Immersive Space to Think: The Role of 3D Space for Sensemaking

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Abstract
Prior work showed the value of large 2D high-resolution-display spaces to support the sensemaking process, by providing a "Space to Think" in which analysts organize information and externalize their thought process. We now investigate how analysts use 3D immersive spaces for the same task. We conducted a user study where participants were asked to solve an intelligence analysis task using an Immersive Space to Think (IST) in a 3D virtual environment using an HMD. The study results confirm that the principles of Space to Think extend naturally to 3D immersive space, and find that 3D offers some additional opportunities. With tethered immersive space, analysts i) organized documents in a surrounding virtual sphere that used the surrounding 3D space to reduce occlusion, and ii) exploited the 3D depth dimension to encode relevance or importance.

Author Keywords
Sensemaking, text analytics, virtual reality

Introduction
Sensemaking is a process that involves comprehending unstructured and ambiguous information, synthesizing that information, and then drawing inferences [1]. For example, intelligence analysts often need to analyze collections of text documents, extract common themes, categorize the documents into a coherent structure, and then infer con-

clusions from the content. Prior work by Andrews et al. [1] has shown the significance of using 2-dimensional (2D), large, high-resolution display spaces (referred as "2D space to think") for synthesizing information during sensemaking. 3-dimensional (3D) immersive displays, in contrast, afford a potentially richer space, and offer users a sense of presence or "being there" with the data [5]. Furthermore, 3D displays allow for natural interaction methods for users to manipulate virtual objects such as text documents or images. Additionally, recent studies [2] [4] have shown promising results in visualizing text within 3D immersive environments. Therefore, immersive displays should be investigated to determine their ability to enhance sensemaking processes for textual datasets.

Research questions for IST study:
RQ1: How do analysts use the 3D immersive space to support their sensemaking processes?
RQ2: How do analysts organize textual data in a 3D immersive space, and what spatial cues do they use for organization?

In our study, we seek to address the question: *How do the principles of space to think extend to 3D immersive spaces?* To this end, we conducted a study similar to Andrews et al. [1], but instead using 3D immersive space. We developed Immersive Space to Think (IST), an HMD-based VR system, to conduct a study in which users were asked to solve an intelligence analysis task. The ***research questions*** addressed in this study are shown on the left.

The results of the study indicate that the principles of space to think, namely (i) external memory and (ii) semantic layer, extended naturally to 3D immersive spaces. Analysts made use of the depth dimension and the surrounding nature of the space to organize, create subspaces, reduce occlusion, and encode relevance. Our results suggest new opportunities for the use of 3D immersive space for sensemaking.

Study

The primary goal of this study was to explore how Andrews et al.'s study conducted in 2D [1] can be extended to 3D immersive space. Specifically, we explore whether 3D immersive space provides additional advantages in sensemaking of textual data as compared to 2D space.

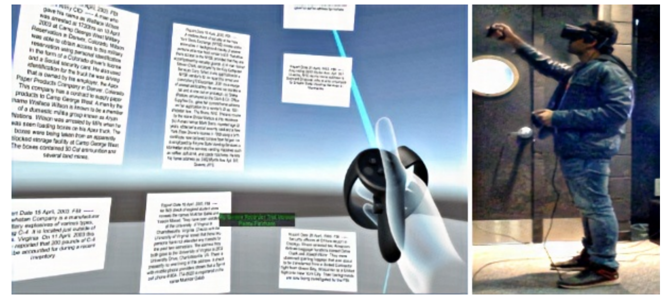

Figure 1: The view from within Immersive Space to Think (IST) of a user performing a sensemaking task (left). The user is arranging the documents in temporal order. Photograph of the user with Oculus headset and controllers (right).

Prototype

To enable our investigation, we developed *Immersive Space to Think* (IST), a replica of (2D) "Space to Think" in 3D immersive environment. IST is a simple HMD-based immersive display prototype that supports interactively organizing a number of short textual documents. IST is implemented in the Unity 3D engine and can be used with any VR headset (tethered Oculus Rift DK2 VR in this case) and tracked controllers compatible with Unity. We used a tracked area of about 4m x 4m. Figure 1 shows the view from within IST as a user performs the sensemaking task. When designing IST, we considered the following design goals.

Visualize textual data similarly to Andrews' study: As per the prior 2D study, we chose black text (17 font size, with a scale of 0.02 and "Arial" font style) on a white background. We conducted pilot studies to find the most suitable font size, style and scale of the text for users. Within

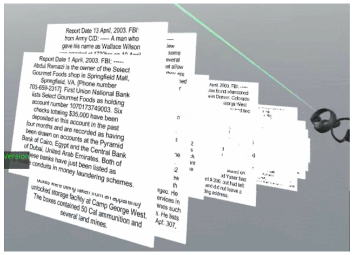

Figure 2: Initial arrangement of documents within IST. The collection of documents was stacked in a pile.

IST, each document is displayed as a thin white slate and stacked in a pile as shown in Figure 2. Each slate is sized to view the full document text without the need for scrolling. In general, subjects reported the documents to be easily readable at arms length. The minimum and maximum distance within which analysts could comfortably read the text within IST is approximately 0.8m to 2.2m.

Replicate similar interactions in Andrews' study: To investigate similar tasks from the prior 2D study, we designed similar document interactions in 3D. The ***drag-and-drop*** interaction allows the movement of documents within 3D immersive space with two steps. First, a user points to the document that needs to be moved. Pointing is achieved with ray-casting, using the controller in either hand. Next, the user presses the index trigger button of the controller to grab the document, drags the document by pointing the ray elsewhere, and releases the trigger to drop it. When dragging, the document maintains its distance and orientation with respect to the ray. The ***scale*** interaction enables documents to be resized. Scaling documents uses *two-handed interaction*. Users point to the desired document with both controllers. Then press both hand trigger buttons and move the hands away/close to each other to enlarge/reduce the document scale. The ***push/pull*** interaction allows for full use of the 3D space. When grabbed, documents can be *pushed away or pulled towards* the user using the joysticks on the controllers. There were no virtual navigation methods, only physical bodily navigation of the tracked space. There were no annotation or text highlighting methods.

Study Design

The goal of Andrews' analyst study [1] was to closely observe how analysts use the 2D space available on a large high-resolution display in a sensemaking task. Their study exactly aligns with our research goal of investigating how analysts use the 3D immersive space to organize documents when performing analytic synthesis task. We used the *Sign of the Crescent* dataset, which has been successfully used in previous sensemaking studies [6] and contained 31 textual documents of paragraph-sized intelligence reports. Our study included 8 participants (6 males, 2 females) between the age of 21 and 28.

The study consisted of four stages: **(1)** pre-study questionnaire; **(2)** sensemaking task with IST; **(3)** explain their hypothesis of the terrorist plot; **(4)** explain their spatial organizational structure and their use of 3D immersive space. A demo scene was provided in the beginning to get acquainted with the navigation and interactions of IST. The participants considered these questions while sensemaking: What is the secret terrorist plot? Who is involved? Where and when will it happen? Participants had 60 minutes to complete the sensemaking task. The full study procedure took about 1.5 hours.

Results

Similar to Andrews' study, we used an inductive approach to analyze the qualitative data from participant observations, screenshots, recordings, and post-interview notes. Wherever possible, we also used quantifiable data to verify the qualitative results. As we examined the notes and observations, we identified potential categories, strategies, and spatial structures. Overall, all 8 participants successfully identified one of the terrorist plots in the dataset.

Use of 3D immersive space

We first evaluate how analysts used the 3D space **(RQ1)**. We present the findings based on: (1) the final state of the 3D immersive space at the end of each participant's analysis, and (2) the post-interview where participants explained how they used the 3D immersive space.

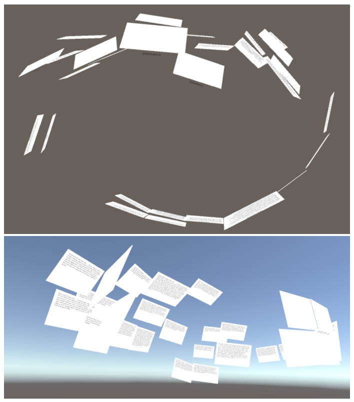

Figure 4: Overview of P1's final spherical workspace from top-view (top) and side-view (bottom) perspectives.

Figure 5: Looking up at P5's dome-like structure at the top of their spherical workspace.

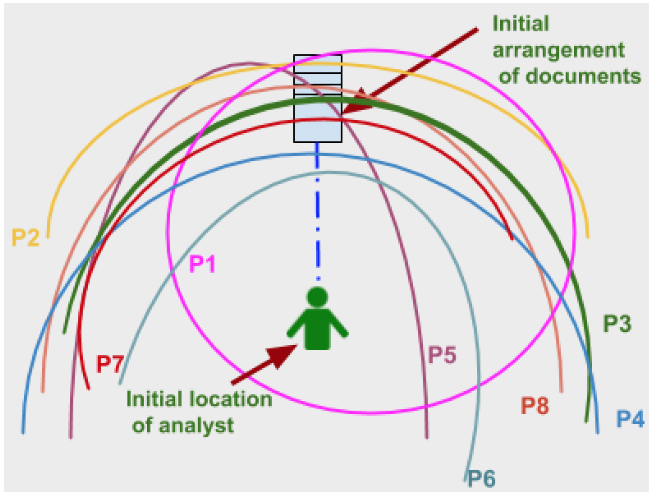

Figure 3: Visualization of the approximate outer edge of the final IST workspaces created by each participant from a top-down perspective. Participants primarily arranged documents on various portions of a virtual sphere around themselves with documents facing inward. The dashed blue straight line indicates the initial distance between the analyst and the documents.

Spatial surfaces: One of the primary purposes of our study is to investigate how the participants perceived the 3D immersive space. Therefore, we need to understand how the participants used the 3D immersive space overall – both which portions and how much of space participants used to organize the documents. Participants were afforded freedom to place documents anywhere in the available 3D space within their reach, either physically or virtually, through the controllers using the raycasting technique. Figure 3 shows an overview of the amount and arrangement of space used by each participant to place documents. All measures provided in this section are approximate.

We found two types of spatial surfaces constructed by participants: ***virtual sphere*** and ***virtual wall***. Most participants (P1, P3–P8) created a virtual sphere, except for P2 who created a virtual wall. P2 was the only participant to create a virtual wall, like a part of a large cylinder that is vertically flat and horizontally curved slightly at both ends of the wall.

For those who created a *virtual sphere*, they organized the documents around them, with the user at the center and documents facing inward, with documents covering some portion of the sphere. Documents placed above head level were facing slanted down toward the user. The spheres were distinct for each participant. The radius of the sphere ranged between 0.8–3.8m. The bounds of the sphere were unique across each participant. For example, P3 organized documents on the left side within an arc radius of 2.3 meters, on the right side within an arc radius of 3.5 meters, and an arc radius of 1.9 meters to the front. Initially, documents were stacked in a pile in front of the participant at waist level, with a distance of 0.8 meters from the participant's initial position. Figure 3 shows the initial location of the participant and the documents.

The yaw angle of the sphere arcs ranged from 150–190 degrees. In other words, most participants primarily used the front half of their virtual sphere. P1 was an exception to this, since they positioned documents in the entire available 360 degrees as shown in Figure 4. The height of the used portion of the spheres ranged from waist level to slightly above head level. P5's space arced to the top of the sphere, creating a dome-like structure as shown in Figure 5. The portion of the sphere surface that was used also varied in aspect ratio, creating either a horizontal *landscape* format (P1, P3, P4, and P7), or a vertical *portrait* format (P5, P6, and P8).

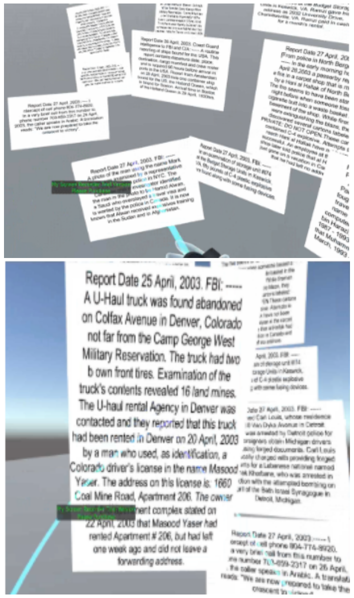

Figure 6: Two subspaces created by P3, on the left (top) and front (bottom) portions of their sphere, which were separated by a large gap. Other participants created similar subspaces.

Subspaces and Focus-spaces: All participants (P1–P8) reported that they divided the overall workspace into *subspaces* as they progressed in their analysis. These subspaces were constructed by subdividing the virtual sphere into smaller regions. For example, Figure 6 shows two subspaces constructed by P3. The total number of subspaces created by each participant ranged from 1–6, depending on how each individual participant approached the sensemaking task. All participants also reported creating a special subspace used as a *focus-space*, located close to the user, positioned between the user and the overall spherical surface. This focus-space was used to store working documents or important, frequently-referenced information.

Spatial Organization

Second, we examine how the analysts organized the textual data within the 3D immersive space **(RQ2)**. Organization played a key role in Space to Think, and therefore we focus on the various organizational metaphors created by analysts within IST.

Organizational metaphors: Like Andrews [1], we identified groupings of documents as organizational metaphors by analyzing how participants positioned the documents and how they described those positions during post-interviews. We found four organizational metaphors constructed by participants: a) ***temporal***, b) ***topic cluster***, c) ***relevance divide***, d) ***working set***. Furthermore, all participants combined ***multiple metaphors*** in their final organization in unique ways. Metaphors had inter- and intra-arrangements. For example, P3 used temporal ordering, topic clusters, and relevance divide.

All of the participants (P1–P8) at some point created *temporal ordering*. We can attribute the formation of this metaphor to the initial chronological arrangement of the documents, from oldest to newest. Participants arranged the temporal ordering on a horizontal timeline across the 3D space, usually around the equator of their virtual sphere. However, the start position of the chronological arrangement varied among participants.

A *topic cluster* is a group of documents related by topics such as name, location, phone number, date, etc. P1, P3, P4, and P7 constructed topic clusters in their final state. The total number of clusters ranged between 4–9 among these participants. However, the foundations of these clusters varied. For example, P1 created clusters based on important dates. On the other hand, P3, P4, and P7 created clusters based on events, names, places, and phone numbers (Figure 7). Cluster arrangements were also unique with reference to visibility. P1, P3, and P4 kept each cluster spread out (tiled) to avoid occlusion. In contrast, P7 used depth within the clusters, with some documents partially occluded, and thus confined the location of the clusters between waist level and neck level as shown in Figure 8.

P2 and P5–P8 constructed metaphors that *divided the space based on relevance*. They placed relevant documents between waist level and neck level. Documents that were not germane to the problem context were placed above head level, but still available for recall if needed.

P3 and P4 created a *working set*. Both of the participants permanently maintained one working document for frequent access, in a subspace near their waist and rotated to face the user's head, that was not a part of the overall virtual sphere. However, the working document was different for both participants, but both the documents were dated 27th April, a critical turning point in the dataset. When asked about this document in the post-interview, P3 and P4 both reported that the working document was of high importance as it had information related to many other documents.

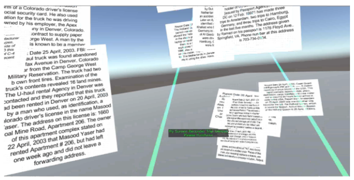

Figure 7: Three clusters constructed by P7. Clusters are determined by events, names, and places. Clusters are spatially separated by a gap.

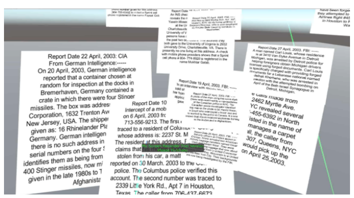

Figure 8: Subclusters within a big cluster constructed by P7. Usage of depth within clusters, with more relevant documents placed in front.

Spatial cues: We observed that participants used ***depth*** as a spatial cue for organizing documents. For P3 and P7, depth played a role in distinguishing documents based on relevance. For example, P7 kept important documents in front within a cluster, and less important documents behind as shown in Figure 8. Depth was also used in forming subspaces (P1–P8). Another strategy used by all participants was to pull a document or two (from the background virtual sphere) closer and just below the head level, and then perform detailed analysis activities like reading and comparing.

Discussion

Confirm 3D Space to Think: One of the goals of this study was to investigate whether the principles of "Space to Think" naturally extend to immersive 3D spaces. Although this was not a comparative study between 2D and 3D, it is possible to make some inferences by comparing behavioral results to Andrews et al. [1]. One of the key findings of 2D space to think was the use of *space as a form of external memory* that can be efficiently accessed through physical navigation. Similar use of 3D immersive space was reported in this study. Another key finding was the use of *space as a form of semantic layer* that added meaning to the displayed information. We confirmed similar incremental formalism processes to those of Andrews et al., who found similar organizational metaphors: clusters, temporal ordering, and multiple metaphors. However, another goal of this study was to investigate whether 3D provides additional opportunities for sensemaking beyond that of Andrews' 2D space to think. We did find new opportunities discussed next.

New 3D depth encodings and metaphors: Beyond the existing metaphors, we observed new organizational metaphors (relevance divide, and working set), and found new use of spatial cues for 3D depth and document scale. Participants mapped relevance, importance, and working activity to 3D spatial locations in new ways. There was a natural tendency to map proximal spatial locations, in the depth dimension, as more relevant or frequently accessed. This might relate to the cost of navigation access, either physically or virtually, but might also have deeper embodied cognitive connotations.

3D surrounding space to reduce occlusion: We observed a tendency towards arrangements that reduced occlusion by using more surrounding 3D space. Five participants (P1-4, P8) clearly preferred to arrange the documents in a non-occluded tiled format on their virtual spheres, and needed significant rotational physical navigation to access the documents around them. Three participants (P5-7) arranged the documents in a more confined area with more partial occlusion and more varied depths, but needed to drag and peek around to access the occluded documents. Even so, they greatly reduced the amount of occlusion from the initial stack by using the surrounding space. The use of both surrounding space and depth in 3D (combined with greater physical navigation) suggests future potential for increased scalability of IST via wireless HMD and larger tracked spaces.

Embodiment within IST: Compared to 2D, IST potentially provided a greater sense of *being present* within the space. 3D interactions enabled new embodied task behaviors, such as placing working set subspaces near the waist, mapping relevance to depth with respect to body position, and pulling/pushing for temporary focus and comparison. P3 noted, "I felt the 3D environment was my mind and I was walking through it." Actions like rotating, moving, pushing/pulling all had underlying spatial meaning that facilitated embodiment within IST and reflected "space to think".

New 3D semantic interactions: We hypothesize that the rich 3D gaze and interaction sensors associated with im-

Table 1: Potential cognitive inferences from the IST study, offering opportunities for possible new Semantic Interactions.

3D Interaction	Cognitive inference
Cluster documents	Group documents by learned similarities
Arrange chronologically	Temporal ordering is significant
Division of subspace	Subtask or special focus
Move document to waist	Create important working set
Use of depth, document scale, or overhead space	Distinguish documents by relevance or importance

mersive spaces could enable design of more powerful *Semantic Interactions* [3]. Table 1 shows a summary of the potential cognitive inferences that could be drawn from our 3D study. Only some of these (cluster) were implemented by Endert et al. [3] in their 2D ForceSpire system based on findings of Andrews' 2D study. Our results could be used to expand the palette of potential analytic inferences that could be designed within IST. Further studies are needed to test and verify these new semantic interactions.

3D interaction design influences user behavior: The design of the drag-and-drop ray-casting interaction technique might have encouraged participants to create a virtual spherical shape rather than a virtual wall or other spatial arrangements. Likewise, the use of a tethered HMD may have hindered users' physical navigation, also leading to spherical organization. In comparison to simpler 2D interaction design, the complexity of 3D interaction design magnifies the effect of design on user behaviors, making study design more difficult. This suggests the need for further studies to investigate alternative 3D interaction techniques and wireless displays for IST.

Limitations: Due to low resolution of the Rift, documents beyond 2m were blurry and jittery (although comfortably readable within 2m). Prior studies [2, 4] with reading text inside immersive environments (with similar or lower resolution), have been conducted successfully. Therefore, we believe our study results can be further improved if repeated with higher resolution HMDs.

Conclusion

In this paper, we approximately replicated in 3D the seminal 2D study conducted by Andrews et al. The motivation behind our study was to analyze 3D immersive space as a new physical medium for "space to think." The results of our study shed a positive light in using such 3D space for sensemaking, since the principles of space to think carried over to the immersive environment. Furthermore, 3D immersive space provided some new possibilities for organizational metaphors, 3D spatial encodings, and scalability, showing more opportunity for organizing text as compared to 2D space to think. Our study provides initial insights on the use of 3D immersive space for sensemaking of textual data and opens many new questions for future research. We conclude that Space to Think, in support of sensemaking tasks, may be an ideal application for the Immersive Analytics [5] research agenda.

Acknowledgements

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