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

*A Hybrid Tablet and Augmented Reality Interface for Space Syntax Data Analysis

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***Abstract*—We developed a hybrid interface with tablet and head-worn augmented reality(AR) VizSSTA, a system using two design spaces, one used the space above the tablet to place AR content and the other used the space around tablet to align AR content in the virtual space. The purpose of this study is to evaluate the effectiveness of the above and around the display aspects for data comprehension across the space syntax domain. Two research questions were evaluated one to assess participants ability to understand how two spatial attributes (Openness and Visual Complexity) are related to each other and to the raw isovist data and other one to assess how well participants can identify regions with similar space syntax attributes across the entire floorplan and understand how isovist perimeter and connectivity are related. Using a within-subjects user study (n=48), we did a comparative study across a hybrid AR interface and tablet-only interface without AR for both design spaces. Quantitative and qualitative data analysis showed that the AR systems helped comprehend the space syntax attributes. Hybrid interface with AR, compared to the interface without AR, had more accuracy for tasks involving identifying how isovist shape and size are related to the openness and visual complexity, also identified regions with similar regions across the floorplan, and understood how the isovist perimeter and connectivity correlates. Further exploration needs to be done to identify a better placement of the tablet surface such that head-worn augmented reality devices do not add to the physical constraints. Moreover, we need to be considerate about the habituation period.**

***Index Terms*—hybrid interface, space syntax, information visualization**

I. Introduction

Space syntax [1] 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) [2]–[4], storytelling in AR [5] and urban planning [6]–[8]. Space syntax has also helped detect crime patterns [63] with the help of axial analysis, which helped by correlating high levels of integration and connectivity with the crime rate. Space syntax has also been used for the placement of game objects as per the requirements [2], [12] such as a crime will happen in a place of low visibility, and a party event will happen in an open space and keys to an open chest is placed at a location of low visibility. 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 [2], [9]–[12]. As per the prior work in space syntax [9]–[11], 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 [9]. The users also described some use cases which may help to understand the space syntax attributes [2], [12] such as displaying two space syntax attributes in a comparative view and identifying regions with similar properties to understand the space syntax attributes. The space syntax tools output the axial, isovist, and agent analysis in the form of CSV data. This data can be projected in scatterplots or heatmaps through information visualizations.

Information visualizations can help understand the data better since the visual form of data amplifies the comprehension of the data [13], [14]. It can also help identify relationships, trends, and patterns in the data [14] which may be otherwise hard to find. As a visual representation of data conveys more information than the raw data, the users can also interact with the visual graphics by applying filters and zooming/panning the data [13]. Using the virtual space around the conventional displays to display the data dates back to the early nineties [15]. Projecting data in AR has been proven effective in terms of sensemaking by offloading the data into the large space [16], [17]. 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 [18]. The combination of conventional displays and AR has also been proven effective in improving task performance [19]. While there has been a considerable amount of recent work exploring the potential of immersive visualization [16], [18], [20]–[23] and little work in space syntax domain (through AR or VR displays) [2], [5], work remains to be done to understand the benefits of immersive visualization for

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visual representations of the space syntax attributes. As part of the current research, we were able to answer the following research questions:

A. Research Questions

1) How can 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?

   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 correlate for ARD technique.
2) 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 better than physical screens for space syntax?

   The participants were assessed on their ability to understand how two spatial attributes (Openness and Visual Complexity) are related to each other and the raw isovist data for the ABD technique.

We compared each technique in AR i.e., above the tablet display by projecting the visualization on the tablet display(ABD) and around the display by extending the visualizations around the tablet display(ARD) (on performing zoom and pan operations) against a baseline non AR visualizations presented on the tablet.

We 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. It was also observed that task accuracy was reduced as the participants found it challenging to see the overlapped information on a baseline(ABD) physical monitor. 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 physical monitor interface for ARD. Through self-reported data, participants reported that they faced physical load challenges concerning the weight of the Head Mounted Device(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. Participants performed better in the AR interface concerning specific tasks despite these challenges.

II. Related Work

A. Space Syntax Understanding

Space syntax helps to determine the relationship between humans and space. Considering how usually people utilize any given area, they tend to exhibit patterns [24] 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 [25], are the set of visible points from a given point and are used to analyze the spatial environment. 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 in previous research has been used to identify scenic spots/best viewpoints [6], [7] to create an environment exhibiting the properties that enhance the viewer's experience. 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. Visibility graph analysis(VGA) is a graph-based representation describing mutual visibility between any given points in space [26]. The attributes used in this research are:

1) Connectivity which represents the number of visually accessible points in the space from a given observation point [27].
2) Isovist Area that represents the spaciousness of an area [28], [29] and is represented by the space visible from the given point [5].
3) Isovist Perimeter [28] denotes the perimeter of the space occupied by the Isovist.

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 [11]. Existing publications in isovist analysis focus on attributes like connectivity, isovist Area, and through vision which is relatively easier to understand. Various commercial and research tools are available for conducting space syntax analysis, including DepthMapX [30], QGIS [31], and Grasshopper [32]. In this research, We are using DepthMapX for space syntax analysis.

B. Information Visualization in AR

Information Visualization are a computer-supported visual representation of abstract data which intend to amplify cognition [33]. Dynamic and interactive visualizations support features like zooming, panning, filtering, selection, marking, connecting one data to another, and others [33]. As per the current research [21], [34], there are four categories of information visualization for presenting data overview+detail, zooming, focus+context, and cueing. In this research work, we 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. We 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. Carr et al. [35] 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 [36] that are performed by the users when interacting with visualizations.

C. Hybrid Interfaces

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 [16], [19], [23], [36]. Information visualizations using hybrid systems help create 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 [37]. ARts(Augmented Reality with Tablets) by Hubenschmid et al. [21] 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. [16] arranged the 2D and 3D visualization above, around, and between the tablet surfaces. Langner et al. [16], and Hubenschmid et al. [21] helped in identifying how the visualizations can be distributed across the interfaces and how they can be aligned to the physical monitor. Havard et al. [38] 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. [16] helped in making the design decisions during the design and implementation process such as readability of the details in AR is essential, what interactions can be supported in the tablet, and which type of tracking technique should be considered while supporting a non-laboratory environment. 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 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 [19], [23], [40]–[42], [59] implored 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. We can conclude that intensive research has been done to implement hybrid interfaces. However, very little research has evaluated the prototypes through controlled studies.

III. Preliminary Work

This section illustrates the research contribution which leads to the development of VizSSTA. This work helped us identify the gaps in the space syntax domain and analyze how we can work towards improving the current systems. Story CreatAR, developed by Singh et al. [5], was designed for the Unity platform, and HoloLens 2 was used for the deployment. The platform used both isovist and convex analysis for the spatial rules and object placement. This work is essential as the motivation behind visualizing the space syntax attribute in AR was derived from this project.

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 CreatAR tool was evaluated by three Dalhousie film and media studies students. Each student created a story across multiple sessions, discussing space syntax analysis techniques and implementing various story sections through the tool. The story authors defined 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 defined the rules, the story elements were placed as per the rules. The tool offers the capability to preview the story in VR and later deploy it in AR once satisfied with the placement. 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
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?

It was realized that it was difficult for the authors to use the spatial rules as they had not previously used them. Research by Lerman et al. [10] also states that it is difficult to understand the space syntax attributes. Though high-level names were given to the space syntax attributes like openness for isovist area and visual complexity for isovist perimeter, still some terminologies appear to be misleading. The authors had preconceived ideas about the terminologies, which confused the authors and led them to misinterpret the terms. Such as one author said, "visual complexity does that just mean where there's a lot of stuff?". High-level spatial attributes as shown in the table also confused the authors such as 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 and could mean a variety of things". Authors using the Story CreatAR provided various suggestions to improve upon the tool, such as:

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 simple use cases of the space syntax attributes.

Moreover, the authors also learned by exploring the different combinations of space syntax attributes. Output from the depthmapX provided some context to the authors with respect to spatial attributes. From this discussion, we concluded that a tool to understand how the spatial attributes are distributed across the floorplans or urban systems, which also provides an ability to compare the space syntax attributes and help them explore a space syntax attribute, will help understand the spatial concepts. Through the discussion and the author's suggestions, it was identified that spatial understanding would help the author use space syntax tools efficiently and accurately.

While the researchers were working with depthmapX tool, it was recognized that it is challenging to operate with space syntax tools. As part of our research work, we were using DepthMapX. Various tutorials and manuals are provided to run the analysis still to extract all the required spatial attributes. It takes the tool a lot of time to do the VGA, also suggested by related work also [43] and some understanding to set the values for grid size, global measures, and gate counts. These terms might make no sense to a user who has no or less familiarity with the space syntax terminologies. A similar thing is highlighted in the literature section by behbahani et al. [11]. Moreover, it does not provide a side by the side of spatial attribute view that could help compare the spatial attributes. The DepthMapX tool provides a view where we can see only a single spatial attribute at a given point in time. Through the author's suggestions, it was analyzed that a comparative view of spatial attributes helps to understand the space syntax attributes.

IV. Design and Implementation of VizSSTA

This work is part of the larger ARTIV(AR Techniques for Information Visualization project). 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 of those other domains. The process of development and implementation of VizSSTA is broadly divided into three stages-

1) Stage 1-Brainstorming Ideas: Some use cases were identified to understand better the space syntax domain where space syntax visualizations may help users make informed decisions. Space syntax visualization use-cases were inspired by experiences designing the toolkit and working with authors who used the toolkit. Two primary use cases developed were comparing two space syntax attributes and identifying regions in the floorplan with similar properties. These two use cases 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 use cases were essential to this 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. We discussed ideas, opinions, and issues on the sticky notes 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 several "sticky notes" on the Miro Board [44](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. After this process, all the researchers involved in the study met for an affinity diagramming session [45]. The researchers reviewed the information collected by each researcher and classified the ideas into themes- Visual representation and layout, implementation software and hardware, embodied interactions, algorithms to be used, multimodal interactions, and embodied interactions.
These themes helped the researchers identify the areas which require more background information and the aspects we need to focus on while creating visualizations.
   a) Interactions that need to be supported in the tablet and AR:
      i) Cross-media brushing and linking.
      ii) Objects that are filtered out should become inactive

iii) A way to move content from AR to tablet, Semantic Zoom, probing
iv) exploring the role of tablet in immersive viz (e.g. for navigation and filtering)
v) For Space syntax analysis- The researcher commented- "I think we can use Strongly co-ordinated actions like applying the 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, the technique of highlighting the selected data was used. This discussion also influenced how to implore the tablet's role in the interactions. Later through the literature review, It was identified that current research supports that tablet interaction over interactions in AR.

b) Software and hardware requirements and techniques required to establish the connection between Tablet and AR:
   i) Can we use R with Unity and/or HTML in some way?
   ii) If we use Unity, how do I display 2D interface? Using Vuforia?
   iii) A way to present 2D visualizations in AR.

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

c) Visual presentation and layout of the data in AR: Few notes from the discussion which helped with the design of ABD and ARD-
   i) Layer 2D AR visualizations on top of each other, with a tablet at the bottom,
   ii) 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 tablet at the bottom.

2) Stage 2-Sketching and Low Fidelity Prototyping: Three sets of iterations helped arrive at the final sketches.Through first set of sketches, it was observed that since through the brainstorming session, the research is 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 where the background in AR will be transparent and remove the contents, which makes the visualization as windows in AR.
3) Stage 3- Proof of Concept and Design Choices: During the initial research, a proof of concept was built using the unity platform [60] from the initial designs evolved from the sketching activity. 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 a number of data generated in the form of 3D objects. Hence, we decided to develop 2D spatial models on the web for further development as it took less time to display the 2D models developed through the 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.

V. Design Decisions

This section lists the design decisions for VizSSTA resulting from the design process just described and from reflecting on related research findings.

A. D3.js for Information Visualizations

2D displays were created using a powerful library called D3.js [61] in combination with Node.js. Existing literature [16], [17], [47] 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.

B. 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 with AR content owing to the learning curve [23], [41]. Moreover, the interactions in 2D display are more accurate and less tiring [23], [42], [59]. In VizSSTA, all interactions occur on the tablet's touchscreen display while content is presented on the tablet and in AR.

C. Using QRcodes for Anchoring

Existing literature [48], [49] supports the use of the outside-in 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.

1) Color Selection: For ARD, the rainbow color gradient similar to the one implemented in depthMapX was used during the initial implementation. Prior research indicates that [50], [51] rainbow colour scales represent strong colour variations and are perceptually more error-prone and much slower than single-hue colour scales. Hence as per the recommendations, [50], [51], 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 Augmented Reality, and very dark shades of a colour appear to be black in Augmented Reality. Thus colours were carefully chosen through multiple tests with fellow researchers.

a) 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 [52] also establishes that the background color affects how well the holograms are perceived in AR. The white color or light shaded [53] background on the tablet hinders the color and contrast perception, and the colors appear less salient [52] in AR.

VI. Implementation

This section explains the implementation process, highlighting how the design process helped make decisions related to the implementation and development of the prototype. It enabled us to arrive at the stage where we had the low fidelity prototype ready for the initial implementation. The implementation process was followed as per the below steps.

A. Preparing the Floorplan Images

The primary stage comprised of preparing the data for DepthMapX. We used a floorplan of the Dalhousie University, Mona campbell building's fourth floor, and another image of a maze floorplan from the internet [54]. DepthMapX supports images to be exported in the dxf (Data Exchange Format). Hence, Inkscape tool [55] was used to trace the bitmap from the images, and floorplans were saved into dxf format compatible with DepthMapX.

B. Floorplan Spatial analysis in DepthMapX

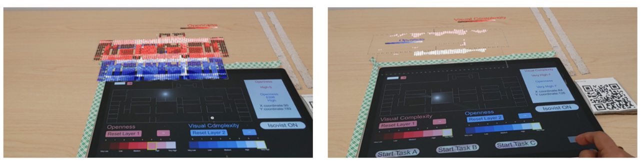
Once the floorplans were in the compatible dxf format, they were exported in the depthMapX. Floorplan analysis initiated with selecting the grid size and selecting the region in the floorplan for which we want to do the analysis. This data is saved in the graph format to be used in the command line interface. 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 make sure 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, namely Isovist Area, Isovist Perimeter, Point first Moment, Point second moment, Visual Integration[HH], Visual Integration[Tekl], Visual Integration[P-value], Connectivity, Isovist Min Radial, Isovist Max Radial, Isovist Occlusivity, Isovist Compactness, Visual Mean Depth, Visual Node Count, Visual Entropy, Isovist drift magnitude, Isovist drift angle, and Visual Relativised Entropy. DepthMapX supports other kinds of analysis as well convex analysis, axial analysis, and agent analysis. Due to our preliminary work primarily focused on the VGA, we are focusing on representing the same attributes through this work.

Information visualization guidelines [35] 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 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.

1) Above the Display Implementation in AR(ABD): 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 the AR layer was achieved with the help of third layer in the 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 with the help of the 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 Webview [56] in Unity due to its ability to visualize web data in AR and to adjust transparency among the virtual layers.

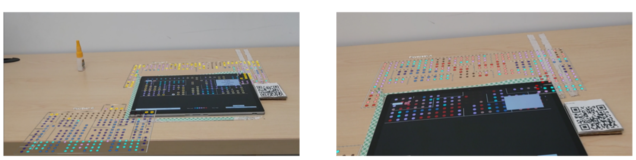
The composite view type was used to represent data in the ABD information visualization. Transparency between each layer was achieved for viewing the AR layers from above, which gives a combined view of both the layers while viewing from the side allows the user to see individual layers. The distance between each layer was chosen so that the user could see the individual layers while seated. The layers appear to be merged from the top view. Multiple iterations and pilot studies were done to ensure the gap size between the layers as appropriate. The connection between each layer was established through the WebSockets (NodeJS Express edition).



(a) (b)

Fig. 1. 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

2) Around the Display Implementation in AR(ARD): 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.



(a) (b)

Fig. 2. Around the display 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.

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:2 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.

VII. Study Design

This section focuses on study design and regarding the participant recruitment. We 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 were part of the study, two Master's student and a fellow Ph.D. researcher, was part of the data analysis process. This study evaluates 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 immersive head-worn displays (AR/VR). 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.

VIII. Data Analysis

The data analysis process was initiated by the summation of responses and projected in bar charts by the researcher. Task completion time, errors made throughout the task, subjective workload, and user experience through semi-structured interviews were used to evaluate the systems.

A. Study population

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. 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.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 HMDs before.

B. Above the Display

1) Self Reported Data: The system usability score for the ABD and physical monitor was 70 and 75, respectively, which is a good ratingx' [57], [58]. Through Kruskall-Wallis(α=0.05), significant difference was computed for the physical activity required to perform the tasks in AR and physical monitor interface , χ^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 monitors(M=20, SD=22.12).

2) Observational Data analysis: The video data was collected from both sessions of ABD and ARD for both AR and physical monitor through the HoloLens 2. In the video, we 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 [64] speech to text. We performed a top-down deductive coding method as discussed by Braun and Clarke [65] to understand participants' behavior as we wanted to identify how the participants interacted and whether the interface helped or not. We 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), we also added *physical strain to the list*(since the participants felt physical strain while doing the task). Two researchers 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. We 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.

a) Time taken to complete the tasks: 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, χ^2 = 5.53, p = 0.01),df=1 with ARD (M = 20.47, SD = 6.49) and physical monitors(M=18.13, SD=4.59). No significant difference was observed for the any of the tasks.

Task 13 involved identifying the isovist properties and how the visual complexity and openness values changes 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 monitors 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 monitors and the accuracy rate was calculated for these tasks which conveyed that toggle On/Off affects the accuracy rate in physical monitors. No significant difference was observed for the toggle/no toggle condition with time taken across the ABD/physical monitor, Task13 χ^2 = 2.31, p = 0.50),df=3.

Task16 and Task17 involved identifying the regions with specific properties for the placement of objects. E.g. One of the task involved identify two places for the placement of Object A and object B in the floorplan where the openness and visual complexity is very high and isovist is big. The time taken to achieve these tasks in physical monitors (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 χ^2 = 0.80, p = 0.84),df=3 Task17 χ^2 = 3.5, p = 0.4),df=4.

From qualitative analysis of the interview data, it was determined that the once the participants grasp knowledge of how the openness and visual complexity are distributed they felt confident that they can determine the values by themselves without using any filter. In P7' quoted that, "I didnt use filter since I knew the openness is less in the corners since isovist is small there".

3) Accuracy: 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 monitors and "No toggle" reduced the accuracy furthermore. Significant difference was also observed for these tasks of using the Toggle/No Toggle with ABD/Physical monitors , 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, $p = 4.42{*}e^{-05}$,df=3, Task13 χ^2 = 48.49, p = $1.66{*}e^{-10}$,df=3. 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.

C. Around the Display

1) Self Reported Data: The system usability score for the ARD was 69.9, which is right above the average of 68 [57], [58], and for the physical monitors/tablet was 73, which is a good rating. Through the self reported data, participants preferred physical monitor over ARD for keeping track of the entire floorplan (M= 2.89, SD= 1.5) t(47)=2.62, p=0.005, Cohen's D=0.37". 27 participants preferred AR versus 14 participants for physical monitors. 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=5.304e-11, Cohen's D=1.19". 33 participants preferred physical monitors versus 1 participants for AR. Zooming into the floorplan (M= 1.9, SD= 1.08) over AR for , t(47)=-5.18, p=2.214e-06, Cohen's D=0.74". 33 participants preferred physical monitors versus 6 participants for AR. 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 monitors versus 14 participants for AR. 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 monitors versus 9 participants for ARD. Completing tasks accurately(M= 1.91, SD= 1.04), t(47)=-5.38, p=1.123e-06, Cohen's D=0.77. 32 participants preferred physical monitors versus 6 participants for ARD.

2) Observational Data analysis:

a) Zoom and Pan Operation: 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 monitors (F(1,94) = 75.24, p= 1.21e-13), participants used zoom operation more in physical monitors(M=144,SD=149.5) than ARD(M=8,SD=0.5). A significant difference was calculated through one-way ANOVA using pan operation for all the tasks in both ARD and physical monitors (F(1,94) = 75.24, p= 1.21e-13), participants used pan operation more in physical monitors(M=433,SD=598) than ARD(M=12,SD=4.1).

b) Time taken to complete the tasks: A significant difference was observed for the following tasks.

1) Identifying points with specific zone/range(range with highs and lows) with zooming and panning. Significant difference was observed, χ^2 = 70.50, p = $2.20 * e^{-16}$,df=1.
   Learning effect was observed for the above task in ARD since the time was reduced as the participants proceeded to do a similar set of tasks for spatial attributes from connectivity to isovist perimeter. 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, χ^2 = 64.07, p = $1.23 * e^{-15}$,df=1. While performing the tasks for spatial attribute: Isovist Perimeter, participants got familiar with observing the floorplan B in AR layer and took less time to perform the tasks using less number of operations, namely zoom and pan((freq of operations calculated by overall time taken = 0.18 for Isovist Perimeter) than the physical monitors(freq=15). This was marked as a habituation period while doing video coding.
   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. Eighteen participants tried to do the same thing. Habituation period and transfer error added up to more time to complete the tasks in AR for initial tasks with spatial connectivity attribute, which decreased as we moved towards the isovist perimeter attribute. It was also identified that the participants performed more zoom and pan operations for the tasks and took extra time in physical monitors as the participants had to switch between floorplan A and floorplan B by zooming and panning for the physical monitor. A significant difference was observed between operations(zoom and pan) performed in physical monitors(M=30,SD=0.7) and ARD(M=3.1, SD=1.1) for these tasks:χ^2 = 71.393, p = $2.2 * e^{-16}$,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. 31 participants in the 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.

2) Understanding relationship between Isovist Area and Isovist Perimeter. Significant difference was observed, χ^2 = 44.76, p = $2.20 * e^{-11}$,df=1.
   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 monitors (M=1.34,SD=0.26). A significant difference was observed between operations(zoom and pan) performed in physical monitors(M=70,SD=6.3) and AR(M=28.3, SD=6.2) for these tasks:χ^2 = 71.393, p = $2.2 * e^{-16}$,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 led to less time taken in ARD.

c) Accuracy: Accuracy for tasks was less in physical monitor(Accuracy rate=0.84) than ARD(Accuracy rate=0.84). As explained in the above time taken section, they had to perform more operations(zoom and pan)(M=30,SD=0.7) to complete these tasks in the physical monitor. These operations included the participants panning 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 Floorplan B was. For ARD (M=3.1, SD=1.1), the participants performed less zoom and panned operations as they could complete the task by looking at both focus+context regions simultaneously.

In the final task of understanding the relationship between Isovist Perimeter and Isovist Area, participants performed better in AR than in physical monitor due to the same reason as the above task. The operations(zoom and pan) were less in ARD(M=15.3, SD=3.1) than in physical monitors(M=5.1, SD=2.6).

D. Interview Data

Quick short notes were created from the transcribed interview data in the Miro, and these notes were equally 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. 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, and first time AR users(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"), tablet bias("I was filling out the form(Post Study Questionnaire) and at times I was thinking like is it because I am more used to using iPad"), how visual distinction of SS data was engaging in AR, applications of the interface, and some miscellaneous comments about the interface issues.

Twenty 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 a tablet all the time, but that was very interactive. " P23 said, "I can see both floorplans with zoom display the single time." Thirty-five 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 enjoyed it."

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

Almost all participants complained about ergonomic issues like neck strain due to the headset's weight. P31 expressed that "I felt my neck was definitely strained the whole time."

IX. Discussion

This section discusses the implications of the results for both above and around the display visualizations towards the space syntax domain and hybrid interfaces.

A. Implications on 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. [9], [10], [12]. The tool's user base did not have any prior knowledge of space syntax. Hence this could open new pathways to understand the space syntax terminologies along with the work of behbahani et al. [11] which works on existing resources(manuals, documentation) to provide a better understanding of the space syntax domain. Moreover, VizSSTA also reduced dependency on DepthMapX tool. 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. [11].

B. Implications on Hybrid Systems

VizSSTA also provides guidelines and feedback from the user study that was a gap in the recent research [16], [21], [22], [40], these could be adopted and will be helpful to improve hybrid systems. Through VizSSTA, we identified that for domain-specific tasks also, hybrid systems provide an understanding of space syntax, as Zhu et al. [62] identified through generalized tasks. An attempt was made to build a lightweight system with internal tracking through QRcodes to mitigate the challenge of the heavy device and lab equipment required to run hybrid systems as faced across various researches [16], [19], [42], [62]. QR Anchoring will help with the weight of the hybrid systems. Despite contributions through VizSSTA towards the current research through HoloLens 2, similar results were observed concerning the physical load of the holoLens 1 in the previous research as well [19], [42]. As per both ABD and ARD interfaces, it was observed that more habituation period was required to get the participants familiar with the interface. The participants expressed that a hybrid system with a combination of AR and physical monitor would help.

C. Limitations

The main implementation limitation identified while doing the study for both ABD and ARD 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 QRcode in the current system 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. The current system was evaluated with the tablet lying flat on the surface, which added 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 from a 3D perspective. The learning effect was observed, which can be mitigated by giving the participants some more habituation time to get familiar with the AR interface.

As part of the analysis, we 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. We need to explore whether ABD and ARD hybrid systems help understand space syntax attributes other than isovist area, isovist perimeter, and connectivity.

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.

X. Conclusion

In this research, the researchers identified the gaps in understanding the space syntax domain. Two display paradigms were explored in AR and physical monitor representing the focus+context data around the tablet and a composite comparative view above the tablet. A comparative study was conducted within the subjects' user study to explore two research questions with the display paradigms in AR and physical monitor. The study helped answer research questions. The study found that the AR display provides a better understanding of the isovist properties for both ARD and ABD. However, the participants faced a couple of challenges due to the device's weight, learner's error, habituation period, and expressed bias towards the tablet due to familiarity. Much work is required towards the hybrid systems and space syntax domain.

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