A Longitudinal Exploration of Sensemaking Strategies in Immersive Space to Think

Kylie Davidson, Lee Lisle, Kirsten Whitley, Doug A. Bowman, and Chris North

Abstract—Existing research on immersive analytics to support the sensemaking process focuses on single-session sensemaking tasks. However, in the wild, sensemaking can take days or months to complete. In order to understand the full benefits of immersive analytic systems, we need to understand how immersive analytic systems provide flexibility for the dynamic nature of the sensemaking process. In our work, we build upon an existing immersive analytic system – Immersive Space to Think, to evaluate how immersive analytic systems can support longitudinal sensemaking tasks. We conducted a user study with eight participants with three separate analysis sessions each. We found significant differences between analysis strategies between sessions one, two, and three, which suggest that immersive space to think can benefit analysts during multiple stages in the sensemaking process.

Index Terms—Human-Computer Interaction, Immersive Analytics, Virtual Reality, Information Visualization, Sensemaking

1 Introduction

We are living in a world of Big Data [1]. With the vast influx of data, we need effective technologies to help us parse through a large amount of data and make sense of it. With the growth of big data and its importance over the past ten years [1] a simultaneous acknowledgment of the value of information visualization has taken place. Aiming to build views of this big data, work in information visualization allows analysts to make more informed hypotheses and decisions through better representations of trends, clusters, and outliers in their data.

In recent years we have seen the advent of low-cost Virtual Reality/Augmented Reality (VR/AR) display technologies. As these technologies are becoming widely available in consumer markets, we have seen a growth in the field of immersive analytics, which aims to investigate how immersive technologies can be used to support analysis and decision making. Immersive analytics was first introduced by Chandler et al. [2] in 2015. In 2019, Skarbez et al. [3] redefined immersive analytics as "the science of analytical reasoning facilitated by immersive human-computer interfaces" to provide a more flexible definition. This definition focuses on analytic reasoning, which refers to the computer-aided sensemaking process (knowledge generation) [4]. The sensemaking process consists of two loops: information foraging and the sensemaking loop. The goal of immersive analytics is to unobtrusively support both parts of these processes in a way that aids the analyst's cognition.

One approach to immersive analytic include Batch et al.'s work with ImAxes [5], [6] which focuses on immersive data visualization. Another unique approach which focuses on test-based data includes Space to Think [7] and Immersive Space to Think [8] which provide a vast amount of space for structuring the unknown by offering opportunities for distributed cognition [9]. These immersive analytic systems offer a way to externalize your memory into the environment. However, one limitation of the existing research is that it focuses on a single analysis session. Moreover, in an application such as intelligence analysis, analysis can be ongoing for months or years at a time [10]. In our work, we focus on a sensemaking task completed across three sessions to simulate a long-term sensemaking task that leverages that ability to externalize cognition into the environment. In this paper, we build upon an existing immersive analytic software prototype - Immersive Space to Think (IST) [8]. Using this software prototype, we conducted an exploratory three-session user study with the following goals: 1) Understand how immersive technologies affect the overall sensemaking task from foraging to presentation, 2) Understand users' 3D organizational structures and how they change over time, and 3) Understand how immersive technologies can be used in combination with more traditional computing technologies while completing the sensemaking task.

- *Kirsten Whitley is with the US Department of Defense*
- *Kylie Davidson, Lee Lisle, Doug A. Bowman, and Chris North are with the Department of Computer Science, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24060.*
  E-mails: kyliedavidson@vt.edu, llisle@vt.edu, dbowman@vt.edu, north@cs.vt.edu

2 Related Work

2.1 Sensemaking

Sensemaking is a process in which we take the information in the world around us and make sense of it. During this process, we collect information, formulate hypotheses, and reevaluate findings based on new information we collect during the process. The sensemaking task is a cognitively demanding task that requires creativity, comprehension, mental modeling, and situational awareness [11]. To ease the cognitive load during the sensemaking task, we formulate mental and physical models to organize the "unknown". These structures or frameworks allow us to develop a deeper understanding of the underlying data collected for analysis [12].

In an attempt to formalize the sensemaking (knowledge generation) process, Pirolli & Card defined the Sensemaking Process for Intelligence Analysis [4]. The process consists of

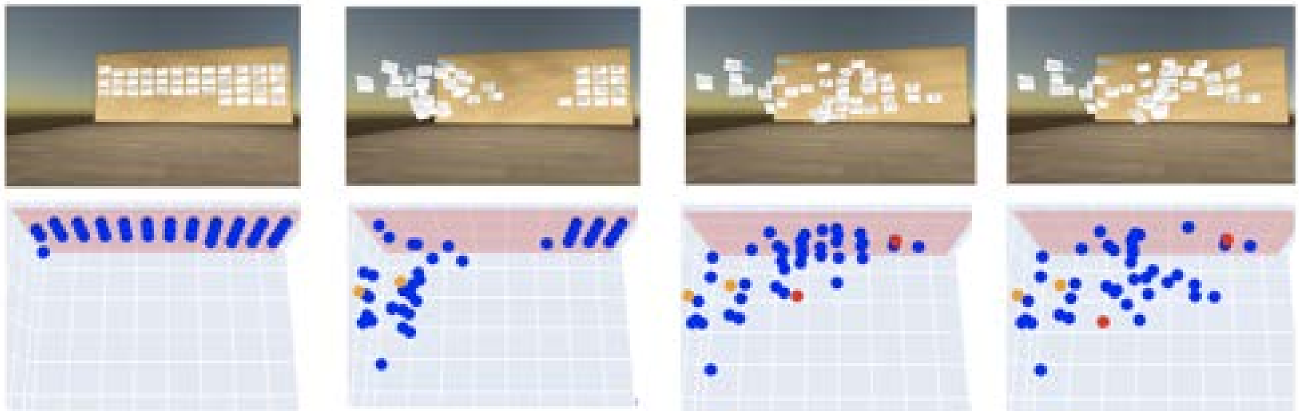

Fig. 1. Example of participant five's spatial layout over time from left to right: start, end of session 1, end of session 2, and end of session 3. Top Row: view of immersive space. Bottom Row: view of 3D scatterplots used for analysis in a top-down orientation.

two loops: information foraging and the sensemaking loop. In the foraging loop, analysts search for, filter, and extract meaning from relevant data, while in the sensemaking loop, analysts form schemas, hypotheses and develop presentations of their findings. During this process, analysts move up and down within the stages as needed while completing their analysis.

Since sensemaking is a psychologically demanding task, many technologies have been developed to help support analysts during sensemaking. One research area which addresses this is visual analytics. Visual analytics is the process of analytical reasoning facilitated by interactive visual interfaces [13] with the goals of synthesizing information, detecting the expected/unexpected, and providing timely support [14]. Sacha et al. drew upon the model for the sensemaking process and created a model for the knowledge generation process for visual analytic tools [15]. Overall, visual analytics tools should support understanding, reasoning, and decision-making with complex data sets.

Many visual analytic systems have been developed to help analysts during the knowledge generation process. One approach to visual analytics is providing interactive visualization assistance during the sensemaking process [16], [17], [18]. In this work, essential elements of information can be extracted and linked together through interactive diagrams. Another approach for visual analytics is to provide large high-resolution space in which to perform analysis [7], [19], [20]. In this work, the space around the user can be accessed as a form of externalized memory during the sensemaking process. While both strategies provide the ability for analysts to forage and create schemas while sensemaking, one limitation, as pointed out by Endert et al., is the lack of support for the entire sensemaking process from foraging to presentation [21]. In our work, we study how an immersive analytic prototype supports the sensemaking process as a whole in an attempt to design tools that can be used during the whole knowledge generation process.

2.2 Immersive Analytics for Sensemaking

Immersive analytics is the science of using immersive human-computer interfaces for analytic reasoning [2]. Immersive analytic tools are designed to help facilitate data exploration. Ultimately, these systems should help distribute cognition and decision-making during knowledge generation (sensemaking). The technologies used in immersive analytics can include large high-resolution displays, virtual/augmented reality headsets, CAVEs, tabletops, and other technologies that foster a more immersive environment than a traditional workstation (i.e., a laptop/desktop computer). Increased immersion can provide benefits such as better depth cues, decreased clutter, better spatial orientation, increased peripheral awareness, increased information, increased bandwidth, and increased engagement [22], [23], [24].

Skarbez et al. argue that most current immersive analytics systems should support knowledge generation through the use of abstract data visualizations [3]. There has been a large body of research on developing immersive analytic prototypes. One approach which focuses on interactive data visualizations is Cordeil et al.'s ImAxes [6] which utilized embodied interactions for creating visualizations in an immersive analytic system. Another approach by Satriadi et al. looks at geospatial data analysis within an immersive analytic prototype [25]. Another map-based approach by Yang et al. uses Tilt Map, where both 2D and 3D visualizations are used based on the users' interactions with the system to provide details on demand [26].

Along with using embodied interactions to create data visualizations, immersive analytics systems benefit from the vast space available to the user during analysis. In our previous work, Lisle et al. proposed Immersive Space to Think (IST) [27] a virtual reality system for immersive analytics of large text-based document sets. This system is an approach to immersive analytics that allows analysts to organize their thoughts into the immersive space around them for text-based analysis. In addition to our approach to immersive analytics, there has been additional work in understanding the use of space in these systems. More systems have been developed to harness the space around the user for organizing semi-structured information [25], [28], [29], [30] which have also found benefits in externalized memory.

Our work builds upon the existing Immersive Space to Think approach to understand how immersive analytic systems can support the entire knowledge generation process. Specifically, we try to understand how sensemaking changes over time within an immersive analytic system. In our work, we look at spatial layouts, navigation, and final presentation development across multiple sensemaking sessions.

2.3 Sensemaking Over Time

User studies have been conducted for visual and immersive analytics to evaluate these approaches' benefits to the knowledge generation process. While these user studies have provided many design considerations and insights, most fail to understand how users would work "in-the-wild". Two examples of case studies that evaluated longer-term analytic systems include Kang et al.'s analysis of Jigsaw [31] and Batch et al.'s evaluation of ImAxes [5]. Kang et al. found some exciting results which informed future design decisions. Batch et al.'s study found that participants' use of space changed based on the stage of the sensemaking process the participants were in. Overall they found similar findings to Andrews on "evidence marshaling" within the secondary curation step [7].

While these case studies have explored how participants use analytic systems in the wild, these studies have not looked at how analysis using an analytic system changes across multiple sessions. In an application such as intelligence analysis, analysis can be ongoing for months or years at a time [10]. To address the gap in the literature in multiple-session analysis tasks, we conduct a multi-session user study to understand how immersive analytic systems can support the entire sensemaking process. Our work attempts to understand how the immersive spatial structures or organizational patterns evolve from the shoebox stage in the sensemaking process to schemas. Additionally, we evaluate how the immersive space is transformed into a report through the presentation stage. Lastly, we seek to understand how immersive analytic prototypes can support the whole knowledge generation process and propose where additional features are needed to help in the complex analysis task.

3 The Immersive Space to Think Approach

The immersive analytic prototype used in this work builds upon our existing work on Immersive Space to Think (IST) [8], [27], [32]. IST provides a large immersive workspace to conduct a text-based sensemaking task. An example of the immersive space can be seen in figure 1. The text items are displayed as virtual documents that are pre-loaded onto a virtual bulletin board. They can then be arranged in 3D space during analysis to help analysts organize their thinking. The IST prototype allows analysts to create complex spatial schemes during their analysis to extract meaningful information from the documents provided. In our previous iteration of IST, we supported many different interaction techniques to aid sensemaking. These techniques included: *Document Movement*, *Highlighting*, *Annotations*, *Note Taking*, *Label Making*, *Wizard-of-Oz Text Input*, *and Searching*. Based on feedback from previous user studies, we added additional features to our system to support the analysts during their sensemaking.

3.1 New Interaction Techniques

Document Randomization In our prior work, we found participants had a strong document selection order bias [8]. To mitigate the effects of document selection order bias, we developed a randomized loading feature. When documents are loaded into IST, all documents are shuffled before placement onto the bulletin board. By providing this feature during our user study we hoped to prevent the effects of ordering bias.

Text Entry To address the limitations of the previous wizard-of-oz technique, we developed a new text-entry feature. Using a tracked physical rolling table and keyboard, as seen in figure 2, participants can enter text with a standard device and can move the keyboard around the immersive environment with them. The table and keyboard are represented with similarly sized 3D models in the virtual environment. However, the user's hands are not tracked. So users must place their hands properly on the keyboard using the sense of touch or by viewing their physical hands and keyboard outside the headset.

Copy/Paste to/from Clipboard To support the later stages of the sensemaking process, we wanted to provide the analyst with a way to export information from IST into traditional workspaces. We provide our users with a copy and paste button to get text from the immersive space onto the computer clipboard. From there, the users can paste the information in the immersive space or into other applications.

4 User Study

4.1 Goals and Research Questions

In our study, the primary goal was to understand how IST supports the complete sensemaking process, from foraging to report generation, over a longer period of time (multiple sessions). Additionally, we were trying to understand the relationship between the IST spatial structure and the report's structure. Lastly, we aimed to explore how users blend the use of traditional workspaces (laptops, keyboards, text-editors, etc.) with 3D immersive spaces. With these goals in mind, we generated the following research questions:

RQ1 - Spatial Structures

1) ***RQ1A*** *What spatial structures do analysts form in IST, and how do these spatial structures change over multiple sessions?*
2) ***RQ1B*** *How do the 3D spatial structures map to the 1-dimensional, hierarchical reports?*

RQ2 - Physical Navigation *How do analysts navigate the virtual space while conducting analysis and writing the report?*

RQ3 - Bridging Technologies *How do analysts use both traditional and immersive technologies simultaneously during the presentation stage of the sensemaking process?*

RQ4 - Interactions/Strategies *How do the interactions/strategies of participants correlate to the quality of the reports generated?*

Fig. 2. Left: Keyboard stand with wireless keyboard, HTC Vive Tracker, and example space for a controller. The keyboard is on a wheeled table which allows the participant to move the keyboard around the space as needed during their analysis. Right: Virtual representation of the keyboard. Attached to the keyboard are four menu options. These options from left to right are *New Note*, *New Label*, *Search*, *and Save*. These menu options are attached to the table and will move with the table as it is moved around the space.

These questions seek to understand how immersive analytics can be used to support the entire sensemaking process (foraging to presentation) while completing a dynamic sensemaking task. Additionally, these questions aim to address how we can better support the most time-consuming stage of the sensemaking process – Presentation – as quantified by Pirolli and Card [4].

4.2 Apparatus

In our experiment, we used a wireless HTC VIVE Pro Head Worn Display running on a desktop PC. The desktop PC had an Intel i7-8700k processor and an NVIDIA 1070 graphics card. The user held one Valve Index wireless controller in their dominant hand to interact with the documents. For text input, participants used a wheeled table with a wireless keyboard, as seen in figure 2. To provide better support for text entry, small amounts of foam were cut off the HTC VIVE Pro headset to allow users to look down and see their fingers on the physical keyboard. Additionally, for writing both the outline and report, participants used a 2019 Mac Book Pro with Chrome Remote Desktop connected to the desktop PC. A SteamVR 2.0 Lighthouse tracking system tracked user movements, which covered a four-by-eight meter space.

4.3 Experimental Task

This experiment aimed to understand how immersive analytic systems can support the dynamic nature of the entire sensemaking process, from foraging to presentation. For the task, participants were asked to analyze a set of text-based documents, of which our participants would have no prior knowledge, with the goal of writing a report of their findings at the end. The task provided to our participants was as follows:

Today is April 27th, 2003. You are an intelligence analyst working for the federal government. It is believed that terrorists are planning an imminent attack on the United States. Other analysts have gathered a set of potentially relevant documents containing information about potential suspects. These documents have been loaded into the Immersive Space to Think system for your analysis.

Your goal is to analyze the information and develop a specific hypothesis about any potential planned terrorist attack(s) against the US. Your hypothesis should identify ***who, what, when, and where****.*

Over the course of 3 sessions, you will develop a report for the Office of Homeland Security. To do this effectively, you must prepare a defensible and persuasive report that describes exactly what your conclusions are based on the documents provided. During session one, you will focus on analyzing the documents and preparing a specific hypothesis of your findings (who, what, when, and where). During session two, you will continue your analysis and prepare a written outline of your findings. During session three, you will finalize your analysis and write a 1-2 page report of your findings. Your report must state what action or actions the terrorist(s) are planning, where they will occur, and when they will occur using evidence and citations from the documents provided. Our hope is that your report can be used to thwart the terrorist(s) threat.

4.4 The Dataset

The goal for the dataset was to be complex in its features making it challenging for analysis. Ideally, this dataset should have many different features which force the participant to use the space around them to create organizational structures that are meaningful, similar to the organization structures seen in Space to Think [7] and previous iterations of IST [8].

The dataset we used for this study is a fictional intelligence analysis dataset called **Sign of The Crescent** which contained a total of 40 documents. Each document is about a paragraph in length. The features of the dataset include aliases, addresses, phone numbers, bank account information, places of business, etc. Additionally, this dataset contains both relevant documents (23), and distractor documents (17). Along with relevant/irrelevant documents, there are three major plotlines contained in this dataset connected through documents called coordination documents. Plotlines are defined, in this dataset, by the location in which the events are happening (i.e., Atlanta, Boston, or New York). Plotline 1 contains five documents, Plotline 2 contains seven documents, Plotline 3 contains four documents, and there are seven coordination documents.

Along with all of the features described above, the documents purported to come from three different reporting organizations: FBI, CIA, and Sanctioned Intercepts. There were 24 FBI documents, 11 CIA documents, and 5 Sanctioned Intercept documents.

4.5 Participants

We recruited eight university students for our study. We had two females, five males, and one other, with a mean age of 22.6 (standard deviation of 3.85). Five of the participants had tried VR or AR technologies once or twice; one participant had tried VR or AR 3-10 times, and two participants had tried VR or AR technologies more than 10 times. All participants had normal or corrected vision. The participants were recruited using internal university listservs. This study was approved by Virginia Tech's institutional review board.

Participants were compensated for their time in this study pro-rated by how many sessions they completed.

Session 1 – $20.00, Session 2 – $20.00, and Session 3 – $30.00. The payment was made in cash at the end of the experiment.

4.6 Measures

Before the study, participants were asked to take a pre-study questionnaire that asked them general background information such as sex, age, VR/AR usage, etc. A log file was generated during the study that tracked the participant's head, controller, and keyboard position and orientation. This data was reported at a rate of about 10 logs/second. Additionally, this log file tracked every action the participant conducted within the immersive space, i.e., highlighting, moving a document, or searching.

In addition to the log file, a record of the spatial layout of all documents was generated once a minute for the entirety of the user study. These save files created a minute-by-minute snapshot of the participant's analysis in the immersive space.

A screen recording was taken from the first-person point of view of the participant conducting the analysis. After each session, the participants were interviewed about session-specific questions, and after the study, the participants took part in a post-study semi-structured interview.

Lastly, we also collected both an outline (generated during session 2) and a report (generated during session 3) of the participant's findings from their analysis. These documents were created using Google docs with the laptop placed on the tracked table.

In addition to the data collected for this study, we worked with a set of professional intelligence analysts to develop a grading rubric for the final reports. The rubric was designed to produce subjective quality scores and objective correctness scores. The quality score measured conciseness, persuasiveness, clarity, completeness, relevance, and bias—the correctness score measured plotline level details (Who, What, When, Where). A copy of the report grading rubrics can be found in the appendix.

4.7 Procedure

The user study was broken down into three 75-minute sessions. Participants were encouraged to schedule all 3 sessions in the same week and if possible on 3 separate days. Each session was broken down into different stages: pre-session, tutorial, session, and interview. Details on each of the sessions can be found below.

4.7.1 Session 1

Pre-Session Before arrival each participant was screened for our COVID mitigation protocol. Upon arrival, participants were asked to review the informed consent form and ask questions if they had any. After signing the form, participants were asked to fill out a questionnaire to answer some demographic and background questions.

Tutorial Participants were trained on how to use both the HTC VIVE Pro headset and the Valve Index controller. After the training, participants would don the headset and begin the IST tutorial. Using a practice dataset, the experimenter taught the participants the immersive boundary limits for walking, how to manipulate documents, how to use the wheeled keyboard/table, and all of the features related to the IST system. After reviewing all of the features, participants were given 5 minutes to practice using the features, walking with the headset, and typing using the keyboard on their own.

After finishing the tutorial phase, participants were asked to take off the headset and have a seat while the experimenter loaded up the experimental dataset. During this time, the participants were given a print out of the experimental task see section 4.3. Participants were encouraged to ask questions if clarification was needed and when ready, participants were asked to don the headset once more to begin their analysis.

Session Before starting the session participants were told they would be spending today's session on analysis and develop some initial hypothesis. Participants were given about 40 minutes for this task. Participants were encouraged to ask questions on the task or the system if they needed help.

Interview Session 1 ended with a 5-minute post-session interview. This interview phase was designed to gather information about their overall strategy for analysis and overall spatial structures/organizational pattern that they had formed.

4.7.2 Session 2

Pre-Session Session 2 began with a quick pre-session questionnaire which asked about tiredness and how they were feeling.

Session The goal of today's session was to continue with analysis and develop an outline of their findings. The participants had about 50 minutes for analysis, 15 minutes for their outline generation, and 5 minutes for the post session interview.

During the outline stage, the participants used a laptop on the wheeled table stand to write their outline with Google docs. In order for the participant to see the laptop, participants were encouraged to lift the headset lenses off their eyes and rest the headset on the top of their head. The participants were encouraged to use the immersive space as much as needed while developing the outline and were able to use *copy and paste* features to get text from the immersive space and paste it into their working outline.

Interview This session ended with a post-session interview which aimed to answer questions on strategy, spatial structure/organizational patterns. Additionally, this interview asked questions about the transformation process used to move from the spatial organization of documents and notes to the outline.

4.7.3 Session 3

Pre-Session Session 3 began with the same pre-session questionnaire as session 2. Following the questionnaire, participants were reminded that they would be writing the report of their findings during the session.

Session The goal of today's session was to develop a final report of their findings. Participants were given about 1 hour to write the report of their findings. During this time, the participants were able to use the headset to see their immersive space, and use the tracked laptop and table to write their report in a Google doc.

Interview After completing the report, participants took part in a final 15-minute semi-structured interview. During this interview they answered questions about the task including: overall strategy, overall spatial layout, and how the layouts changed over time. Additionally, the participants answered questions about they system as a whole and what additional features would be helpful for analysis.

During each session, participants were given a time warning at the halfway mark and given the option to take a break if needed. Additionally, time calls were given at 15 minutes, 5 minutes, and 1 minute before the end of the session.

5 Results and Discussion

To address RQ1, we looked at the overall spatial structures formed by our participants, how the spatial structures changed over time, the deeper organization patterns used during analysis, and mapping of the spatial layout to the report structure. To address RQ2, we examined how the user moved through the space and how much time they spent in different parts of the space across sessions. To address RQ3, we looked at how users bridged multiple technologies. Finally, to address RQ4, we investigated Report Scores and the overall strategies of the participants.

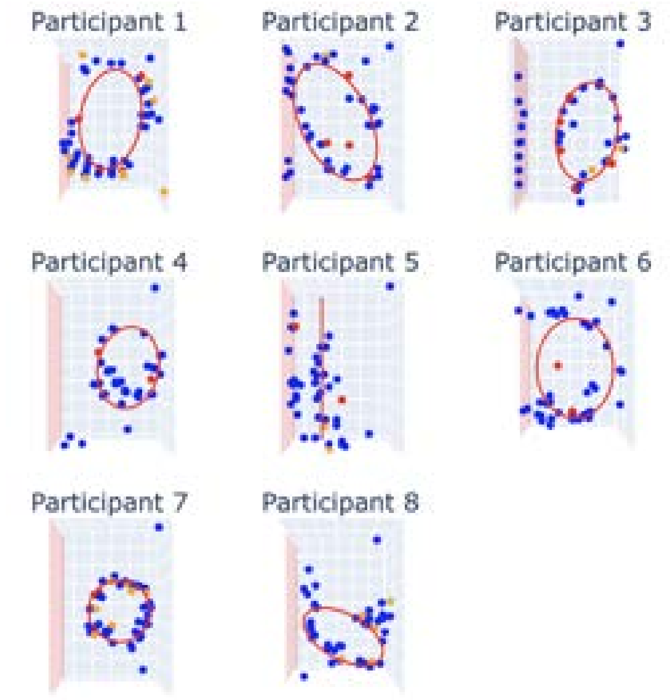

Fig. 3. All participants' final spatial layouts formed during their analysis. These spatial layouts are portrayed using a top-down scatter plot. The red area on the left side denotes the bulletin board. Each document is represented using a blue dot, while notes are red and labels are yellow. The red curves approximate the overall organization structures formed by the participants.

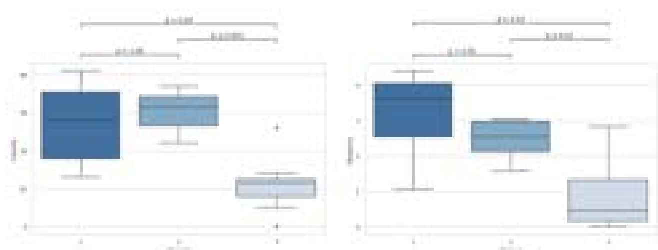

Fig. 4. Number of documents moved during each session of analysis (Left). Distances (meters) that participants moved each document in each session (Right).

5.1 RQ1A: Spatial Structures and Change Over Time

5.1.1 *Spatial Layouts*

Using a bird's-eye view of each participant's immersive space after the task was complete, we can see the overall organization pattern each one used for analysis. We examined the overall placement of the documents, notes, and labels to look for patterns within the data. In previous work conducted by Lisle et al. [8], there were three overall spatial layouts formed by participants: Semi-circular, Environmental, and Planar. Using these organizational structures, we categorized each of our participants' final spatial layouts. In our study we had seven semi-circular/circular layouts and one environmental layout (P5). Each of the final spatial layouts can be seen in figure 3.

5.1.2 *Change Over Time*

In the development of the experimental task, we aimed to target different stages of the sensemaking task in each session of the study. Session 1 focused on the foraging and shoe box stages of the sensemaking task. Session 2 continued foraging and began the schema formation stage. Lastly, session 3 focused on the presentation stage of the sensemaking process. Diving deeper into RQ1A, we wanted to understand how the organization patterns (spatial structures) changed across time/ across the sensemaking task. In order to evaluate change over time, we looked at overall document movement patterns as well as overall organizational patterns.

We first examined the number of documents moved in each session, as seen in figure 4. We have a median of 28 documents moved during session 1, 31.5 during session 2, and 11.5 during session 3. Additionally, we see a statistically significant difference between sessions 1 and 3 ($p = 0.04$) and sessions 2 and 3 ($p < 0.001$) using T-Test for Independent Samples with Bonferroni's Correction.

We also looked at the distance that those documents moved, as seen in figure 4. The median movement distance in session 1 was 3.61 meters, session 2 was 2.54 meters, and session 3 was 0.44 meters. There were significant differences between sessions 1 and 3 ($p = 0.03$) and sessions 2 and 3 ($p < 0.01$) using T-Test for Independent Samples with Bonferroni's Correction.

These findings show that participants moved the most documents early on in the sensemaking process. Additionally, these early movements that the participants make are long movement distances. However, as the participant progresses further into their sensemaking, they make fewer document movements with smaller overall document movement distances. We believe this matches the overall sensemaking process of forming a shoebox, schemas, and re-

representations of those schemas to formulate a hypothesis of findings. Overall, these results show the most refinement of the spatial layouts occurring during sessions one and two. We found more minor refinements of the spatial layouts during session 3 when the participant was focused more on the report writing.

We also analyzed the spatial organization at the beginning, middle, and end of each session for each participant. An example visualization (for P4) can be found in figure 5.

Our primary finding from this analysis was that participants' spatial layouts became more refined over time. These refinements create more structure within the immersive space (e.g., turning a cluster into a timeline column (Figure 7). This suggests that as incremental refinement occurred, the location of IST artifacts became more nuanced and purposeful. Using this change over time visualization, we are able to see these small refinements in the overall spatial layout made by the participants. In figure 5, for example, we are able to see a subset of documents that are pulled closer to the center of the cylinder from the start of session 2 to the middle of session 2. Additionally, we are able to see more small refinements when we look from the end of session 2 to the end of session 3. While this is only one participant's change over time, we saw these incremental refinements of the spatial layout in all of our participants.

In addition to looking at the quantitative data collected, we also reviewed the interview questions: **1) How did you organize documents to extract meaningful information over the course of this analysis? And 2) Did your spatial layout change over the course of multiple sessions? If so, How?** The responses to the interview questions supported the notion of incremental refinement. For example, P4 stated:

> *"I guess on the first day, I organized all the documents into different organizations so CIA, FBI, then correspondence or sanctioned intercepts. On the second day, I started deriving all the different documents that I thought were useful, and then I just organized them into a timeline. I started connecting names from the different documents from the different organizations that I had previously organized on the first day. Then today [session 3], I just went off the outline I created yesterday and continued to connect names and relationships across all the different documents."*

Additionally, P1, stated that:

> *"At the beginning, it was all very scattered, and I was trying to make sense of all the documents and how they related to each other. By session two, I was starting to form clusters around the left side with relevant topics and then eventually settled on columns because they more compactly organized my thoughts and then created this layout. Session 3 was mostly the same because it seemed like this layout was working just fine, and I was able to extract the information quickly. Then all these other documents that I consider to be less relevant just stayed more or less scattered around here on the other side [right side of the space]."*

Lastly, we also looked at how, if at all, the overall organizational pattern changed over time. We found that 7 out of 8 participants who started with a given organizational pattern (i.e., semi-circular or environmental) ended with the same overall organizational pattern. This could be due to factors such as the time limit of the task or inertia (participants: only being willing to change the way they were analyzing the documents if there was a significant perceived benefit for doing so). We suggest additional longitudinal studies to understand how overall organization pattern changes from session to session as participants become more familiar with an immersive analytic tool. This would provide a deeper insight into the organizational patterns and sensemaking strategies users would use "in-the-wild" as they become more comfortable and even an expert with immersive analytic tools such as IST.

5.1.3 Other Spatial Organization Features

We were also interested in how the spatial layouts reflected the content and properties of the text documents including relevance, plotlines, reporting agency, and chronology.

Relevant vs. Distractor Documents

One of the features of our text-based dataset is a set of distractor documents. To understand the spread of the documents, we calculated the average distance of all the distractor and relevant documents from the center of the space. Distractor documents were on average 2.60 meters from the center (SD = 0.798 m), while relevant documents were on average 2.24 meters from the center (SD = 0.844 m). We found that relevant documents were significantly closer to the center of the space ($p < .001$) using T-Test for Independent Samples with Bonferroni's Correction.

Important documents are organized closer to the center of the immersive analysis space, which is where the participant was placed at the start of their analysis. This suggests that we could determine a document's relevance to the overall analysis based on its physical location in the immersive space. This knowledge could be used in the future with semi-automated features to provide insight to users based on the documents closer to the center of the space.

Plotline Encodings

We also wanted to see where documents that belong to a specific plotline appear in relation to other documents in that plotline. In other words, we wanted to evaluate the clustering that may occur between documents related to the same topic. Details on the dataset's plotlines can be found in section 4.4.

Using the plotline encodings, we generated plots similar to those seen in figure 5, which illustrated how each plotline's spatial organization changed over time. We found that while documents within plotlines tend to be clustered together, not all documents from a single plotline end up in a single large cluster. Often the documents within a plotline are organized into multiple small clusters organized around the immersive space. Additionally, we found that the plotline clusters are not clearly defined. Documents from different plotlines are often mixed in with each other in the clusters formed by our participants. Lastly, as participants get further into their sensemaking process, the small clusters of documents related to the same plotline become

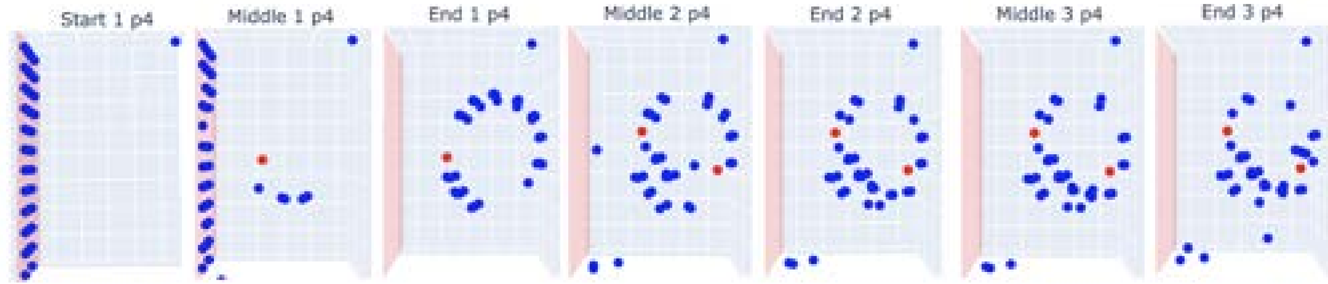

Fig. 5. Evolving spatial organization for participant 4. From left to right we have the start, middle, and end (session 1) middle, end (session 2) and middle, end (session 3).

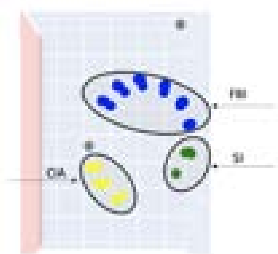

Fig. 6. Reporting agency of each of the documents in P4's spatial layout after session 1. Yellow represents CIA, Blue represents FBI, Green represents SI, and gray is the prompt/note.

more defined, with fewer distractor documents mixed in.

Reporting Agency Organization

Another organizational strategy that we looked into was if the reporting agency (CIA/FBI/SI) affected the spatial structure formed by our participants. We found that for one of our participants, P4, the reporting agency largely affected their spatial layout. After day 1, they had sorted each of the documents by reporting agency into a sphere around them, as reported in their interview (section 5.1.2) and as seen in figure 6.

After this organizing by reporting agency, the participant then began to move documents in the same plotline closer to each other and out of their initial organizational clustering. While we only had one participant organize their documents by reporting organization, this strategy of developing their organizational structures could be used to inform future design ideas for IST and similar immersive analytic systems. One feature which could be developed is an automatic sorting feature in which users can sort based on different features of the dataset.

Timelines

Another common strategy we found that our participants used for organizing their documents was to use chronological order. Often, these timelines were formed in columns within the space. In total, six of our participants organized things in either chronological or roughly chronological order within their final spatial layout. An example of a column-based timeline formed by our participants can be seen in figure 7. Additionally, P4 and P1 referenced their column timelines in the interview responses in section 5.1.2.

Fig. 7. Two columns that are organized into timeline order, on the left the top document is posted on April 18, and bottom on April 22. The right hand column goes from April 24 (top) to April 27 (bottom)

Since this task was focused on reports from specific dates, we believe that our participants were forming these timelines to develop an understanding of the evolution of the events. This suggests we could add additional features to our system to help support the user during the sensemaking task. A built-in timeline generator might be useful for participants in a task where time is a relevant factor, such as intelligence analysis or news analysis.

Trash Pile

Finally, participants utilized trash piles (clusters of irrelevant or unwanted documents) in their spatial organization. These piles are often located in the extremities of the immersive space. Some of the common places for trash were in the corners or along the sides of the tracked area. An example of a trash pile can be found in figure 5 in the bottom left-hand corner of the plots starting in the middle of session two. Additionally, trash piles are referenced by P1 in their interview response seen in section 5.1.2. These trash piles were found in five of the participant's spatial organizations. In addition to creating trash piles, three participants placed documents that were not needed in their analysis back on the bulletin board. The use of bulletin board and trash piles were not mutually exclusive.

Overall, in our analysis of RQ1A, we found that participants formed similar spatial patterns to those seen in [8]. We also found that the spatial layouts change over time with most refinement happening between session 1 and 2, and smaller refinements happening between session 2 and 3. Additionally we found many different sub-organizational strategies within the spatial layouts; these included plotline organization, relevant/distractor document organizational patterns, reporting agency organization, timelines, and trash piles. We do not claim this is a comprehensive list of all strategies used by our participants. However, it is clear that variety in organizational strategies is possible because IST provides great flexibility and freedom of choice for completing a dynamic and complex task such as intelligence analysis.

5.2 RQ1B: Mapping of Spatial Layout to Report Structure

To address question RQ1B, we were interested in how the organizational layout formed within IST mapped to the reports that were generated by our participants.

One approach to understanding the mapping was through the interview question: **Does your spatial layout reflect the organization of your report? If so, how?** Two participants mentioned a clear organization that was reflected in their report, such as P1 stating, *"Yes, I started right here and then, I just kept moving this way [Left → Right].... with a very natural flow of information."* Additionally, two participants reported a rough mapping between spatial layout and report, such as P5 stating, *"It would mainly show the documents that I looked at most, it is a bit messy, but I think the information I used in the report will be closest to me or the desk"*. Four participants said they did not use any clear mapping between the two, such as P8 stating, *"Not actually, I think maybe each label would be one of the findings"*.

Next, we looked at the citation order of the documents within the written reports and compared the order to the location of the documents in the immersive space.

For each participant we developed a document reference order, which was on average 13.75 documents long (SD = 2.45). Using this reference order, we drew a line through their immersive spatial layout to understand the transformation of the 3D space to the 1D hierarchical reports. Additionally, we were interested to see patterns between documents cited in a paragraph together. An example of the scatter plot with the reference line and paragraph coloring can be found in figure 8.

We calculated the length of each reference path starting at the first document cited in the report and tracing the line to the last document cited in the report; we also normalized this length by the total distances between all documents in the immersive space (accounting for spread of documents).

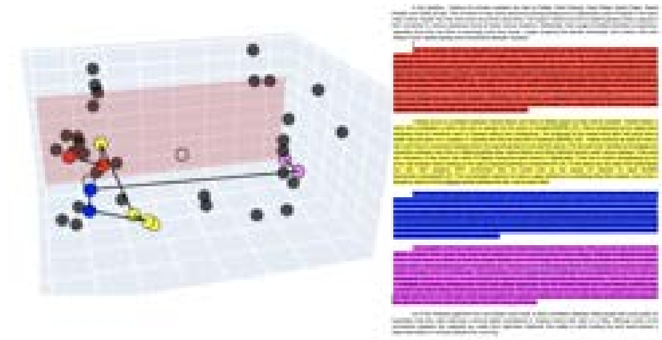

Fig. 8. 3D scatterplot of P6's spatial layout with the document reference order traced. Gray documents were not referenced in the report. The red rectangle represents the bulletin board, and the open gray circle represents a free-standing note. Colored documents were referenced in the report coordinated with the paragraph coloring on the right.

Overall, we found participants had a average length of 21.77 meters (SD = 9.58) on the reference path with a normalized value of 0.13 meters (SD = 0.04). While we were expecting to see clear transformation paths from the spatial layouts to the reports, we only found patterns for four participants. These patterns (either roughly Right → Left or roughly Left → Right) had few intersections on the reference line. An example of the roughly Left → Right pattern can be see in figure 8. The remaining four participants had no distinct pattern to their transformation path. This could be due to participants having freedom in organizing their immersive space, and potentially not thinking about a linear report while creating the spatial organization. Such layouts would not always correlate with a clear report structure. Additionally, the tool was unfamiliar to users, and they may need to practice to fully develop organization patterns which make the reporting stage of the sensemaking process flow seamlessly. Future studies with more expert participants could be conducted to further evaluate the mapping between spatial layout and report.

We were also interested to find whether documents that were cited near each other in the report tended to be close together in the spatial layout. We would expect to see this due to clustering based on similar information; however, we were surprised to see that documents that are cited within the same paragraph do not always appear next to each other in the immersive space. As users become more familiar with the tool, we might see more organization based on report structure. Overall, the relationship between the immersive spatial layout and the report is more complex and needs further study.

5.3 RQ2: Physical Navigation

To address RQ2, we examined how participants navigated the virtual space while conducting both their analysis and their report writing.

Participants' movement through the space was reflected in the log files. We smoothed the data from the logs to get one log per second. Using this data, we calculated the overall distance that each participant moved during each session. We then normalized the distance walked by the total time spent in the headset. Overall, we saw no difference

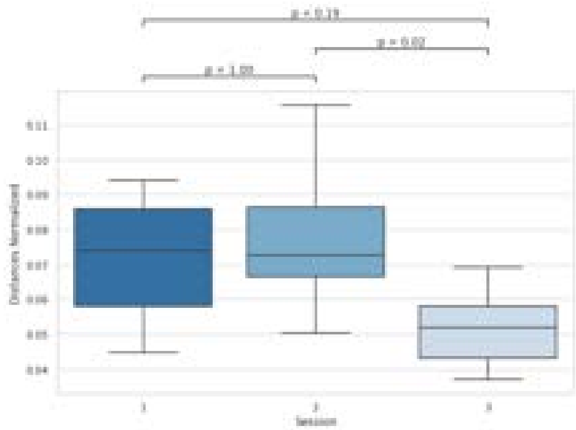

Fig. 9. Participant walking movement normalized by time spent in headset per session.

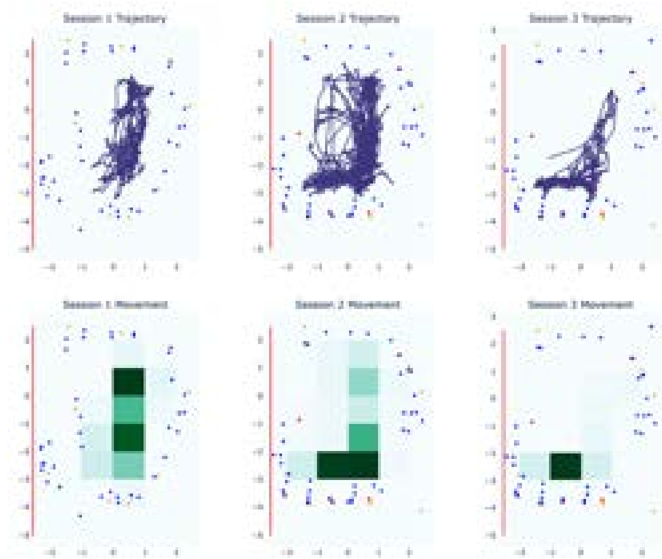

Fig. 10. Trajectory of movement for P1 during each session (top row) and the dwell times of the participant across each session (bottom row) where a darker color indicates more time spend in that location. Each plot has the document locations at the end of the session represented with blue (document), yellow (label), and red (note). The red line denotes the bulletin board.

between the normalized walking distance between sessions 1 and 2, or sessions 1 and 3, but we did see a statistically significant difference between sessions 2 and 3 ($p = 0.02$) using T-Test for Independent Samples with Bonferroni's Correction. See figure 9.

We also looked at both the trajectory and the dwell time (time spent in each region of the workspace) as seen in figure 10. The overall trajectories revealed two categories of movement pattern. Four participants navigated through the majority of the space provided during their analysis, while the other four participants remained mostly stationary during their analysis. In the figure, we can see that the participant (P1) navigated the majority of the space provided, and as the sensemaking process evolved (session 2 → session 3), we see less navigation of the space and more time spent in one location (figure 10), as indicated by one dark green area. We saw this pattern in the four participants who navigated the space during their analysis. The remainder of the participants had similar dwell times across all three sessions, which was largely due to minimal walking movement around the overall space.

While we did see an overall downward trend in number of places dwelled, from session 1 to 3, our participants still utilized the space to reference information far from the dwelled location, as suggested by the trajectory lines, which span the majority of the space inside the spatial layout of documents. This suggests that the ability to reference information organized in the space is not limited to the early stages in the sensemaking process.

Similarly, we analyzed participants' use of the wheeled table and keyboard during their analysis. Overall, we found that the four participants who navigated the space during their analysis also moved the keyboard around. The participants who tended to stay stationary also had a primarily stationary keyboard. These results matched the findings from the participant's navigation across sessions.

Overall, we found that participants navigated the most space during sessions 1 and 2, while in session 3, the participants were more stationary, due to writing the report. However, while more stationary, the participants still navigated through the space to use the reference material around them. Our findings suggest that participants continue to search for support and reevaluate their hypotheses while completing the presentation stage in the sensemaking process.

5.4 RQ3: Bridging Technologies

RQ3 asked how participants would make use of immersive and traditional technologies simultaneously to complete the task. We observed three strategies for bridging the technologies during the report writing stage:

1) **Reference**: Entering and exiting the immersive space multiple times by lowering or lifting the headset, in order to reference information in the virtual environment as needed during report writing.
2) **Export**: Creating a note in the immersive space with the information that the participant needed for the report and exporting that note into the Google doc using the copy and paste feature.
3) **Hybrid**: A combination of the two techniques where information was offloaded to or taken from an IST artifact and moved into the Google doc on multiple occasions during the report writing stage.

Six participants used the reference technique, one used the export technique, and one participant used the hybrid technique for the report writing process. While raising and lowering the VR headset repeatedly is not ideal, this probably reflects the perception that creating content directly in the Google Doc using familiar tools was preferable to creating content in the immersive environment and then exporting it. While there are current limitations in the technologies available, using augmented reality (AR) or a pass-through view of the laptop within the virtual environment could provide the benefit of spatial organization in the world around the user as well as the benefits of easy bridging between traditional and immersive technologies, especially for users who utilize the reference strategy.

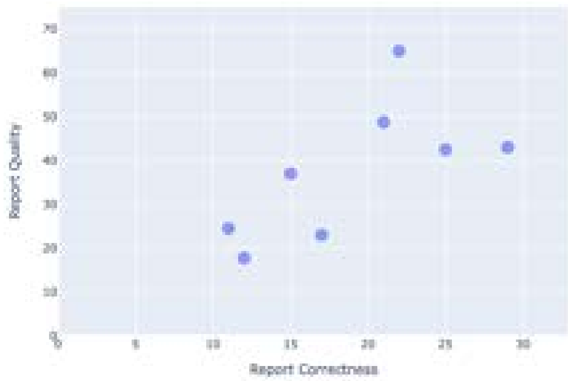

Fig. 11. Report Correctness score vs. Report Quality score.

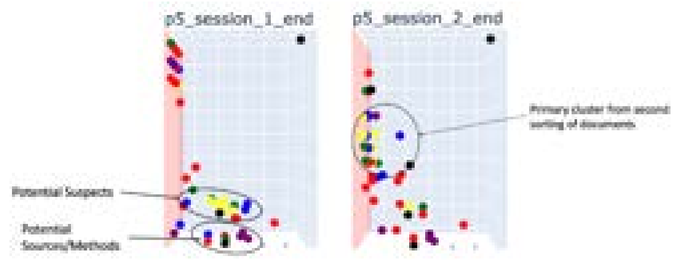

Fig. 12. P5's Spatial Layouts: end of session one (left), and end of session two (right). The colors represent plotline encodings where red represents distractors, blue/green/purple represents plotlines, yellow represents coordination, and black represents notes/labels/prompt.

5.5 RQ4: Report Scores and Strategies

Quality To grade the reports for quality, we worked with a set of four professional intelligence analysts. Before grading the reports, the experimenter met with the analysts to onboard them to the grading process. They were then each provided the rubric in a Google forms format, a document which specified the order in which to grade the reports (randomized for each grader), and a PDF copy of each of the participants' reports. The analysts were given a total of two weeks to complete the grading.

Correctness Using the correctness rubric, the experimenter graded each report generated by the participants. Reports were graded in a randomized order.

5.5.1 Scores

There was a total of 75 points possible for quality. We had an average score of 37.69 (SD = 15.62). For correctness, there were 33 points possible, and we had an average score of 19.13 (SD = 6.17). Figure 11 plots the quality and correctness scores for each participant. There is an overall positive correlation between correctness and quality scores using Pearson's correlation coefficient; however, these results are not statistically significant ($p = 0.07$).

To understand what factors might influence report correctness/quality, we ran correlation analyses between the report scores and various interactions performed by the participants. The interactions we looked at were the number of highlights, notes, searches, distance traveled, labels made, highlight length, note length, time spent grabbing documents, and number of documents grabbed per session. We saw a significant negative correlation (-0.77) between the number of searches made during session three and the overall report score using Pearson's correlation coefficient ($p=0.015$). This means that using more searches in the report writing stage was linked with a lower overall score, suggesting that participants who relied on the search tool instead of externalized memory in the last session performed worse on the reporting task. None of the other correlations were statistically significant.

We also investigated possible correlations between report score and other features, including spatial organizational pattern (environmental/semi-circular), the shape of the reference path, length of the reference path, the overall spread of spatial layout (total distance between all documents in immersive space), distances between documents within a plotline, number of distractor documents referenced in the report, and number of topic switches in the report (switches between plotlines/distractors). We found a significant positive correlation (0.72) between the reference path shape and the overall report grade using Pearson's correlation coefficient ($p = 0.043$). This suggests that the more organized the reference path of the spatial layout to the report, the better a participant scored on the report rubrics. None of the other correlations were statistically significant.

Finding few significant correlations between the interactions/features of our participants and the overall grades received on the reports could be due to the small participant pool (resulting in limited power for statistical analysis), or the diversity of strategies used by participants. The IST system may provide users with the flexibility to complete the task well with various analysis strategies.

5.5.2 Overall Participant Strategies

Using screen-captured videos of analysis sessions, we developed a narrative description of the overall strategy that each of our participants used for their analysis. In this section, we highlight the strategies of our two highest and two lowest report scoring participants.

Highest Scorers' Strategies

Participant 4 began his analysis by reading the content of the first few documents on the bulletin board. After analyzing the content of the documents, he organized the documents into 3 different categories in a sphere around him. These categories aligned with the three different reporting agencies as seen in figure 6. Additionally, the participant placed the documents into chronological order within their categories. Once the categories were established, the participant created a note capturing relevant names and aliases for all the documents within a category. During the development of the notes, the participant moved documents with key characters in between two clusters (creating a new cluster). Additionally, the participant used the search to find more documents relating to the key characters, which were moved into the new cluster. During the report-writing stage, the participant used the reference strategy to incrementally get information from the immersive space into the written report.

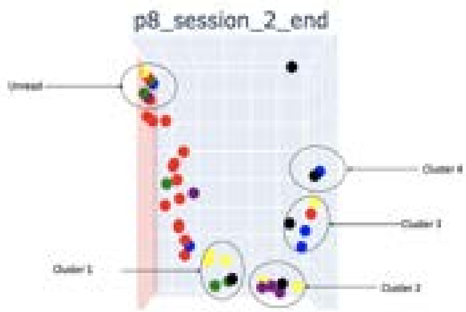

Fig. 13. P8's spatial layout after the end of session two. Color encoding is the same as figure 12.

Participant 5 began her analysis by sorting the documents provided. She would select a document off the wall, read it, and place it into the environment around her. Once she gained enough information on the dataset, she created labels to help organize the sorted documents as seen in the left side of figure 12. As she continued with sorting, she cross-referenced information within the groupings based on people, places, and phone numbers. After completing her initial sorting, she started cross-referencing documents between the groupings, and moved documents into a new cluster in the center of the room (second sorting) as seen in the right side of figure 12. Once the documents were sorted a second time, small refinements of document location occurred and highlights were applied to some more relevant documents. During the report-writing stage, she utilized the reference strategy to incrementally get information from the immersive space into the written report.

Lowest Scorers' Strategies

Participant 7 started his analysis by taking documents off the wall, reading them, highlighting names, places, and phone numbers, and placing them in the immersive space. When the number of names became cumbersome, he created a note in which he kept track of all names seen within the documents. A small amount of cross referencing between documents occurred before placing the document into the space. Once all of the documents were off the bulletin board and sorted around him, the participant used the search feature to find connections between documents. During the final session, he continued with analysis and spent time focusing on offloading information into an IST note. This participant used the export strategy to bridge between the immersive and the traditional space.

Participant 8 began her analysis by selecting documents off the wall, highlighting names, places, and phone numbers, and putting the documents back onto the wall. Additionally, during the initial reading, she would offload some information into the notes attached to the documents. After reading a majority of the documents, she created some distinct clusters on one side of the room. By the end of session two, she had created four distinct clusters and labels were applied to each of the clusters as seen in the right side of figure 13. There were still some documents that were left unread on the bulletin board at the end of session two. During the final session the participant continued to refine her spatial layout, and during the report-writing stage, she used the reference strategy to access information within the immersive space.

One commonality between our two highest scorers was creating meaningful organizations early on in the sensemaking process and refining those structures as knowledge was learned. Another difference between our two highest scorers and the lower scorers was when highlights were made. Our lowest scorers tended to highlight a lot of information during the first reading of the documents. We believe that this may have led to distractor information being highlighted as important and therefore distracting the participant from the main storylines.

We have chosen to share the overall strategies for these participants not just to highlight some commonalities/differences but to reinforce how immersive analytic systems provide flexibility in completing sensemaking tasks. In our study we had eight different participants, which led to eight different strategies for analysis! While there are similarities within participants, each user was given the flexibility to complete the analysis in a way that worked for them.

6 Limitations

One limitation of this work is that intelligence analysis is a complex task, and our participants were not trained specialists in this area. This may have led to low analysis scores and different organizational patterns than we may expect to see with professionals. More work would need to be done to understand the strategies that professionals use in an immersive system such as IST. Another limitation of this work is the text-entry system. While we provided the users with the ability to enter text using the wheeled keyboard and table, the participants still struggled to see their fingers on the keyboard despite our efforts to improve visibility by removing some of the face cushion on the lower portion of the VR headset. Lastly, due to the COVID pandemic, we had a relatively small participant pool. More work could expand this study to provide more power in statistical analyses.

7 Conclusions and Future Work

This work examined how the IST approach supports the sensemaking task from foraging to reporting. Our analysis found that participants formed both environmental and semi-circular spatial organizations, and these organizations are incrementally refined in later stages of the sensemaking task. The refinements that occurred late in the sensemaking process include a few documents moving a short distance compared to the movement patterns seen in sessions one and two. Additionally, we saw the most navigation of the space occurring in sessions one and two and less movement with more dwell times in session three. Next, we found that our participants used three different strategies to bridge the immersive space and the traditional technologies (laptop and text-editor) during the report writing stage. These strategies included reference, export, and hybrid.

In the analysis of the reports developed using IST, we compared the spatial organizations and the report structures. We found that half of our participants had a roughly linear transformation path with few intersections along the path. We found an overall positive correlation when comparing these transformation paths to the overall report grade. Additionally, we found a negative correlation between the number of searches within the third session and the overall report score when evaluating interactions and report scores. Lastly, when assessing the overall strategies that our participants used, we found that the IST approach provides flexibility in the method used for analysis.

We believe the results from our study show promise for immersive analytic systems, such as IST, in providing flexibility in text-based analytic tasks. Based on our findings in this study, we suggest the following work for improving immersive analytic systems. First, we believe that immersive analytic systems could benefit from the use of AR technologies. We suggest a comparative study to evaluate the differences between VR/AR technologies. Second, we believe that immersive analytic systems such as IST could benefit from semi-automated clustering algorithms. These algorithms could help users with organization as well as provide the ability to move multiple documents at once. Lastly, we propose to conduct a study using professional analysts to understand differences between novice users and professional users. By understanding the strategies and organization professional analysts use, we could develop immersive analytic systems which provide real-time feedback and support during the sensemaking task.

Acknowledgments

This material is based upon work supported in part with funding from the Laboratory for Analytic Sciences (LAS). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the LAS and/or any agency of the United States Government.

This work was supported in part by NSF I/UCRC CNS-1822080 via the NSF Center for Space, High-performance, and Resilient Computing (SHREC).

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Kylie Davidson is a Ph.D. Student at Virginia Tech. She is a member of the Center for Human-Computer Interaction (HCI) and the Sanghani Center on campus. She focused on HCI research as it is applied to virtual/augmented reality for the analytics. She is a student member of the IEEE Computer Society.

Lee Lisle is a Ph.D. Candidate at Virginia Tech. He focuses on human-computer interaction research as it applies to mixed reality with a speciality in 3D user interfaces and immersive analytics of non-quantitative data.

Kirsten Whitley works in the Department of Defense, researching visual analytics for intelligence and cyber analysts, recently concentrating on immersive analytics and its opportunities for government use cases. Her successes stem from combining cognitive task analyses of analysis expertise with emerging technology. She has also supported the visual analytics research community, sponsoring Visualization for Cyber Security (VizSec) in its early years, serving as VizSec 2014 general chair and introducing cyber use cases to the annual VAST challenge competition (2010-2012). She earned her Ph.D. in computer science at Vanderbilt University.

Doug A. Bowman received the PhD degree in Computer Science from Georgia Tech. He is a Professor in Department of Computer Science and Director of the Center for Human-Computer Interaction, Virginia Tech. He is a member of the IEEE Computer Society

Chris North is a professor of computer science with Virginia Tech. He is the associate director of the Sanghani Center. His research seeks to create effective methods for human-in-the-loop analytics of big data. His work falls in areas of visual analytics, information visualization, human-computer interaction, large high-resolution display and interaction techniques, and visualization evaluation methods, with applied work in intelligence analysis, cyber security, bioinformatics, and GIS.