Space for Two to Think: Large, High-Resolution Displays for Co-located Collaborative Sensemaking

Lauren Bradel[1]
Virginia Tech

Christopher Andrews[2]
Virginia Tech

Alex Endert[3]
Virginia Tech

Katherine Vogt[4]
Elon University

Duke Hutchings[5]
Elon University

Chris North[6]
Virginia Tech

ABSTRACT

Large, high-resolution displays carry the potential to enhance single display groupware collaborative sensemaking for intelligence analysis tasks by providing space for common ground to develop, but it is up to the visual analytics tools to utilize this space effectively. In an exploratory study, we compared two tools (Jigsaw and a document viewer), which were adapted to support multiple input devices, to observe how the large display space was used in establishing and maintaining common ground during an intelligence analysis scenario using 50 textual documents. We discuss the spatial strategies employed by the pairs of participants, which were largely dependent on tool type (data-centric or function-centric), as well as how different visual analytics tools used collaboratively on large, high-resolution displays impact common ground in both process and solution. Using these findings, we suggest design considerations to enable future co-located collaborative sensemaking tools to take advantage of the benefits of collaborating on large, high-resolution displays.

KEYWORDS: Visual analytics, collaborative sensemaking, large, high-resolution displays, single display groupware.

INDEX TERMS: H.1.2 [User/Machine Systems]: Human Information Processing – Sensemaking; H.5.3 [Group and Organizational Interfaces]: Collaborative computing, Computer-supported cooperative work.

1 INTRODUCTION

Collaborative visual analytics has been a growing research area within the visual analytics community due to the ability to integrate social and group dynamics into the analytic process [1, 2]. In the real world, as opposed to controlled laboratory environments, collaboration on intelligence analysis tasks occurs at an informal level, if at all, due to the competitive workplace culture [3, 4]. Additionally, in reality, collaboration occurs when there is little initial effort required to beginning collaboration [5]. We have addressed these points by providing a set-up where all that is needed to commence collaboration is pulling up a chair and keyboard, in hopes that this set-up will provide a practical means of collaborating in the intelligence analysis community. We seek to better understand how large, high-resolution displays can be leveraged by collaborative visual analytics tools in order to enhance the collaborative sensemaking process for intelligence analysts.

Large, high-resolution displays (Figure 1) have been shown to enhance individual sensemaking for intelligence analysis tasks through the ability for users to spatially arrange information and to have information persisted on the display, using the display as external memory [6]. Do these same benefits apply to co-located collaborative sensemaking for intelligence analysis?

In an informal exploratory study, we previously analyzed the overall collaborative sensemaking activities employed by users, as well as the user roles that developed during the collaborative sensemaking process [7]. We will now analyze the spatial strategies employed by teams of two (2) participants using different visual analytics tools for an intelligence analysis task and how this use of space contributes to the collective understanding of the document collection. The two tools used in this study are: Jigsaw [8], which is a function-centric tool, and a simple multi-window document viewer [9], which is a data-centric tool. The study presented in this paper involves co-located collaborative sensemaking, which is facilitated by the integration of multiple-input device technology that enables simultaneous use of multiple mice and keyboards on the same display.

2 RELATED WORK

Collaboration cannot always be done in a co-located setting due to factors such as geographical distance. However, when co-located collaboration is possible, it may be preferable because co-located collaboration mitigates a major design concern in collaborative tools, especially remote collaborative tools: the need for tools to aid in establishing common ground. Broadly, common ground is "the knowledge that enables [collaborators] to communicate and, more generally, to coordinate their activities" [10].

Specifically, common ground features include explicitly and implicitly shared objects and events. The explicitly shared objects (e.g. physical artifacts, visuals, audio) are the focus of the communication. Communication is an important part of establishing common ground through the process of "grounding" to ensure that a successful transaction has taken place [11]. The implicitly shared objects are the surroundings that compose the environment, such as background noises and artifacts scattered throughout the room. Common ground also includes the level of attention a collaborator pays to certain objects and their thoughts and interpretations about the data [10].

Co-located collaboration also eliminates the need to explicitly synchronize views between remote collaborators [12]. Remote collaboration must address the design tradeoffs between "individual control over the application, and support for *workspace awareness*"[13]. Design decisions that enhance individual work often hinder group work, and vice versa. Previous

[1]email: lbradel1@cs.vt.edu
[2]email: cpa@cs.vt.edu
[3]email: aendert@cs.vt.edu
[4]email: kvogt@elon.edu
[5]email: dhutchings@elon.edu
[6]email: north@cs.vt.edu

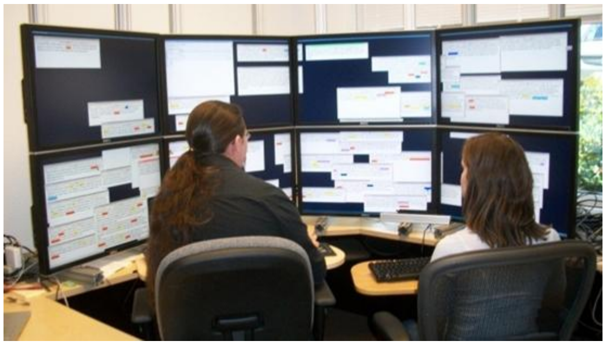

Figure 1: Two users with their own input devices in front of the large, high-resolution display used in the study

groupware interfaces have either supported group work through consistent view sharing, known as "What You See Is What I See (WYSIWIS)," or the individual user through more relaxed view sharing [14]. As Gutwin and Greenberg state, "the ideal solution would be to support both needs – show everyone the same objects, as in WYSIWIS systems, but also let people move freely around the workspace, as in relaxed-WYSIWIS groupware" [13]. This balance can be achieved through some types of single display groupware.

Collaborating face-to-face around a single shared display is known as Single Display Groupware (SDG) [15]. Early SDG systems include Liveboard [16], Tivoli [17], and the Digital Whiteboard [18]. Wallace et al. [19] found that singe display groupware, as compared with multi-display groupware, produced more collaborative awareness, making common ground easier to establish between collaborators.

In subsequent work ([20, 21]), Stewart et al. investigated SDG systems further. Additionally, they conjectured that the "very limited screen space" "may result in reduced functionality compared with similar single-user programs" [21]. This concern can be alleviated by increasing the display screen's physical size, and subsequently resolution, to provide adequate virtual and physical space for SDG systems.

Stewart et al. found that two input devices (one per person) are preferable in SDG systems because they increased interaction and kept both participants "in the zone" [20]. Although it has been shown that multiple input devices allow for more parallel work but less communication [22], mult-input devices allow for more reticent participants to contribute to the task [23]. Because we sought to keep users in the "cognitive zone" [24], we chose to implement two mice and keyboards, one for each user, to enable them to contribute to the collaborative sensemaking task simultaneously.

The sensemaking loop, as defined by Pirolli and Card [25], describes the cognitive steps intelligence analysts take over the course of their investigation. The sensemaking process is broadly divided into two categories: the foraging loop and the sensemaking loop. The first involves foraging, filtering, and extracting information while the second is more of a mental process where a schema, hypothesis, and presentation are developed. The analyst may begin at the top or bottom and loop through the steps continuously [25]. Individual sensemaking has been studied on multiple monitor and large, high-resolution displays [6, 8, 26].

In an ethnographic study observing collaborative sensemaking for healthcare information, Paul and Reddy found that collaborative sensemaking must focus on the prioritization of relevant information, the trajectories of the sensemaking activity, and activity awareness [27].

Previous work has been conducted on collaborative sensemaking based on web searches ([28, 29]), as well as remote collaborative sensemaking for intelligence analysis ([30]). Additionally, co-located collaborative sensemaking has been explored on tabletop displays ([31-33]), but co-located collaborative sensemaking for intelligence has not yet been investigated on large, high-resolution vertical displays.

Large, high-resolution displays have been shown to improve individual user performance on simple tasks such as pattern matching [34]. Additionally, users were observed using *physical navigation* (head turning, body shifting, glancing, etc.) more than *virtual navigation* (manually switching between windows, minimizing and maximizing to view different documents, etc.) when using large, high-resolution displays such as the one pictured in Figure 1.

Andrews et al. [6] sought to expand this search into more cognitively demanding tasks, such as sensemaking for intelligence analysis tasks using fictional document collections. Two studies were conducted to evaluate novices and experts completing sensemaking tasks on large and small displays. The study participants using the large displays used the large display space as a form of external memory, using physical navigation to recall information from different documents. The studies showed that in addition to use the large display as a form of external memory, the analysts also used the space to add a semantic layer of meaning to the displayed information through document proximity and alignment [6]. To the best of our knowledge, it is not known if these individual benefits of large, high-resolution displays extend to co-located collaborative sensemaking for intelligence analysis tasks. We seek to explore this uncertainty to determine if large, high-resolution vertical displays can aid and support the co-located collaborative sensemaking process for intelligence analysis through an exploratory study.

3 Study Description

The purpose of this exploratory study was to observe spatial strategies (e.g. use of space, use of whitespace, meaning of space) employed by pairs of users working with different analytical tools on a large, high-resolution display to complete an intelligence analysis sensemaking task. We observed teams of two participants who were asked to assume the role of intelligence analysts tasked with analyzing a fictional collection of text documents to uncover a hidden terrorist plot against the United States.

We came into the study with several research questions:

- How do pairs of users arrange information on the large display?
- Is there any meaning attached to the location of information? If so, was this meaning perceived the same by both users?
- Would some pairs use more or less of the display space? If so, why?
- Does the large display space facilitate common ground between collaborators? If so, how is this achieved?

3.1 Participants

We recruited eight pairs of participants (J1-J4 used Jigsaw, T1-T4 used the document viewer). Six of the eight pairs were students and the other two pairs consisted of research associates and faculty, and all pairs knew each other prior to the study and had previous experience working collaboratively. There were four all male groups, one all female, and three mixed gender. Each participant was compensated $15 for participation. As a form of motivation, the verbal debriefing solutions formed by the teams of participants were scored and the participants received an additional financial award for the four highest scores.

3.2 Study Set-Up

The teams of users sat in front of a 108.5 in. x 35 in. display consisting of a 4x2 grid of 30" LCD 2560x1600 pixel monitors totalling 10,240x3,200 pixels or 32 megapixels [Figure 1]. The display was slightly curved around the users, letting them view the majority, if not all, of the display in their peripheral vision. A single machine running Fedora 8 drove the display. A multi-cursor window manager based on modified versions of the IceWM and x2x was used to support two independent mice and keyboards [35]. Thus, each user was able to type and use the mouse simultaneously and independently in the shared workspace. A whiteboard, markers, paper, and pens were also available for use because these external artifacts were explicitly requested during the pilot study. Each participant was provided with a rolling chair and free-standing, rolling table top holding the keyboard and mouse so that they could move around if they chose to do so. The desks and chairs were positioned side-by-side in the central area of the display space.

3.3 Analytic Tools

Jigsaw. Jigsaw [8, 36] is a system that has been designed to support analysts in the sensemaking process. Jigsaw visualizes document collections in multiple views based on the entities (people, locations, etc.) contained within those documents, making Jigsaw a *function-centric* visual analytics tool. It also allows textual search queries of the documents and entities. Jigsaw can sort documents based on entity frequency, type, and relations, and this information can be displayed in a variety of ways, including interactive graphs, lists, word clouds, and timelines. There is also a recently added Tablet view within Jigsaw where users can write notes, draw connections between entities, and create timelines. Because of the complexity of Jigsaw, participants were given a thirty minute tutorial prior to the start of the task.

Document viewer. To gain a better understanding of collaborative sensemaking behavior, we chose a different style of tool to observe in addition to Jigsaw. We chose a basic document viewer, AbiWord [9], which allows for manually highlighting individual documents sections, editing existing documents, and creating text notes. Teams using this document viewer were also provided with a file browser in which they could search for keywords across the document collection. This document viewer is a *data-centric* tool because it only displays the raw documents (with optional highlighting added), as opposed to also including information about the document contents. Participants were given a five minute tutorial for this tool.

Table 1: Group number, overall scores, individual report similarities and percentage of empty space for each group

Group	Total Score	Report Similarity	% Whitespace
J1	11	8	86.77%
J2	-1	4	55.60%
J3	-2	3	86.84%
J4	-7	-17	27.24%
T1	13	2	61.23%
T2	-1	-26	50.88%
T3	10	4	54.80%
T4	14	10	51.64%

3.4 Task and Procedure

After the tutorials on Jigsaw or the document viewer with a sample set of documents, each team was given two hours to analyze a set of 50 text-only documents and use the information gathered to predict a future terrorist attack on the United States. The scenario used in this study comes from an exercise developed to train intelligence analysts and consists of a number of synthetic intelligence reports concerning various incidents around the United States, some of which can be connected to gain insight into a potential terrorist attack. This same scenario was also used in a previous study evaluating individual analysts with Jigsaw [36].

3.5 Data Collection

Following the completion of the scenario, each participant filled out a report sheet to quantitatively assess their individual understanding of the analysis scenario, then verbally reported their final solution together to the observers. The rubric for evaluating the participants' verbal and written solutions was based on the strategy for scoring Visual Analytics Science and Technology (VAST) challenges [26]. The participants earned positive points for the people, events, and locations related to the solution and negative points for those that were irrelevant or incorrect. They also received points based on the accuracy of their overall prediction of an attack. The joint verbal debriefing was scored to produce the group's overall score. The individual reports filled out by the participants were compared against their teammate's to calculate similarities and differences.

Additionally, individual semi-structured interviews were

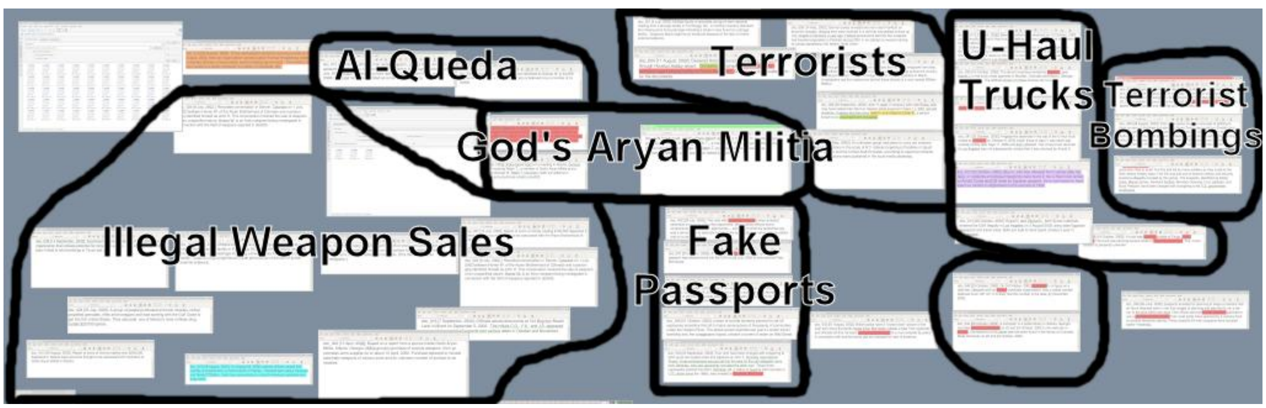

Figure 2: Group T2's clustering based on relevance (screenshot lightened to enhance readability)

Figure 3: Geographical document clustering done by group T4

conducted where each participant commented on how they solved the scenario, how they arranged information on the display, and how they felt the collaboration affected their ability to solve the scenario.

During each study session, an observer was present taking notes. Video and audio of every scenario, debriefing, and interview was recorded. We also collected screenshots in fifteen second intervals, logged mouse actions (movements and clicks), and logged active windows.

3.6 Results

As seen in Table 1, the document viewers groups tended to perform better than the Jigsaw groups. These differences were not statistically significant, although significance is difficult to find in such a small sample size. These scores raise the question of why document viewer groups performed better. Many factors impact collaborative sensemaking success. One important factor is common ground. How was the large display space used to form a collective understanding of the document collection? To answer this, we must first understand how the participants used the display space.

4 Spatial Strategies

As a result of the data-centric nature of the document viewer tool, all document viewer groups (T1 – T4) displayed all 50 documents on the display screen. They did not have access to the advanced features, such as connecting entities across documents, which Jigsaw provides. Instead, their only method of learning the contents of the document collection was to read every document. After reading the documents, all document viewer groups arranged the documents on the display, only closing documents once they were deemed irrelevant to the solution.

The Jigsaw groups (J1 – J4), however, did not find the need to use the entire display space. They were able to complete a sizeable amount of their investigations through Jigsaw's different analytic views. Participants in these groups only opened one or two documents at a time in Jigsaw's document viewer. Three out of four Jigsaw groups (J1, J2, and J4) used Jigsaw's Tablet view to record connections between people, places, and events. These groups spatially arranged information in their Tablet views, which will be discussed in more depth below.

4.1 Meaningful Clusters

In this exploratory study, we found that teams used clustered layouts to organize information that, if explicitly communicated, enhanced collective knowledge between the participants by maintaining an awareness of where specific information could be found.

Clustering can be discussed in terms of the different analytic tool used due to the difference of information that was represented in the clusters. With the document viewer condition, entire documents were clustered. In the Jigsaw groups, entities (names, organizations, locations, etc.) were clustered. This is the difference between connecting people/groups/locations that span multiple documents and associating entire documents by proximity which requires one or two pieces of information to drive the location decision. It is unclear which clustering method is more effective at collaborative sensemaking. However, for the sake of simplicity, we will discuss the clustering strategies used by document viewer teams first, then Jigsaw groups.

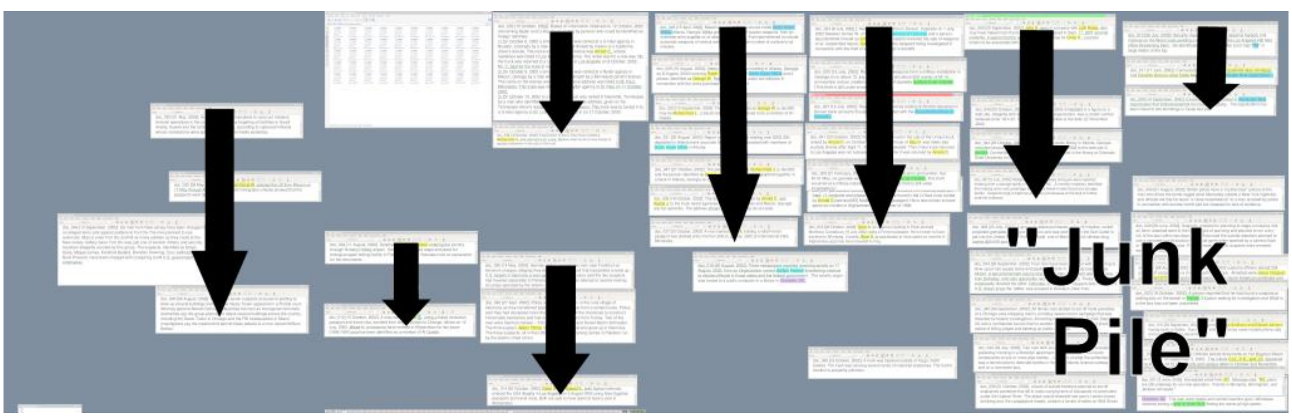

Figure 4: Group T3's timeline clusters grouping events they believed to be related (arrows pointing forward in time), as well as the "junk pile."

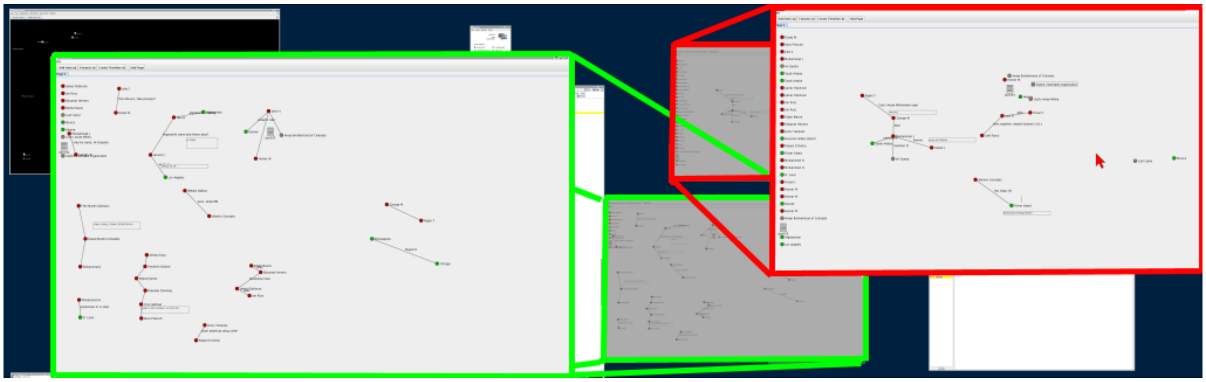

Figure 5: J4's separate Jigsaw Tablets (edited to zoom in on each separate Tablet, green for the left user, red for the right user)

4.1.1 Document Viewer Clusters

All document viewer groups chose to cluster the documents on the display screen. The method of creating this spatial representation was not constant across the teams. T1 and T2 both clustered documents based on relevance (T2's clusters can be seen in Figure 2). T4 chose to arrange their documents geographically, using the entire display to represent the United States, with the rightmost side representing foreign countries [Figure 3]. T3 switched between arranging documents temporally (as in Figure 4) and by relevance. These relationships were informal and based on document proximity because there were no explicit relationships labeled between documents.

In order for these arrangements to aid the collaborative sensemaking process, they needed to be agreed upon. For example, in T4's geographical representation of the document collection, T4-B was moving documents around the screen while T4-A commented on the correctness of their position. Upon finding a document that mentions Los Angeles, the following exchange occurred:

T4-A: *"Let's just put it in California for now."*

T4-B: *(moves document to where she believes Los Angeles is located)*

T4-A: *"No, no, put it down." (motions downward at the screen) "That's not where L.A. is. It's much farther south, as far as Texas" (points to the screen where Texas documents are located)*

T4-B: *"Really? Okay" (moves the document farther down the screen) "There?"*

T4-A: *"Yeah."*

They continued this kind of discussion throughout the entire organization of the large display space. Communication played a key role in establishing a collective understanding of document location. This common understanding of the spatial layout was not always achieved, however. In Figure 4, the bottom right corner is labelled "Junk Pile." During the post-study individual interviews, the participants revealed that there was a lack of understanding concerning the importance of those documents. The participant sitting on the right side of the display (in front of the "Junk Pile"), T3-B, explained the meaning of the documents:

T3-B: *"We put things that didn't make sense yet in the bottom right corner."*

The participant sitting on the left, T3-A, told a much different story:

T3-A: *"The bottom right corner was the junk pile, the garbage bin."*

This demonstrates that meaning attributed to spatial location can be personal if not explicitly communicated and agreed upon.

4.1.2 Jigsaw Clusters

The Jigsaw groups that chose to use the Tablet view formed clusters, but these were composed of entities, not entire documents, and were contained in the Tablet view, as opposed to expanding across the entire display. These types of clusters will be discussed further

The main difference between the document viewer groups' clusters and the Jigsaw groups' clusters is the information represented at each data point. The document viewer groups clustered entire documents, whereas the Jigsaw groups clustered entities (people, locations, organizations, etc.) and drew explicit connections between connected entities which were labeled with their relationship, such as:

"*Muhammad J., who is an alias for George W., is a member of Al-Queda and is friends with Kamel J.*" [Figure 8]

This was a much more formal method of clustering than was seen in the document viewer groups due to the labeled connections between nodes.

Group J1 clustered their Tablet information based on relevance, linking events, locations, and people together, and also used the Tablet to keep track of known aliases. J2 constructed a timeline in their shared Tablet, which they connected to events, people, and organizations [Figure 6]. They also used the Tablet to update aliases and mark connections. The participants in group J3 did not use the Tablet view; they wrote their connections on sheets of paper. There is little clustering on the notes made by J3 other than listing events by location. The final Jigsaw group, J4, maintained two Tablets, one for each participant [Figure 5]. Both J4 participants clustered entities based on relevance and recorded specific connections found in the document collection, similar to J1's Tablet organization. Interestingly, very little information was

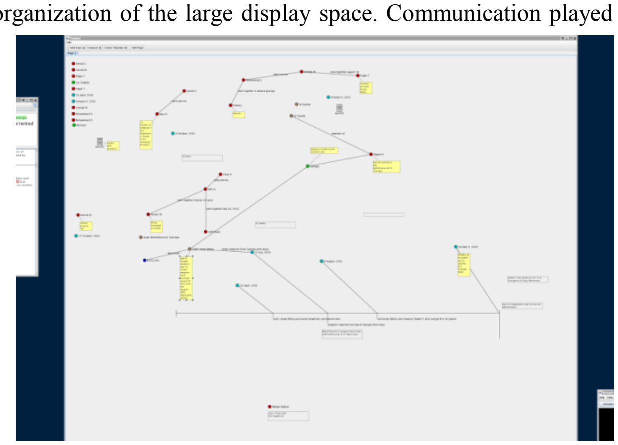

Figure 6: Zoomed in: J2's shared Jigsaw Tablet view

redundant between the two Tablets, because the participants used them essentially as one continuous Tablet.

While the multi-mouse technology allowed all participants to interact with the display simultaneously (two windows could be "active" at the same time, clicking did not override the other person's actions), two users were not capable of entering text in the same window at the same time. Jigsaw groups attempted to type in the Tablet at the same moment as their partner, but found that actions were being overridden.

Each Jigsaw group that used the Tablet view addressed this usability issue differently. Some groups, such as J1, solved this by "passing" the Tablet back and forth across the screen when one partner wanted to enter information. J2 solved this issue by taking turns, entering information sequentially instead of in parallel. With this shared Tablet, they were able to keep track of commonalities in their investigations:

J2-A: *"I have information about Arnold C., too!"(after seeing Arnold C. was already added to their shared Tablet view)*

Other groups did not choose to take turns while typing, so they found a different solution to using the Tablet. J4 got around this technical problem by creating two Tablet views to record their thoughts. By stacking these views, J4 created a column of Tablets in which information was recorded. As evidenced by the mouse activity logs, the participant sitting on the right only clicked in the top Tablet, and the participant sitting of the left only clicked in the bottom Tablet. Thus, even though the separate Tablets create the appearance of a central space to make connections, they are still a reflection of individual, rather than collective, knowledge.

Additional Jigsaw views were not arranged into clusters. The groups did not attach any relational meaning to the location of their different views. We conclude that there was not any additional attached meaning because the position of the windows was never discussed, disputed, or agreed upon, which happened in all document viewer groups.

4.1.3 Multi-Mouse Use

The multiple mice enabled simultaneous interaction of the space, but the use of this technology varied greatly between teams.

We logged all mouse information (movement, button down, button up, etc.) and constructed images of mouse clicks for each group. We colored-coded the data points by participant in order to observe any shared or separate space based on mouse interaction. The document viewer groups' click distributions can be seen in Figure 7, while the distribution of the Jigsaw groups' mouse clicks can be seen in Figure 9.

These images give insight into how much the groups worked collaboratively or independently while arranging documents on

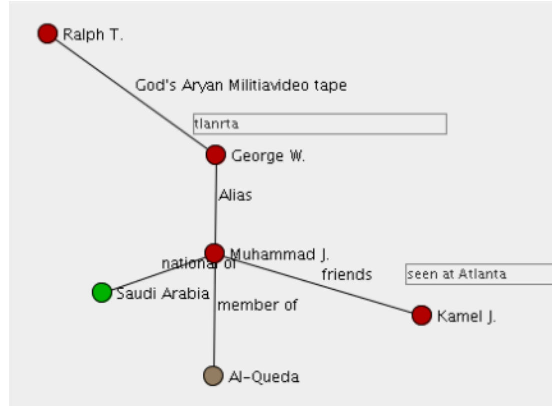

Figure 8: Zoomed in: J4-B's personal Tablet view showing connections between entities

the large display. In T1, both participants used their separate mice to arrange the documents, although the participant on the left (in green) used his mouse more than his partner did. In T2 and T3, we see that there was overlap in the center of the display where clicks occurred from both participants. Even though the sides are largely populated by activity by the participant seated on that side of the display, they are not devoid of clicks from the other partner, showing that these were not harsh boundaries. Group T4 approached mouse interaction differently than the other document viewer groups. In this group, only the participant seated on the right dragged the documents into their location on the display while the participant on the left stood and directed their placement. This contributes to his low number of clicks on the display.

The Jigsaw groups produced harder partitions with fewer common areas between the users, as seen in Figure 9. Even J2, the group that had one shared Tablet that they took turns using, was biased towards clicking towards "their side" of the Tablet. J4, the group with two Tablets, produced an interesting result. The user seated on the left did not click in her partner's Tablet, but he often clicked in hers. However, even this group maintained a distinction between "my workspace" and "his workspace."

Ultimately, there were many ways in which the teams used the multi-mouse technology to spatially interact with the large display. The mouse click distribution images reveal that there were large areas of space that were not clicked on in the Jigsaw views.

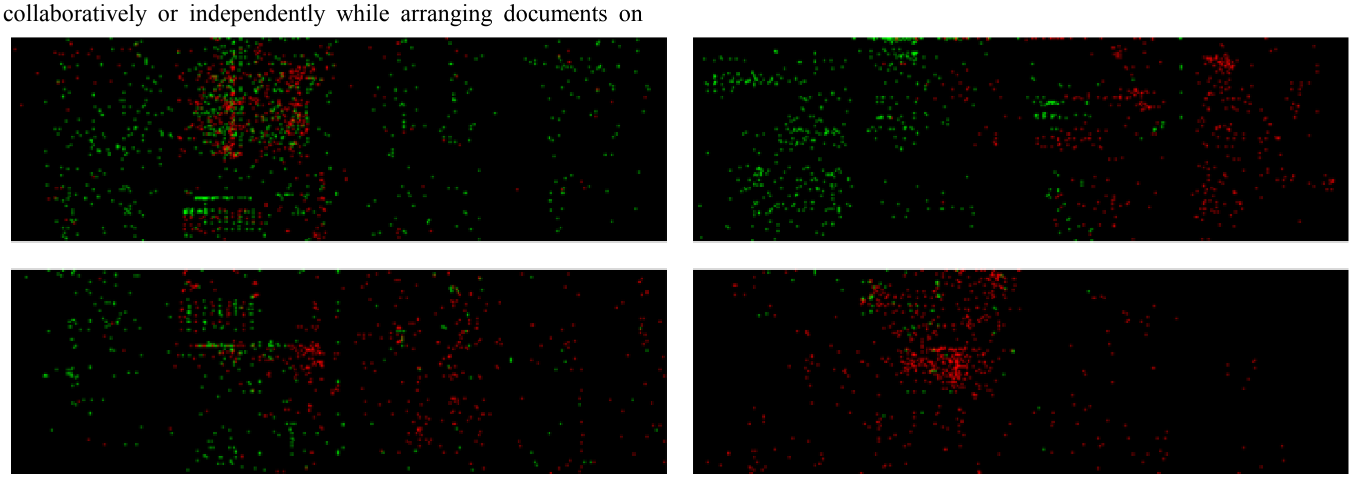

Figure 7: Document viewer groups' mouse clicks. Top row: T1, T2. Bottom row: T3, T4. Left user is green, right user is red

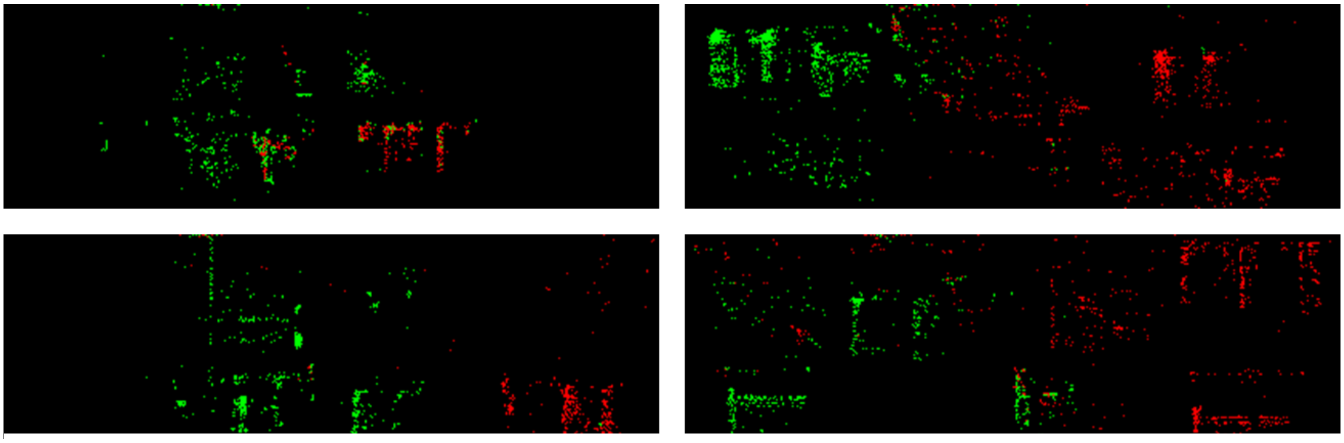

Figure 9: Jigsaw groups' mouse clicks. Top row: J1, J2. Bottom row: J3, J4. Left user is green, right user is red.

4.1.4 Unused Display Space

The whitespace carried a meaningful purpose for all document viewer groups. The whitespace served as a method of partitioning clusters. As seen in Figure 2, Figure 3, and Figure 4, documents that are closely related tend to touch or overlap each other. Whitespace is used to mark a distinct difference in document content in order to make the relevance of clustered documents more noticeable.

The unused display space in between Jigsaw views did not carry any collective meaning for these groups, as view placement was never discussed or disputed between the participants in the Jigsaw groups.

By counting the number of background pixels in every screenshot captured, we calculated the average amount of unused display space during each group's sensemaking task, which can be seen in [Table 1]. With one exception (J4), the document viewer groups tended to use more of the display space than the remaining Jigsaw groups. The exception, group J4, enlarged their Jigsaw views beyond what was needed to display information regarding the document collection, resulting in large areas of unused space within the Jigsaw views. This empty space within Jigsaw skews their unused space average.

The reason for the differences in unused space highlights the fundamental difference between the analytic tools used in this study. In the data-centric document viewer, all four groups arranged all 50 documents on the screen, and then closed documents only after they were deemed irrelevant. They had no other methods, aside from searching inside the document browser, to discover the information within the documents.

In the function-centric Jigsaw, however, all groups were able to gather a sizeable amount of information about the document collection even before opening the first document. Because Jigsaw illuminates connections between entities, the teams only opened selected documents and did not feel the need to leave any of these documents persisted in the space. The only persisted information was within the Tablet views. Therefore, the Jigsaw groups used less of the space because they did not feel the need to expand outside of the Jigsaw views.

A design issue must be mentioned with regard to Jigsaw groups only opening one or two documents at a time. At the time of this study, double-clicking on a document inside a Jigsaw view did not open the selected document in a new window, as many users had expected it to do. Instead, the participants needed to manually open a new document viewer. No users chose to go through this extra work. This usability issue has since been resolved by Jigsaw's developers.

4.2 External Memory

All document viewer groups used the entire display space as a form of external memory to recall relevant information for making connections within the document collection. The Jigsaw groups used their Tablet views in a similar manner.

4.2.1 Interaction

Throughout the sensemaking process, teammates pointed out relevant information to their partner through pointing with their arms. This raises the question: why did they point with their hands/arms instead of the mouse? This has a straightforward answer: because no mouse speedups or navigational hotkeys were used in this study, physical pointing was a much faster method of interaction. However, the reason for pointing at the display is not the focus of this discussion. Instead, it is to decipher what this gesturing represented in this collaborative sensemaking task in terms of how the display was perceived.

Participants continued to point at the display to mentally "connect the dots," point out connections to their partners, and link related events. Even during the debriefing, all document viewer groups (four out of four) pointed to different areas of the screen with their hands when they discussed different locations or events. In contrast, only one Jigsaw group (one out of four) physically pointed at the display during the group debriefing (she pointed at her group's shared Tablet view). This further suggests that groups viewed the display space as a form of external memory, especially in document viewer groups due to the persistent nature of the documents. It is not surprising that Jigsaw groups only perceived their Tablets as available external memory because entities and connections were persistent, as opposed to the transient Jigsaw views where a single double-click can change the entire "meaning" of the view by showing a new set of connections.

4.2.2 Solution Reports

Additional evidence supporting the conclusion that participants viewed the display as a form of external memory can be found in the individual solution reports. Before the collaborative debriefing was conducted, the participants were instructed to separately write down any relevant people, organizations, locations, and events that supported their hypothesis of the fictional terrorist plot. *No one* using either tool recorded any names, organizations, locations, or events that were not explicitly written down, recorded in a Tablet view, in a visible document, or otherwise visible to the study participants. Thus no information was recalled purely from memory. The large display therefore aided their attempt to recall pertinent information by serving as an external memory resource.

5 DISCUSSION

Having described how the pairs of participants interacted with the large, high-resolution display, we can progress into a discussion of how the analytic tool chosen can impact the establishment of common ground, as well as how the large display supports co-located collaborative sensemaking.

5.1 Common Ground

Common ground is facilitated by an awareness of the actions of other collaborators. One way this can be achieved is through visible actions. Common ground can also be observed through the commonality of solutions.

5.1.1 Tool Visibility

In this study, the document viewer functioned as a strict WYSIWIS ("What you see is what I see") tool. Both participants were able to maintain an awareness of actions that were being taken on the display screen due to the visibility of the tool. For example, moving an entire document window across the screen is likely to catch the attention of the other user.

In contrast, actions taken in Jigsaw are more nuanced. In this study, Jigsaw acted as a relaxed WYSIWIS tool, allowing actions to be taken that the other person was not necessarily aware of. For example, when users explored entities in Jigsaw's List view, which often changes the lines that connect a specific entity (such as a person) to other entities (such as locations that person is associated with), the other participant rarely noticed if their attention was directed elsewhere. This effect was likely increased due to the smaller font size of Jigsaw (we were unable to manipulate this). Because it was more difficult for Jigsaw participants to see what their partner was doing, private space was more easily established. All Jigsaw groups that used the Tablet view placed this window in a central location, which served as a common space to record hypotheses. This view was placed in a more visible location for both participants.

The greater visibility of the document viewer compared with Jigsaw contributes to a better understanding of the document viewer participants' actions, granting them a greater awareness of the state of the sensemaking process.

5.1.2 Common and Not-So-Common Ground

Previously, we mentioned that all information reported in the individually-completed solution reports was visible either on physical artifacts (i.e. notes) or the display (Tablet, other Jigsaw views, or documents themselves), but we did not discuss where this information was located in relation to the two participants.

When teams recorded connected in a separate location (i.e. personal note paper, separate Tablet view), such as groups T2, J3, and J4, they constructed their solution reports primarily from their personal notes and thoughts, then supplemented the information with data visible on the display. Teams with a shared area for recording connections and thoughts, such as J2, also wrote down information that was located in the shared area, but interestingly, they were biased towards writing down information located on "their side" of the screen, presumably because they had contributed that piece of information and found it to be more important than their partner did.

Teams that were more successful in their group debriefing tended to have more similar solution reports, and less successful teams tended to have less similar reports [Table 1]. Similarity of individual reports was calculated by summing the people, organizations, locations, and events that were reported by both participants in the team then subtracting the amount of information that was reported by only one participant. These calculations suggest that there was more common ground inherent in the solution reports of the more successful teams. However, no groups produced identical individual reports. Ultimately, all groups were biased, to varying degrees, towards recording information on "their side" of the display (i.e. participant sitting on the left tended to record information on the left side of the display, participant sitting on the right tended to record information on the right side of the display).

None of the document viewer groups created a central document or location to record common thoughts, hypotheses, or connections. Even in the groups that chose to write on the whiteboard, only one person per group actually wrote on the board, and the other participant did not associate any meaning with the information recorded.

Interviewer: "*Does the whiteboard mean anything to you?*"

T4-B: "*No, no. Well the names for sure.*"

(She pauses to look over the whiteboard)

"*…But other than that, no, really not so much.*"

Instead, they relied on personal notes and common spatial awareness of the display space. During their group debriefing, it became clear that, in the more successful groups, expertise about certain people or events were left up to certain individuals. Both participants knew how these people and events fit into the bigger picture of the sensemaking scenario, but one person better knew the details contained in the relevant documents. In their debriefings, these teams (T1, T3, and T4) supplemented the explanations of their partners to support a coherent hypothesis. Thus they were able to maintain a common understanding of the relationships between the documents even if they were not experts on the entire document collection. This uneven balance of knowledge for some relevant events is represented in the individual score sheets, where there is a heavy focus on, for example, weapons thefts, while the other participant focused on illegal entry to the United States and the actions of these suspicious persons. However, a common place to record thoughts and hypotheses may have strengthened the cohesion of these groups' individual reports.

5.2 Large Displays for Collaborative Sensemaking

Large, high-resolution displays, such as the one shown in Figure 1, can support collaborative sensemaking by providing a large space that can be used to externalize connections between information due to spatial proximity. Participants using the data-centric document viewer tool laid out all documents on the display, which appears to have been an effective method of collaboratively making sense of the document collection.

It was possible to display 50 short text documents on the display, but the ability to display all documents will not scale to larger document collections. Instead, a better strategy would be to use a function-centric tool, such as Jigsaw, to narrow the focus of the investigation to a subset of documents that appear relevant. Then these documents could be arranged spatially on the large display. The function-centric tool would be needed to supplement this subset of documents as necessary by finding related documents as the collective understanding of the scenario evolves.

Additionally, a common space to record thoughts, connections, and hypotheses is an important component in maintaining collective knowledge and understanding. Jigsaw achieved this through their Tablet view. We feel that this "virtual whiteboard" is an important component of collaborative sensemaking visual analytics tools and tool designers should consider including a similar feature.

6 CONCLUSION

Through an exploratory study, we investigated spatial strategies adopted by teams of two participants as they worked on a large, high-resolution display equipped with multiple input devices to collaboratively make sense of a document collection concerning a fictional terrorist plot. Half of the teams used a data-centric document viewer tool, and half of the teams used a function-centric visual analytics tool (Jigsaw). We found that all of the teams used the large display as external memory and that most of the teams (all document viewer groups, and three out of four Jigsaw groups) used the display to impart spatial meaning upon information arranged into meaningful clusters. We then discussed how the location of information on the display translated into group and individual solution reports.

Through exploring these two tools, we have discovered that data-centric tools more naturally expand to fill the large display space, although function-centric tools are necessary to narrow down larger document collections before they can feasibly be used on a large, high-resolution display similar in size to the one seen in Figure 1.

We have contributed to the existing literature by finding the following results (in terms of co-located collaborative sensemaking for intelligence analysis on large, high-resolution vertical displays):

- Pairs of users spatially cluster information on large displays using a variety of organizational schemas (e.g. relevance, temporal, geographical).
- There is spatial meaning attached to clustered documents, but the meaning attached to document location is only perceived consistently when the organizational schema is explicitly discussed and agreed upon.
- Common knowledge of the organizational schema allows teams to maintain awareness of the other person’s actions and know how their areas of expertise fit into the overall hypothesis.
- The groups using the data-centric tool used more of the large display space than the function-centric tool groups. The groups that expanded to use more of the space were able to use the display as both a place to make connections and recall information.
- Large, high-resolution displays used as described in this study facilitate common ground by providing a transparent work environment, but common spaces are needed to combine thoughts and form hypotheses.

We hope to continue investigating co-located collaborative sensemaking on these displays. Future work includes examining interpersonal interactions more closely as well as investigating ways to enhance collaborative awareness. While large, high-resolution displays have the potential to enhance co-located collaborative sensemaking for intelligence analysis tasks, it is up to the visual analytics tools to tap this potential by exploiting this vast amount of available space to produce an environment that enhances common ground, ultimately producing more successful collaborative sensemaking.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants NSF-IIS-0851774 and NSF-CCF-0937133.

REFERENCES

[1] Thomas, J. and K. Cook, *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. 2005.

[2] Heer, J., *Design considerations for collaborative visual analytics.* Information visualization, 2008. **7**(1): p. 49-62.

[3] Heuer, R.J. and R.H. Pherson, *Structured Analytic Techniques for Intelligence Analysis*. 2010, Washington, DC: CQ Press.

[4] Chin, G., *Exploring the analytical processes of intelligence analysts*. 2009. p. 11.

[5] Gutwin, C., *Supporting informal collaboration in shared-workspace groupware.* Journal of universal computer science, 2008. **14**(9): p. 1411.

[6] Andrews, C., A. Endert, and C. North, *Space to think: large high-resolution displays for sensemaking*, in *Proceedings of the 28th international conference on Human factors in computing systems*. 2010, ACM: Atlanta, Georgia, USA.

[7] Vogt, K., et al., *Co-located Collaborative Sensemaking on a Large High-Resolution Display with Multiple Input Devices*, in *Conference on Human-Computer Interaction (INTERACT '11)*. 2011: Lisbon, Portugal.

[8] Stasko, J., *Jigsaw: supporting investigative analysis through interactive visualization.* Information visualization, 2008. **7**(2): p. 118-132.

[9] Lachowicz, D. *AbiWord*. 2010; Available from: http://www.abisource.com/.

[10] Chuah, M.C., *Visualizing common ground.* Information Visualisation (IV), International Conference on, 2003: p. 365-372.

[11] Clark, H.H., *Grounding in communication*. 1991, American Psychological Association. p. 127-149.

[12] Heer, J. and M. Agrawala, *Design considerations for collaborative visual analytics.* Information Visualization, 2008. **7**(1): p. 49-62.

[13] Gutwin, C. and S. Greenberg, *Design for individuals, design for groups: tradeoffs between power and workspace awareness*, in *Proceedings of the 1998 ACM conference on Computer supported cooperative work*. 1998, ACM: Seattle, Washington, United States.

[14] Stefik, M., et al., *Beyond the chalkboard: computer support for collaboration and problem solving in meetings.* Communications of the ACM, 1987. **30**(1): p. 32-47.

[15] Stewart, J.E., *Single display groupware*, in *CHI '97 extended abstracts on Human factors in computing systems: looking to the future*. 1997, ACM: Atlanta, Georgia. p. 71-72.

[16] Elrod, S., et al., *Liveboard: a large interactive display supporting group meetings, presentations, and remote collaboration*, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. 1992, ACM: Monterey, California, United States. p. 599-607.

[17] Pedersen, E.R., et al., *Tivoli: an electronic whiteboard for informal workgroup meetings*, in *Proceedings of the INTERACT '93 and CHI '93 conference on Human factors in computing systems*. 1993, ACM: Amsterdam, The Netherlands. p. 391-398.

[18] Rekimoto, J., *A multiple device approach for supporting whiteboard-based interactions*, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. 1998, ACM Press/Addison-Wesley Publishing Co.: Los Angeles, California, United States. p. 344-351.

[19] Wallace, J., et al., *Investigating teamwork and taskwork in single- and multi-display groupware systems.* Personal and Ubiquitous Computing, 2009. **13**(8): p. 569-581.

[20] Stewart, J., et al., *When two hands are better than one: enhancing collaboration using single display groupware*, in *CHI 98 conference summary on Human factors in computing systems*. 1998, ACM: Los Angeles, California, United States. p. 287-288.

[21] Stewart, J., B.B. Bederson, and A. Druin, *Single display groupware: a model for co-present collaboration*, in *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*. 1999, ACM: Pittsburgh, Pennsylvania, United States. p. 286-293.

[22] Birnholtz, J.P., et al., *An exploratory study of input configuration and group process in a negotiation task using a large display*, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007, ACM: San Jose, California, USA.

[23] Robinson, A. *Collaborative Synthesis of Visual Analytic Results*. in *IEEE Visual Analytics Science and Technology*. 2008.

[24] Green, T.M., W. Ribarsky, and B. Fisher, *Building and applying a human cognition model for visual analytics.* Information Visualization, 2009. **8**(1): p. 1-13.

[25] Pirolli, P. and S. Card. *The Sensemaking Process and Leverage Points for Analyst Technology as Identified Through Cognitive Task Analysis*. in *International Conference on Intelligence Analysis*. 2005.

[26] Plaisant, C., et al., *Evaluating Visual Analytics at the 2007 VAST Symposium Contest.* Computer Graphics and Applications, IEEE, 2008. **28**(2): p. 12-21.

[27] Paul, S.A. and M.C. Reddy, *Understanding together: sensemaking in collaborative information seeking*, in *Proceedings of the 2010 ACM conference on Computer supported cooperative work*. 2010, ACM: Savannah, Georgia, USA. p. 321-330.

[28] Paul, S.A. and M.R. Morris, *CoSense: enhancing sensemaking for collaborative web search*, in *Proceedings of the 27th international conference on Human factors in computing systems*. 2009, ACM: Boston, MA, USA. p. 1771-1780.

[29] Morris, M.R., J. Lombardo, and D. Wigdor, *WeSearch: supporting collaborative search and sensemaking on a tabletop display*, in *Proceedings of the 2010 ACM conference on Computer supported cooperative work*. 2010, ACM: Savannah, Georgia, USA. p. 401-410.

[30] Pioch, N.J. and J.O. Everett, *POLESTAR: collaborative knowledge management and sensemaking tools for intelligence analysts*, in *Proceedings of the 15th ACM international conference on Information and knowledge management*. 2006, ACM: Arlington, Virginia, USA. p. 513-521.

[31] Tobiasz, M., P. Isenberg, and S. Carpendale, *Lark: Coordinating Co-located Collaboration with Information Visualization*, in *IEEE Transactions on Visualization and Computer Graphics*. 2009. p. 1065-1072.

[32] Isenberg, P. and D. Fisher, *Collaborative Brushing and Linking for Co-located Visual Analytics of Document Collections.* Computer Graphics Forum, 2009. **28**(3): p. 1031-1038.

[33] Isenberg, P., et al. *An Exploratory Study of Co-located Visual Analytics around a Tabletop Display*. in *VAST*. 2010. Salt Lake City, Utah, USA: IEEE Computer Society.

[34] Ball, R., C. North, and D.A. Bowman, *Move to improve: promoting physical navigation to increase user performance with large displays*, in *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007, ACM: San Jose, California, USA. p. 191-200.

[35] Wallace, G. and K. Li, *Virtually shared displays and user input devices*, in *2007 USENIX Annual Technical Conference on Proceedings of the USENIX Annual Technical Conference*. 2007, USENIX Association: Santa Clara, CA. p. 1-6.

[36] Kang, Y.-a., C. Gorg, and J. Stasko, *Evaluating visual analytics systems for investigative analysis: Deriving design principles from a case study*, in *IEEE Visual Analytics Science and Technology*. 2009: Atlantic City, NJ. p. 139-146.