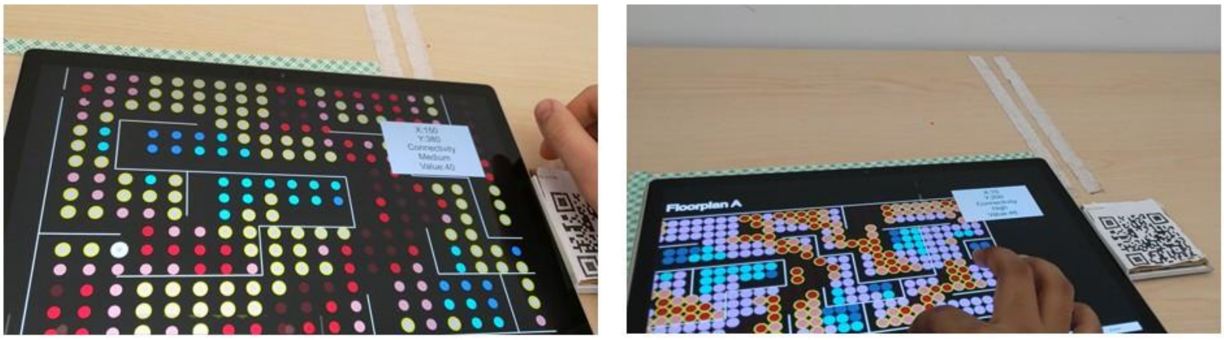
5. Study Design

We ran a within-subjects experiment (n=48) with two factors (AugmentationType, Interface), each with two levels (ArD and AbD, TabletOnly and AR, respectively), giving four conditions. Interface was nested within AugmentationType, and orderings were 2x2 counterbalanced. For the ArD-TabletOnly condition, the visualization and interaction on the tablet were identical to the ArD implementation, minus the provision of AR content around the display (see Figure 4). For the AbD-TabletOnly condition, all three data layers (floor plan/isovist, spatial attribute 1, spatial attribute 2) were superimposed upon each other on the tablet as shown in Figure 3. Interaction and selection features were identical to those on the AbD interface described previously.



(a) (b)

Figure 3 TabletOnly visualization implementation used as AbD comparison.



(a)

(b)

Figure 4 TabletOnly visualization implementation used as ArD comparison

5.1. Participants

We recruited 20 female and 28 male students at our institution from computer science, architecture, information studies, and neuroscience, using campus mailing lists and word of mouth. Three were PhD students, 25 were Master's students, and 14 were Bachelor's students. The participants' prior background in extended reality (XR) was mixed. Twenty-two participants indicated that they were somewhat familiar or familiar with XR technologies such as virtual reality (VR), augmented reality (AR), and mixed reality, while no participant indicated they were highly familiar. Thirty-three participants had used handheld AR applications in the past, and 15 participants had experience with headworn displays (HWDs) like Microsoft HoloLens. None of the participants had conducted space syntax analysis before, including those from architecture.

5.2. Procedure

Experiment sessions lasted approximately 90 minutes and were conducted at *anonymized location*. The procedure is outlined in Table 1. Participants were introduced briefly to the purpose of the study, provided informed consent, and then learned about space syntax through an 8-minute introductory video. This helped participants become familiar with the concepts and terminology used in the study.

Participants then began the pair of conditions for one of the two AugmentationTypes (ArD or AbD). Participants were first briefed about the kinds of tasks they needed to perform and how the interface worked. For each AugmentationType two task sets were prepared, each asking the same kinds of questions in the same order; assignment of task set to Interface was counterbalanced. To mitigate the potential impact of headset comfort on preference, participants wore the headset when completing all tasks, including in the TabletOnly conditions. Tasks involved answering questions about the spatial characteristics of floor plans; participants were asked to state their answers as they completed tasks. Sample experiment tasks are listed in Table 2.

Each task set contained a subset of eight training tasks, which were completed first and in the same order for all participants in both the TabletOnly and AR conditions, using the maze floor plan. For these tasks, participants were stepped through how to use the interface to answer each question correctly, to familiarize themselves with the interface and the dataset. The training tasks were also used to mitigate the learning effect.

Table 1 Design of the Experiment

S. No.	Activity	Duration
1	Introduction and video	12 minutes
2	For each AugmentationType	x 2 (76 mins total)
(2a)	For each Interface (i) Introduce interface (ii) Directed training tasks (iii) Complete task set (iv) SUS, TLX, break	x 2 (60 mins total) 5 minutes 6 minutes 14 minutes 5 minutes
(2b)	Preference questionnaire and interview	8 minutes
3	Debriefing	2 minutes
	Total Durations	***90 minutes***

The remaining tasks were used in our analysis, using the campus building floor plan. Sixteen tasks were completed for AbD conditions using a single floor of the floor plan, and ten tasks were completed for ArD conditions using two floors of the floor plan. Task sets were designed such that the expected completion time for all non-training tasks in a condition was 10-15 minutes. Upon completing a task, the participant stated the answer out loud. Each task had a maximum allowable completion time of 2 minutes, after which it was timed out and marked incomplete and incorrect, and the participant moved 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.

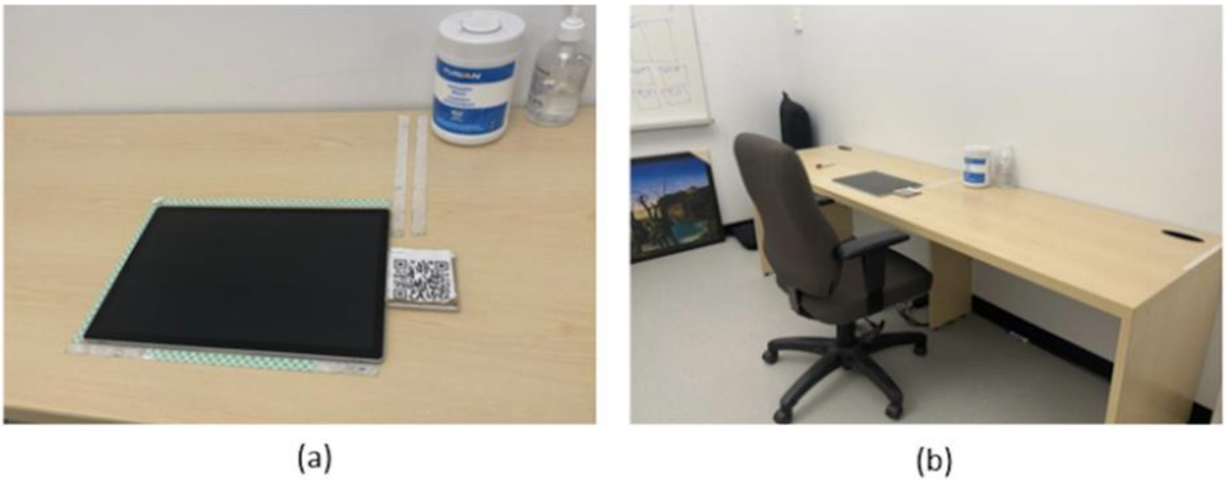


Figure 5 (a) the tablet with QR code (b) the experiment setting

Table 2 Sample tasks for each AugmentationType. Task sets were counterbalanced between the TabletOnly and AR conditions.

AugType	Sample Tasks
ArD	1. Find the point X:160, Y:400. What zone is the point in? What is its connectivity value? 2. How many points have a "High" isovist perimeter value: <20, 20-40, 41-60, or >60? 3. Give the coordinates of two adjacent points, one with "High" and one with "Low" connectivity.
AbD	1. Select a central location with "Very High" visual complexity. State its coordinates and the numerical openness value. 2. Is the isovist at the selected location best described as "Compact" or "Spiky"? 3. How many rooms are visible from the selected location?

Table 3 Sample questions from the interface preference questionnaires.

AugType	Sample Preference Questions
ArD	1. Viewing the entire floor plan. 2. Zooming and panning on the tablet. 3. Identifying areas with similar characteristics across the entire floor plan.
AbD	1. Visually distinguishing different data layers. 2. Determining visual complexity at a single point on the floor plan. 3. Understanding how isovist size and shape contribute to the calculation of openness and visual complexity.

The remaining tasks were used in our analysis, using the campus building floor plan. Sixteen tasks were completed for AbD conditions using a single floor of the floor plan, and ten tasks were completed for ArD conditions using two floors of the floor plan. Task sets were designed such that the expected completion time for all non-training tasks in a condition was 10-15 minutes. Upon completing a task, the participant stated the answer out loud. Each task had a maximum allowable completion time of 2 minutes, after which it was timed out and marked incomplete and incorrect, and the participant moved 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 timed out) for an InterfaceType, SUS and NASA-TLX were administered. After the two conditions were completed for the AugmentationType, a custom questionnaire was administered asking about preference (see Table 3) on 10 different aspects of interface support for completing tasks. A semi-structured interview was then conducted, probing for reflection on their experience completing tasks and on the design of the two interfaces they used. Participants then moved on to complete conditions for the second AugmentationType, following the same procedure. After completing all four conditions, participants were thanked and received a $30 honorarium.

5.3. Data Collection and Analysis

In addition to questionnaire and interview data, timestamped software logs were recorded on the tablet, including user interactions and application state: which spatial attributes were active, any applied filtering, which portion of the floor plan was being presented, and what location was selected, if any. We also captured an audio and video feed from the headset. For each condition, an accuracy score was assigned to each participant. This was done by reviewing the spoken answer for each task, and correlating that with map datasets, software log data, and/or video to mark it correct or incorrect. Incomplete tasks were marked incorrect for this score. Scores were normalized to a value between 0-1, with 1 indicating no errors. We statistically compared questionnaire responses, completion time, and accuracy between Interface conditions for each AugmentationType. For all statistical tests, unless otherwise specified, we assume $\alpha = 0.05$ as the threshold for statistical significance.

We transcribed the semi-structured interview data and the participants' comments using Microsoft Cognitive Services (Microsoft, n.d.). Then, we further cleaned the data and qualitatively analyzed them using affinity diagramming. Affinity diagramming involves creating paper notes and physically clustering them based on commonality (Lucero, 2015). In our analysis, we used Miro (2025), a web-based whiteboard. Each researcher was given a random subset of notes to place on the Miro board. Notes were iteratively placed in clusters. and could be reassigned by any researcher without verbal discussion. Once all notes were placed and no further changes were made, the group discussed each cluster to identify themes, any relationships between clusters, and possibly to split clusters into sub-themes.

6. Results

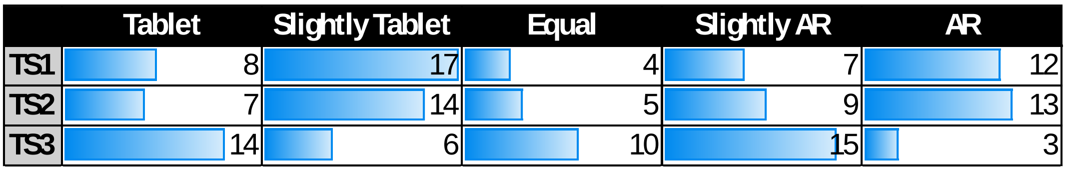
6.1. TabletOnly-AbD v. AR-AbD

Self-Reported Data. The median SUS score for TabletOnly-AbD was 73.75. According to the Wilcoxon signed-rank test, this was significantly higher ($W = 721$, $p = 0.02$) than the median score for AR-AbD ($M = 70$). The median combined raw NASA-TLX score for TabletOnly-AbD ($M = 37.08$) was also statistically lower ($W = 276.5$, $p = 0.03$) than the one for AR-AbB ($M = 38.33$). Despite the statistical significance, we note that the differences between the SUS scores and the NASA-TLX are small. The SUS scores indicate that the participants still found both interfaces to be "usable/good" (Brooke, 1995; Brooke, 2013), the combined TLX scores are both in the "somewhat high" range (Prabaswari et al., 2019), and the difference between median NASA-TLX scores was only 1.25. Participants completed a 5-point Likert-style questionnaire to show their preference towards TabletOnly-AbD and AR-AbD (see Table 3). The scale was as follows: 1 clearly prefer TabletOnly, 2 slightly prefer TabletOnly, 3 neutral, 4 slightly prefer AR, and 5 clearly prefer AR. For each question, we computed N_d, the statistic for the trinomial tests by finding the difference between the number of participants who clearly or slightly preferred TabletOnly and the number of those who preferred AR instead. We report only the statistically significant differences; all other preference questions yielded no overall difference in preference. The trinomial test results are as follows, with the associated frequencies available in Figure 6:

- **TS1:** For *understanding that visual complexity and openness are related to isovist size and shape*, 19 participants preferred TabletOnly-AbD, and 12 participants indicated that AR-AbD was better ($N_d = 7$, $p = 0.03$).

- **TS2:** Twenty-one thought TabletOnly-AbD was better for *completing the tasks efficiently*, while 12 participants thought AR-AbD was ($N_d = 10$, $p = 0.01$).

- **TS3:** Lastly, 29 participants indicated they were *more accurate* while using TabletOnly-AbD, and 9 participants indicated more accurate in AR-AbD ($N_d = 20$, $p < 0.01$).



	Tablet	Slightly Tablet	Equal	Slightly AR	AR
TS1	8	17	4	7	12
TS2	7	14	5	9	13
TS3	14	6	10	15	3

Figure 6 The frequency tables representing how the participants responded to the questionnaire for TabletOnly-AbD v. AR-AbD Tasks. TS1 is relating data layers, TS2 is task efficiency, and TS3 is task accuracy. Refer to Section 6.1.1 for details.

Task Completion Time. The Wilcoxon Rank Sum Test ($W = 307$, $p < 0.01$) showed that there was a significant difference in the total task completion time. The participants tended to be faster with TabletOnly-AbD ($M = 17.58$) than with AR-AbD ($M = 20.40$).

Accuracy. TabletOnly-AbD (M = 84%) yielded slightly lower accuracy than AR-AbD (M = 87%) as seen in Figure 7. The trinomial test (Nd = 3, p = 0.05) showed a significant difference in accuracy between TabletOnlyAbD and AR-AbD across all tasks. It is important to note that while p = 0.05, the result should be interpreted carefully due to the small N_d. N_d is $N_+ - N_-$ where N_+ is the number of positive cases (i.e. improving with AR-AbD) and N_- is the number of negative cases (i.e. worsened with AR-AbD) (Bian et al., 2011). Here, $N_+ = 24$ and $N_- = 21$. This simply means that the techniques affected accuracy, just in both directions. Nevertheless, slightly more users (24 vs. 21) benefited from AR-AbD. The trinomial test is more appropriate than WRST here due to a large number of ties found in the data (Bian et al., 2011).

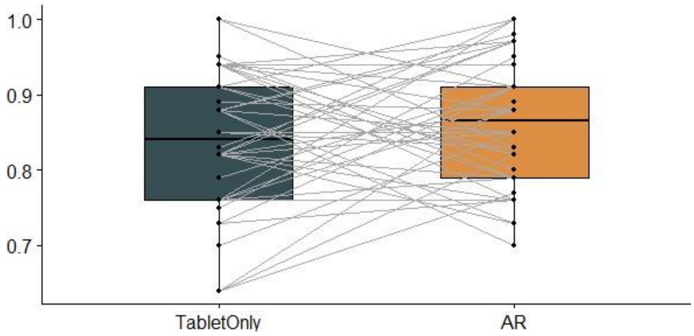


Figure 7 Boxplots displaying the distributions of the accuracies of TabletOnly-AbD and AR-AbD. The lines between the plots indicate individual changes in accuracy between the techniques.

6.2. TabletOnly-ArD v. AR-ArD

Self-Reported Data. The median SUS scores for TabletOnly-ArD ($M = 72.5$) and AR-ArD ($M = 68.5$) indicated that both interfaces were "usable/good" (Brooke, 1995; Brooke, 2013); WRST on SUS did not yield a significant difference ($W = 572.5$, $p = 0.23$). However, WRST on the combined raw NASA-TLX dimension scores were statistically significant ($W = 172.5$, $p < 0.01$). On average, the participants found TabletOnly-ArD ($M = 40.00$) to induce less cognitive load than AR-ArD ($M = 46.79$), although both are in the "somewhat high" range (Prabaswari et al., 2019). The interface preference questionnaire data were structured and analyzed as described for the AbD. Significant differences in preference are as follows:

- **TS4:** For *keeping track of the entire floor plan*, 27 participants preferred TabletOnly-ArD while 14 participants preferred AR-ArD. The test statistic is $N_d = 13$ ($p = 0.01$).

- **TS5:** For *determining coordinates and spatial attribute values at a given point*, 33 participants preferred the physical monitor and one participant preferred AR-ArD ($N_d = 32$, $p < 0.01$).

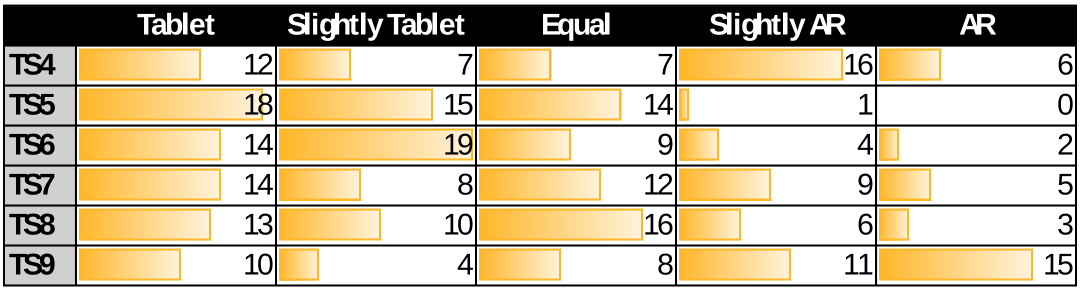
- **TS6:** For *zooming into the floor plan*, 33 participants preferred TabletOnly-ArD and 6 participants preferred AR-ArD ($N_d = 32$, $p < 0.01$).

- **TS7:** For *panning the floor plan*, 22 participants preferred TabletOnly-ArD and 14 participants preferred AR-ArD ($N_d = 8$, $p = 0.03$).

- **TS8:** Twenty-three participants thought TabletOnly-ArD allowed them to *complete the tasks more efficiently* ($N_d = 14$, $p < 0.01$) than AR-ArD ($n = 9$).

- **TS9:** Lastly, 32 participants believed TabletOnly-ArD allowed them to be *more accurate* while 6 participants indicated that AR-ArD did ($N_d = 26$, $p < 0.01$).

The descriptive statistics can be found in Figure 8.



	Tablet	Slightly Tablet	Equal	Slightly AR	AR
TS4	12	7	7	16	6
TS5	18	15	14	1	0
TS6	14	19	9	4	2
TS7	14	8	12	9	5
TS8	13	10	16	6	3
TS9	10	4	8	11	15

Figure 8 The frequency tables representing how the participants responded to the questionnaire for TabletOnly-ArB v. AR-ArB Tasks. TS4 pertains to data visibility, TS5 to data selection, TS6 zooming, TS7 panning, TS8 task efficiency, and TS9 task accuracy.

Task-Completion Time. Overall, WRST test (W = 299*,* p < 0.01) showed that participants required less time to complete all tasks with TabletOnly-ArD (M = 13.74) than with AR-ArD (M = 16.39).

Accuracy. We found that TabletOnly-ArD (M = 0.89) yielded slightly lower accuracy scores overall than AR-ArD (M = 0.95) as shown in Figure 9. The trinomial test showed the result was statistically significant (N_d = 14*,* p < 0.01). We counted the number of participants whose accuracy improved, participants who did not change, and participants whose performance worsened. While WRST is the standard statistical test for paired nonparametric data, we chose the trinomial tests because the data contained many ties.

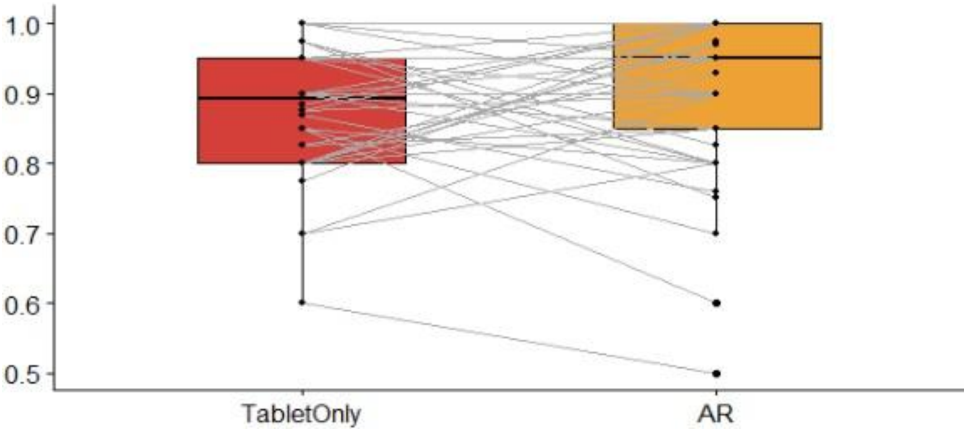


Figure 9 Boxplots displaying the distributions of the accuracies of TabletOnly-ArD and AR-ArB. The lines between the plots indicate individual changes in accuracy between the techniques.

6.3. Interview Responses and Participant Comments

Through affinity diagramming on interview responses and comments made while completing tasks, we identified three major themes: *domain learning and appropriateness*, *device learning and familiarity*, and *AR features and technical issues*. Each is described in this section.

T1: Domain Learning and Appropriateness

- **T1.a: Domain Learning.** Thirty-five participants said that they enjoyed conducting the tasks and learning about space syntax. Participants found the topic “easy to understand", felt they "got to understand a lot of new concepts", and that "It was really interesting and I would really like to learn more". Participants indicated that they could apply what they had learned to their own experiences, "I understood the concepts clearly.. I could relate", and shared personal anecdotes, such as placing a desk in a new apartment. As one participant put it, "for someone like me who’s not into architecture... [I] never knew there was so much depth".

- **T1.b: Domain Appropriateness.** In addition to learning space syntax, participants considered how ViSSTA could be useful in practice. Participants suggested placing furniture, moving to a new home, spatial games (both virtual and physical), conservation and restoration. Participants who studied architecture said ViSSTA could be beneficial to their workflow, if integrated with 3D renderings to show how design decisions impact spatial attributes, and to integrate data with spatial layouts so they can " wear a device instead of [looking] at drawings".

T2: Device Learning and Familiarity

- ***T2.a: Device Learning.*** Five participants stated that at the beginning of their study sessions, they needed some time to become familiar with the headset. One participant stated, though, that they became more comfortable later on: “Honestly, from the last time, this was like very, very convenient to use for someone who is like using it for the second time.” Other participants expressed that with continued use, AR features would be used more effectively: "in the longer run (*sic*) I think [AR] would do a much better job".
- ***T2.b: Device Familiarity.*** Ten participants stated that their familiarity with using a (non-augmented) tablet may have influenced their stated preferences. "The tablet [is] a lot more familiar, and I think that’s like a big part of it", and “I was filling out the [questionnaire], and at times I thought [I liked the tablet] because I am more used to using iPad.”

T3: AR Features and Technical Issues

- ***T3.a: AR Data Layers.*** Despite the overall preference for TabletOnly, many participants expressed that the layers in AR-AbD were beneficial. Participants said "different layers do help show the different features much better", that viewing "from different perspectives can give you different advantages", they "liked..being able to...look at it from different angles", "you could see both [layers] one way and you could make them overlap pretty easily", that with this feature "you might see different patterns [than if] they’re just superimposed", having "positive impact in terms of data comprehension". A few participants expressed that there was a best viewing angle that needed to be found first, while others said there were specific advantages at one viewing angle. Some preferred viewing top-down (such that all data was coordinated spatially relative to the floorplan and layer data was integrated): "It’s definitely better from above ... than from the side", and that "overlapping help[ed] because... I needed to choose a point [where] both [attributes] were high....[they were both] very dark or very light, and that really helped me." Others preferred viewing from the side: "once I found that angle it was really easy to use". Viewing from the side was seen as beneficial for distinguishing data in different layers,"help[ing to] show the different features much better", " differentiat[ing] two colours and... look[ing] between", and also for "keep[ing] track of layers". Participants also expressed concerns about aligning data spatially, that there may be "some alignment issue", that TabletOnly "was clearer when I wanted to be precise", and that viewing from different perspectives might yield "different readings of the data, for better or for worse".
- ***T3.b: Extending the Display in AR.*** Twenty participants expressed that they preferred the AR-ArD experience over TabletOnly-ArD overall. Participants stated that AR-ArD gave "a wider...view where you can see and just visualize things .. better", "see the big picture", and "see more than the tablet can show". This provided useful context for zoom and pan operations, so one was "able to zoom into one of the floor plans and ... see the other floor plan and other parts of that floor plan; that was a pretty nice feature". On the other hand, the extended display could also reduce the amount of zooming and panning: "I did not have to move the screen or zoom in, zoom out", "you didn’t have to drag [the floor plans] around, you could just look... down to find [data]". Participants found the extended display useful for tasks involving both floor plans. Since they could "see both floorplans [at the same] time", they could "find similar points in [the other floorplan], so it was ...

easier". Other participants expressed concerns about visual aspects of the AR extension that could impact accuracy, including alignment with the tablet screen: "the alignment for the floor [plan] was a little off", colour differences: "since all the circles are plotted [together]... maybe the colour contrast was not right", and display quality: "in AR the points were a bit hard to see sometimes".

7. Discussion

7.1. Tools for Learning Spatial Analysis

Participants did not have prior knowledge of space syntax. ViSSTA helped participants understand space syntax concepts- openness, visual complexity, connectivity, and isovists, addressing challenges raised in other work (Heitor & Serra, 2016; Lerman & Lebendiger, 2017; Singh, 2021). Hence, ViSSTA could open new pathways for learning space syntax and other forms of spatial analytics, perhaps in combination with better reference and learning materials as proposed by Amini Behbahani et al. (2017). However, while our results provide some indication that the AR features of ViSSTA were beneficial, these features were not directly mentioned when participants discussed their experience learning the concepts. Indeed, when completing tasks in TabletOnly conditions, some participants made effective use of toggling layers on/off to understand data relationships, applying filters to reduce data density, and zooming and panning to examine large regions of space.

Providing context around the tablet display in AR-ArD was viewed as beneficial by many participants, which is in line with prior work (Langner et al., 2021; Mahmood et al., 2018). Our results provide some evidence that AR-ArD resolves limitations in traditional space syntax tools by allowing a straightforward comparison of an active floor plan with another floor plan. We find some improvement in accuracy scores in AR-ArD, but not for all participants. Participants expressed some hesitancy using the extended display due to display factors (alignment, colour, and resolution).

For AR-AbD, the layers above the display were appreciated by participants as a straightforward mechanism for separating, integrating, and keeping track of layered spatial data. We find that task accuracy increased for some, but not all, participants. As with AR-ArD, participants expressed concerns about accuracy, in part due to display factors like colour rendering, but also due to the unconstrained aspect of taking different perspectives by moving one's head relative to the display.

Taken together, these findings suggest that ViSSTA's value may lie more in supporting complementary educational, collaborative, and exploratory use cases. We envision three different deployment contexts for ViSSTA. First, in a classroom or studio setting, instructors could use the AbD layering to demonstrate how multiple VGA attributes vary across a single floor plan and make the abstract definitions in textbook tangible. Second, in a design review setting, ArD side-by-side extension lets a design team compare two scheme variants on a tabletop with clients who have no prior space syntax knowledge. Third, ViSSTA could serve as a pre-analysis sketching aid: because VGA at high resolution is computationally expensive (Ericson et al., 2021), a quick hybrid-display preview at coarser grid sizes can help an analyst decide which attributes and which regions of a plan require deeper investigation in DepthMapX.

7.2. Limitations and Future Work

During the study, to ensure a consistent experience across participants, the tablet was placed flat on a desk surface, and participants were not allowed to move the tablet in any way. In interviews, some participants mentioned that they would like to place and move the tablet as per their preference. We posit that AR-AbD in particular may have been used more effectively if participants were able to rotate the tablet screen toward them to see an integrated, top-down data view, vs. needing to lean slightly forward and look down, possibly from a standing position.

A QR code was used at the beginning of each condition to calibrate the AR content with the tablet display. A thick tape border prevented the tablet from travelling on the desk, but the tablet display could still be moved slightly–such as while zooming or panning–and AR content would become slightly misaligned; this accounts for alignment issues noted by several participants, and likely impacted our results in favour of TabletOnly conditions. The ArD prototype also occasionally exhibited a noticeable lag in AR content movement when panning due to network communication. While no participants mentioned this issue, it may still have reduced the use of ArD features.

In our study, participants explored a small subset of space syntax attributes. While our results are promising, further research is required to assess how appropriate and effective our techniques are for other space syntax attributes and other forms of spatial data. Finally, our study considered novice users, exploring the benefits of ViSSTA as a learning tool. In future work, we will explore how ViSSTA can support domain experts in the context of their work.

8. Conclusion

ViSSTA is a tablet+AR tool for exploring space syntax attributes. ViSSTA renders spatial attributes as data layers in AR above the tablet display, and around the tablet display to complete a floor plan segment viewed on the tablet, or to show other floor plans for comparison. In a controlled study (n=48) we compared the around display feature (AR-ArD) and above display layers (AR-AbD) with comparable TabletOnly interfaces. Overall, task accuracy was higher in the AR vs. non-AR conditions. Participants expressed enthusiasm and interest in the topic, suggesting that the tool is beneficial for learning. However, participants expressed hesitancy toward the AR features due to perceived or actual issues with alignment, resolution, and colour rendering. Overall, participants preferred TabletOnly interfaces and felt they were more accurate using them.

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