RAMPARTS: Supporting Sensemaking with Spatially-Aware Mobile Interactions

Paweł Woźniak[1*], **Nitesh Goyal**[2*]
Przemysław Kucharski[3], **Lars Lischke**[4], **Sven Mayer**[4], **Morten Fjeld**[1]
[1]t2i, Chalmers University of Technology, Gothenburg, Sweden, pawelw,fjeld@chalmers.se
[2]Cornell University, Ithaca, United States, ngoyal@cs.cornell.edu
[3]Lodz University of Technology, Łódź, Poland, p.kucharski@iis.p.lodz.pl
[4]VIS, University of Stuttgart, Stuttgart, Germany, {firstname.lastname}@vis.uni-stuttgart.de

ABSTRACT

Synchronous colocated collaborative sensemaking requires that analysts share their information and insights with each other. The challenge is to know when is the right time to share what information without disrupting the present state of analysis. This is crucial in ad-hoc sensemaking sessions with mobile devices because small screen space limits information display. To address these tensions, we propose and evaluate RAMPARTS—a spatially aware sensemaking system for collaborative crime analysis that aims to support faster information sharing, clue-finding, and analysis. We compare RAMPARTS to an interactive tabletop and a paper-based method in a controlled laboratory study. We found that RAMPARTS significantly decreased task completion time compared to paper, without affecting cognitive load or task completion time adversely compared to an interactive tabletop. We conclude that designing for ad-hoc colocated sensemaking on mobile devices could benefit from spatial awareness. In particular, spatial awareness could be used to identify relevant information, support diverse alignment styles for visual comparison, and enable alternative rhythms of sensemaking.

Author Keywords

spatial awareness; multi-device system; sensemaking

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Post 9/11, US Department of Justice released the National Criminal Intelligence Plan in October 2003 [21], suggesting better information sharing through colocated interaction between analysts as a measure to promote equal data access and support sensemaking. The plan outlined these measures because sharing privately held data between analysts for crime-solving has so far been a challenge [18, 17, 16]. The plan also
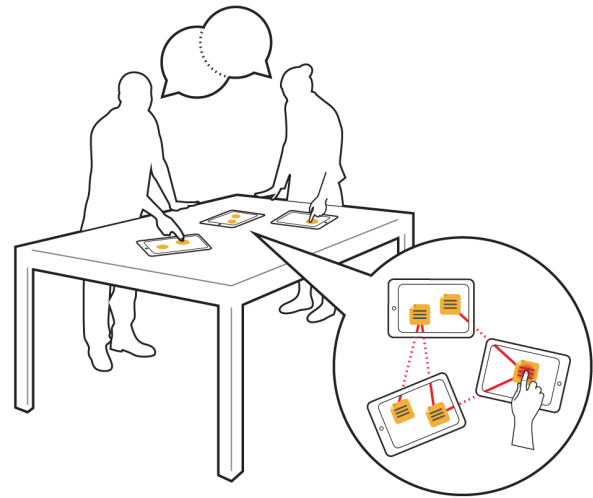
Figure 1. An overview of the RAMPARTS system design, which enables multiple users to collaborate on a sensemaking task using multiple mobile devices which use spatial-awareness to seamlessly share and identify relevant information.

called for development of technology that could mediate and support sensemaking for collaborators meeting ad-hoc with newer technologies like mobile devices. Since then, multiple design solutions like interactive tabletops [61], implicit sharing between collaborators [17, 19], visualizations to reduce biases [16], and ad-hoc connected spatially aware mobile devices for information sharing [52, 53, 64] have been pursued. We believe that providing spatial awareness for mobile devices can enhance capabilities for data exploration of private data shared during sensemaking tasks, which has been rarely explored.

Unlike mobile devices, high-end expensive solutions like tabletops are not always available and are even lesser preferred for collaborative sensemaking [5]. As users increasingly carry multiple mobile devices like tablets or smartphones [67], ad-hoc meetings with collaborators now can benefit from these multiple avenues to forage for and share information in real time. Device ethnography studies [34, 54] have shown that users are indeed seeking new ways to forage, share and perform collaborative sensemaking using mobile devices. While cross-device interaction across multiple devices has been pursued [4, 23, 38, 39, 41, 52], limited

progress has been made towards designing for spatial awareness between such devices [52, 53]. Colocated mobile devices have primarily been viewed as independent entities that are agnostic to the spatial location of other devices, rendering such collaborations tedious and non-optimal [20, 47]. Further, past work on sensemaking over multiple mobile devices has offered limited evaluation for single user scenarios [23]. On the contrary, this work pursues designing for sensemaking in ad-hoc collaborations where multiple spatially-aware mobile devices can now share private information easily.

While recent work in spatially aware solutions for colocated mobile devices like HuddleLamp [52] have been pursued, further research is needed to understand when spatial-aware interactions would be beneficial over the others [53]. To the best of our knowledge, RAMPARTS is the first spatially aware mobile device based system that has been evaluated to test its effectiveness in a sensemaking task. RAMPARTS uses commonplace, consumer hardware like multiple tablets to build an ad-hoc environment for colocated collaboration by supporting spatial information arrangement to forage for and connect data, important for sensemaking tasks like crime-solving. We evaluated RAMPARTS using a study where 27 pairs solved a crime mystery, against two popular alternatives: an interactive tabletop and a paper-based method. Our study showed that RAMPARTS reduced task completion time (TCT) significantly against Paper, and did not significantly affect TCT as compared to **T** yet offered the advantages of an inexpensive multi-device solution. We present design insights for ad-hoc multidevice systems, spatially aware interactions, and mobile collaborative sensemaking.

The paper makes the following contributions:

(1) Design and implementation of RAMPARTS, a research prototype which simulates an environment for spatially aware colocated collaborative sensemaking by focusing on interaction mechanisms for information sharing and analysis.

(2) User evaluation of RAMPARTS involving 27 pairs and comparison with two alternatives (tabletop & paper-based method) in a sensemaking task. Based on the evaluation, we suggest implications for the future design of spatially aware mobile multidevice systems for collaborative sensemaking.

Existing tools are impractical and/or do not provide spatial awareness. With inexpensive spatially aware RAMPARTS, students could collaborate to solve assignments. In crime-solving, investigators collect evidence in the field and hold that data privately in their mobile devices. So, RAMPARTS could enable them to share and analyze data in field by providing an easy, accessible way to do sensemaking using technology they always have in hand anyway.

RELATED WORK
RAMPARTS is a step towards building a new wave of tools for enhanced sensemaking in applications like data governance [63], citizen participation [11], and crime solving [18] where multiple users could bring their devices [2], interact with the information. We begin by unpacking previous work in sensemaking and situate RAMPARTS.

Sensemaking in Collaborative Analysis
As described by Pirolli and Card [51], sensemaking is an iterative process of foraging for information. Analysts iteratively forage clues and generate mental models that explain how these clues connect together coherently until they have found the solution [31]. Similarly, crime-Investigators are required to parse data, identify relevant clues from non-relevant ones, and identify a motive, location, and time of a crime that would incriminate the correct person [13].

While collaboration with other analysts who have access to rest of the clues can be advantageous because sharing solves otherwise unsolvable crimes [17, 27, 66].It has been found that sharing information and building upon shared information requires technology that supports making sharing and analysis *easy* for teams [31]. On the one hand successful collaborative sensemaking systems have to enable multiple collaborators to perform joint analysis, but on the other hand collaborators should be able to introduce pertinent privately held information, without disrupting ongoing analysis. We next discuss the tools for collaborative sensemaking and how they tackle these challenges.

Tools that support collaborative sensemaking
Shared workspaces have been shown to improve shared understanding and awareness [12] by improving information-sharing [27], improving common ground [66] and increasing partner awareness [7, 51]. Shared workspaces have also included creating collaborative visualizations [1, 6, 28, 32, 33, 59, 62], reminding analysts to view their partners analysis, as in AnalyticStream [49], and recommending relevant pieces of information from their partner [3] to increase awareness and reach common ground.

While both explicit sharing as suggested in these tools, and more recently, implicit sharing [17, 16] have been pursued, sensemaking has been pursued primarily using spatially agnostic devices [23]. Most of these tools do not enable ad-hoc introduction of spatially aware personal mobile devices for joint sensemaking sessions. Next we discuss why spatially aware interactions are important for sensemaking and current state-of-the-art.

Multi-device environments
Our work is also inspired by past research in how interaction mechanisms work between multi-display environments, particularly between larger stationary displays and mobile devices. The LunchTable [44] used multiple semi-public displays to create a casual discussion space in a lunch room. Wallace et al. [60] and [29] built systems to support sensemaking on a shared public interactive tabletop, additionally augmented by multiple user's private mobile devices. Lucero et al. [39] proposed a system for information sharing based on proximity through gestures. Further, EasyGroups [40] suggested other ways to couple smartphones to facilitate collaboration using a docking metaphor. Alternatively, Haber et al. [22] showed multiple tablets for reading and annotating text by splitting text across multiple displays. Similarly, Conductor [23] has been shown to facilitate sensemaking using

highlighting to enable easy transfer of content between multiple devices. Past work shows that multiple mobile devices are well suited for a number of tasks in collaborative settings like enabling sharing through proximity, splitting content across multiple devices for easier reading, and highlighting important content to be transferred across devices.

Spatially-aware interactions

Using the space between and around multiple devices as an extended interaction space, as well as using the relative distance between devices, has been receiving increasing attention in Human-Computer Interaction (HCI) literature. Several systems have been developed as non-mobile specialised environments for data analysis. For example, Spindler et al. [56] built a system where multiple spatially aware tablets could enable data exploration on an interactive tabletop using a virtual aquarium metaphor that can be explored using a magic lens. Another system by Spindler et al. [57] explored how depth sensing and top-down projection can augment environments to provide richer interaction with data using a Kinect sensor to detect hand gestures. More recently, Rädle et al. [53] have demonstrated that users do indeed show a preference for spatially aware interactions when performing gestures.

Spatial-awareness itself has also been found to improve interaction between mobile devices. HuddleLamp [52] showed that an inexpensive above-table sensor can be used to enable spatially aware navigation. Further, Thaddeus [64] has illustrated how interacting with information visualisation can be enhanced through spatial awareness using pointing with mobile devices. AdBinning [26] has also demonstrated that a mobile device can facilitate storing and managing map information when interacting with space around a device that acts like a bin. Alternatively, Piazza et al. [50] used a Microsoft PixelSense to simulate an environment where spatially aware tablets and smartphones together create a tool for drawing, reading, and gaming. As is evident, peripheral space has been researched for variety of tasks.

Our design and study is based on findings from [52] which showed that spatial-awareness is technically possible with low-cost sensing; while Rädle et al. [53] investigated short single-user tasks and focused on gesture design instead; and Hamilton et al. [23] focused only on the implementation of cross-device interaction in a limited small-scale study. While prior work shows that spatial awareness is beneficial to interaction with data and helps build effective information patterns, it remains unexplored as to how such systems might support a sensemaking task itself, and further to evaluate their use for sensemaking. In contrast, our work compares the impact of spatial awareness with tabletop and paper on a collaborative sensemaking task. To the best of our knowledge, we are the first to show low-cost spatially-aware mobile devices compared to interactive tabletop and paper-based solution in a specific design context.

Research in interactive tabletops has also shown that stationary horizontal interactive surfaces provide good opportunities for collaboration and enable multiple colocated users to work efficiently [30, 55, 31]. Given the increasing quantity of data being generated every day and the increasing need for data governance [63], tabletops have been suggested to provide a viable solution for collaborative sensemaking tasks like civic engagement requiring information gathering and parsing [11]. However, spatially aware devices placed together on a horizontal surface could potentially offer a better alternative for such collaborations and sensemaking [40] because users have reported spatially aware devices [53] to be more beneficial than spatially agnostic devices. There are three advantages to this strategy over an interactive tabletop: First, expensive and bulky interactive tabletops might not be always available or preferred [5]. Second, one could use both the physical artefacts lying on a table and the digital artefacts on mobile devices without occluding data. Third, users can conveniently share private information on their mobile devices as opposed to a single interactive display/surface. Finally, multi-device environments are likely to be much cheaper and more ubiquitous than tabletop computers for the foreseeable future.

DESIGN

RAMPARTS was designed taking into account the lessons learned from research discussed above in collaborative sensemaking and spatially-aware mobile devices. RAMPARTS focuses on providing functionalities suited for a well-defined task—a crime-solving exercise that requires information sharing across multiple devices in an ad-hoc meeting to identify a hidden profile [58]. Users may choose to spatially arrange data on shared surfaces in multiple ways, ranging from sharing entire datasets to sharing their insights alone. As suggested by Keel [36], arranging information in space supports cognition and additional information can be inferred from the way users arrange data on surfaces. One popular way of arranging data on surfaces in sensemaking tasks has been to write on sticky notes.

RAMPARTS was developed over multiple iterations. We describe below results from a preliminary study, and subsequent fully functional prototype details. In the study, we observed the process and outcome of sensemaking when users tried to parse clues, identifying a hidden profile and creating a story that supported their finding. We used low-fidelity paper sticky notes to understand their use of space, and analysed patterns as users collaborated with each other to move the relevant notes together into clusters for parsing the information.

Study task

For the study, we ran an exercise with multiple collaborators in a complex crime-solving task, like the murder mystery suggested by Stanford et al. [58]. Collaborators are given 31 clues, each on a sticky note, and have to identify the name of the criminal, and the location, time, and motive of the crime. Similar crime-solving tasks have been pursued to better understand how to design collaborative sensemaking [35, 18, 17, 16]. In the task, 5 people were involved in a murder mystery that took place between 11.30 pm and 1.30 am, where the criminal had to be identified within 25 minutes.

This task was made more complex by adding non-relevant information aimed to confuse the participants. The main challenge in the task was the fact that the victim (Mr. Kelley)
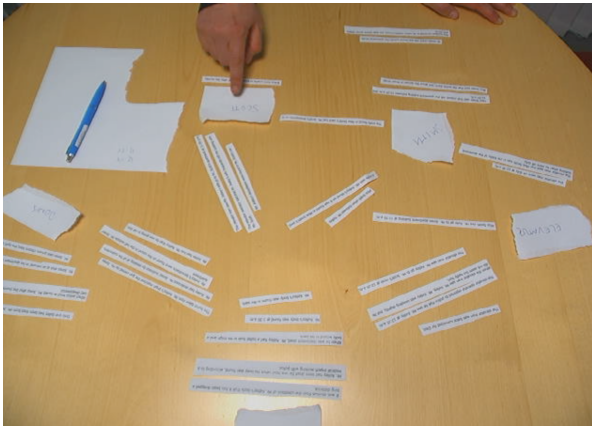
Figure 2. A participant in the preliminary paper-based study solving a crime mystery. The user identifies relevant clues and aligns them vertically as a support strategy.

was both shot and stabbed on the night of the crime. Participants had to understand the content in depth to separate the side plot from the main story. Separating the multiple plots enabled them to determine who wounded whom and which of the events was relevant. The solution, as given by Stanford et al. [58] was: *"After receiving a superficial gunshot wound from Mr. Jones, Mr. Kelley went to Mr. Scotts apartment where Mr. Scott killed him with a knife at 12:30 AM because Mr. Scott was in love with Mr. Kelleys wife.".*

Using a crime-solving task, in a preliminary study similar to Fisher et al. [10] we observed users employing strategies to spatially organise information, as described below.

Preliminary study

We conducted a preliminary study with five participants (3 male, 35–52 years old) to participate in an approximately half-hour study. These participants were recruited through snowball sampling and were peer researchers and students who performed the task voluntarily. After the study, participants were thanked and compensated with lunch. During the study, they were asked to solve a crime mystery using clues printed on strips of paper (shown in Figure 2). We asked the participants to think aloud (which has been shown to generate rich data without affecting their cognitive processes [8, 46] and describe their approach to the solution. All participants used some spatial strategies to organise the information. These could be classified primarily into the following themes.

Relevance: Firstly, grouping information, i.e. creating spatially separated clusters of paper strips, was the most often applied solution. Users would sort the notes several times based on different criteria e.g. selecting notes containing a particular name or place. One participant tore the answer sheet to create markers showing the centres of the different groups. Users also expressed their wish to mark the identified relationships between the clues (e.g. two clues containing the same name) in some way:

> I would like to be able to mark that Mr. Jones is on all of these strips. There's quite a lot of these clues.
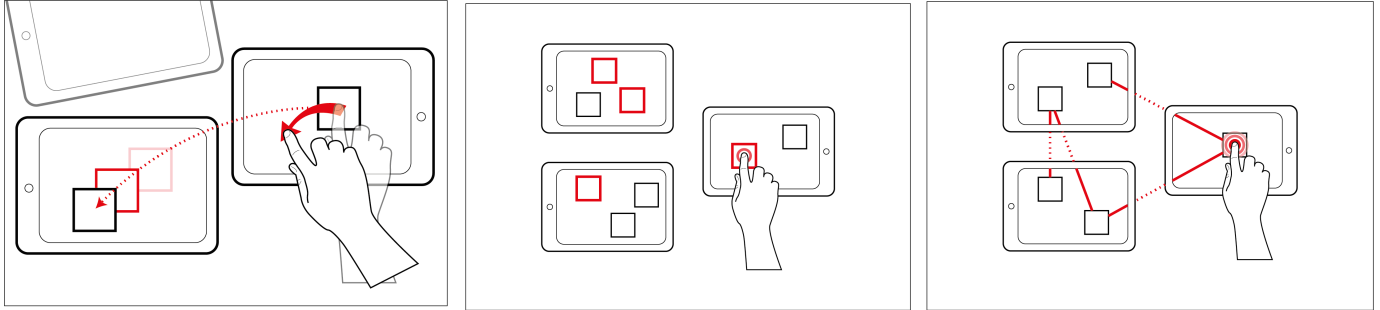
Alignment: Secondly, four participants would align the clues in a grid or along an axis to get an overview of one of the dimensions of the story. One participant constructed a two-dimensional grid where events were sorted chronologically on the horizontal axis and sorted by suspect names on the vertical axis.

Overall, results of our informal preliminary study were promising, suggesting that spatial arrangement of information contributed by multiple collaborators, referred to as *alignment* could be useful for identifying relationships represented by clusters, and *relevance* represented by highlighting. These results extend previous work by Fisher et al. [10] who found that despite the distributed nature of sensemaking, collaborators found organizational structure generated by previous collaborators to be highly useful for sensemaking. Further, we also found that simple paper sticky-notes could support spatial layouts and promote the development of rich mental schemas. We next examine these affordances by using digital sticky-notes that could afford similar interaction mechanisms by designing and evaluating RAMPARTS.

The RAMPARTS system

Through our preliminary study and using previous similar work [10], we noted that spatial awareness enriches the interaction when clues are distributed across collaborators. Users used the spatial relationships between the textual clues to support their sensemaking process. Consequently, RAMPARTS is built to support two design principles, *Relevance* and *Alignment*. We augmented RAMPARTS with features specific to the crime-solving hidden profile task. Here, we present the final design of the prototype. The system enables putting any number of mobile devices owned by collaborators on a horizontal surface and using them together to perform joint analysis. Multiple users share a common interaction space and collaborate by manipulating the clues, displayed as digital sticky notes, on and between these mobile devices. Such digital sticky notes have been shown to support externalizing and spatially organizing insights during collaborative sensemaking tasks previously [18, 17, 16].

RAMPARTS displays the clues available to the user in the form of "digital sticky notes" and enables a user to manipulate them freely. Sticky notes are fixed on tablet surfaces. This way, users can arrange pieces of information as they choose, both by using touch to move them on the device screens and using gestures to move them between devices (as suggested by Rädle et al. [53]). Users could also physically move the devices to move multiple sticky-notes simultaneously. A swipe (flick) gesture is used to transfer a sticky note to a neighbouring device. The direction of the swipe determines to which device the note is transferred. In order to simplify the interface, a note is always moved to the nearest device in the swipe direction. This mechanism is illustrated in Figure 3a. Swiping worked in six degree of freedom (6DoF) e.g. hovering a device above another device allowed users to "drop" a sticky note to the device below or "throw" a note up, just like how one would expect a physical sticky-note to perform.

(a) Swiping to transfer a sticky note to another tablet. RAMPARTS employs spatially-aware gestures to move notes between devices.

(b) Highltighting colours notes on all devices containing the same information as chosen by the user with a long tap.

(c) The timeline display, with a long tap on a date and time clues containing time information are highlighted and connected chronologically with lines across multiple devices.

Figure 3. Three interaction patterns in RAMPARTS. (a) shows moving sticky notes between tablets. The two sensemaking support features in RAMPARTS for solving the logical puzzle are shown in (b) and (c). The dotted lines are not displayed and the solid lines are visible in timeline mode.

As a response to the strategies participants employed in the paper-based preliminary study, we developed two interaction patterns that provided additional support for sensemaking.

Relevance: First, multicolour highlighting based on content helped users identify the distribution of people, objects, and locations among the clues. Our users were able to select a given piece of information (e.g. a name) to highlight all other sticky notes containing that information. The "origin" sticky note was then highlighted in a different colour. The feature was activated with a long tap on the information piece, in order to differentiate between this action and repositioning a sticky note, see Figure 3b.

Alignment: We created the timeline display inspired by how users arranged content along a chronological axis. We observed that the lack of additional visual aids made users employ complex grids. Consequently, we designed a help tool for aligning clues chronologically. Activated by a long tap on a time expression (e.g. a date and/or time), RAMPARTS highlighted all the other notes containing time expressions and connected them with lines in a chronological order as shown in Figure 3c.

Both the highlighting, and timelines spanned between multiple devices thus showing the continuity of a single multi-display interaction space. The display was updated when the devices were moved or sticky notes repositioned so that the users could benefit from the chronological ordering and clustering simultaneously. Having identified *Relevance* and *Alignment* as RAMPARTS's two interaction mechanisms, we now discuss the implementation details for RAMPARTS.

IMPLEMENTATION
RAMPARTS consists of three main components: the motion tracking system, the RAMPARTS mobile application, and the coordination server.

As our work focuses on designing and understanding interaction for spatially aware environments, we chose the most accurate method of acquiring positional information available—infrared marker-bases 6DoF motion tracking. Past work [52] and current commercial developments have shown

that embedded accurate mutual positional sensing will soon be available for commercial smartphone models. Consequently, we assume that a marker-based solution accurately approximates the predictable future technical landscape. This assumption is also a foundation of past work e.g. [26].

We used Qualisys Oqus technology to acquire positional information. The devices are identified in the system and tracked as rigid bodies in 6DoF. The Qualisys Track Manager (QTM) Real Time Server provides tracking information (i.e. the position and orientation of all the devices) and streams it over a network protocol. The positional information is transmitted over a wireless network to the RAMPARTS server. In order to provide accurate tracking even when occlusions occur, we use a ceiling-mounted system with 8 cameras.

RAMPARTS is implemented as an application for the Android mobile operating system. The application needs to be installed on each of the devices in order for them to be part of the system. The RAMPARTS interface is adaptable to screen size. Functionality of the application includes displaying sticky notes, moving them within a tablet, throwing them to a different tablet, activating the highlight and activating the timeline. All the spatially-aware interactions on the devices are prompted by the server. Application can receive signals to display a new sticky note, to highlight a sticky notes or display the timeline. In case of the timeline, the coordinates for drawing the chronological lines are provided by the server.

The RAMPARTS server processes the positional information received from the QTM server to determine the desired behaviour of the mobile devices based on their spatial arrangement. It also acts as an intermediary for communicating user interactions between devices. In order to complete these tasks, the server stores and updates the positions of all the devices and sticky notes in the global coordinate system (i.e. the coordinate system of the motion tracking data). All devices receive commands from the server. The server notifies devices about: interaction with other devices, the need to display new content and activating the sensemaking support features. The devices also report any user input to the server and server replies with the appropriate response. It

is capable of simultaneously responding to events occurring on all the devices. When a user performs the swipe action to throw a sticky note to another device, the original device provides the coordinates of the sticky note and the swiping vector in the device's local coordinate system. The vector is then transformed to the global coordinate system using the device size and the Euler angles provided by motion tracking. Virtual lines are connecting the original device with all other devices are then created. The line closest to the vector is identified to choose the target device. Boundary conditions prevent swiping into spaces where no device is present. Similarly, to display the timeline, each consecutive pair of chronologically ordered sticky notes is connected with a line in the global coordinate system. Next, the visible parts of the lines are recalculated to the local coordinate systems of the devices and a line drawing command is sent.

HYPOTHESIS AND RESEARCH QUESTION

We adopted the following hypothesis for the study:

H: Due to sensemaking features, RAMPARTS (R) will shorten task completion time in comparison to paper (P).

As prior work has shown that digital tools can support sensemaking effectively, we expected that the enhanced sensemaking support features of **R** would allow for solving the crime mystery faster than when using analogue tools. Additionally, we investigated one research question:

RQ: How well does low-cost **R** perform compared to a high-end tabletop (**T**)?

As no past work explored spatial-awareness for sensemaking, but several sources confirmed the effectiveness, we endeavoured to explore how the low-cost ad-hoc **R** would compare to the an expensive tabletop system.

EVALUATION

This section describes the study we performed to evaluate RAMPARTS to better understand the cost vs. benefit ratio analysis of enabling such a system over traditional interactive tabletops—as well as paper—in terms of accuracy, efficiency, and team-experience. In a between-subjects study we compared RAMPARTS (condition **R**) to two systems, a tabletop system (condition **T**) and a paper-based solution with sticky notes (condition **P**). Participants were asked to solve the crime solving task we used in the preliminary study.

Participants

A total of 54 participants (38 male, 16 female, aged 18–61, $M = 28.81, SD = 10.16$) completed the study. The participants were recruited by word of mouth at the university campus. Remuneration was provided in the form of a small gift of choice selected from a gift box (maximum value 20 USD). 60 Users were recruited individually and 30 pairs were matched through matching schedules and preferred study times. Six users quit the study while it was incomplete or did not provide full answers to the measures. Consequently, we excluded these participants from the analysis. This resulted in 18 participants in the **R** condition, 20 participants in the **T** condition and 16 participants in the **P** condition. Users self-reported as strangers. We anticipate that some of them might have familiar with interacting with a tablet. None of them were familiar with interactive tabletops. None of them were familiar with digital implementations of sticky notes.
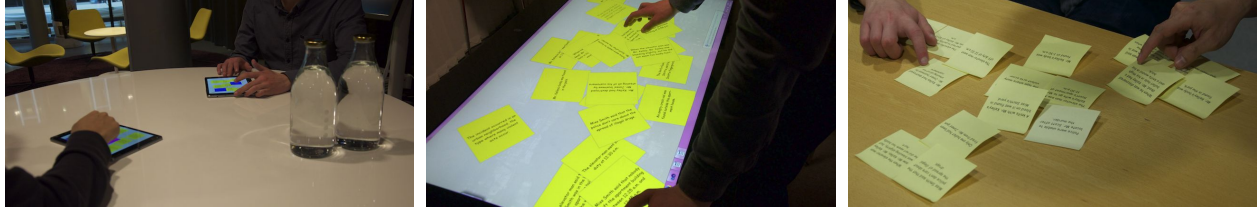
Apparatus

In the **R** condition, the RAMPARTS system was deployed on three HTC NEXUS 9 tablets (8.9 in screen diagonal) as shown in Figure 4a. Tablets were placed on a table measuring $100\,cm \times 130\,cm$. A Qualisys Oqus with 8 cameras hanging from the ceiling of the room was used for motion tracking with markers ($0.5\,cm$ in diameter) attached directly to the tablets. A high table was used and two chairs were provided so that the participants could freely choose to perform the task sitting or standing. The chairs were placed slightly off the table to suggest that the participants were free to arrange the furniture as they wished. The clues were equally distributed in stacks on the three tablets. The server software logged features used throughout the experiment.

In the **T** condition, a tabletop application was developed for the user study (see Figure 4b). The system provided the same features as RAMPARTS, but it worked on the Samsung SUR40 interactive table, which implies a working area of $88.5\,cm \times 49.8\,cm$. The table ran the Microsoft PixelSense framework and represents a common format for an interactive table, with a history of successful deployments (e.g. [42, 43]). The application presents clues in three stacks of sticky notes that use the same font and colour as RAMPARTS. Due to the dimensions of the table, participants were initially seated in this condition, but were reminded they could move freely around the room.

In the **P** condition, participants were presented with three randomised stacks of pre-printed sticky notes containing clues placed on a table measuring $120\,cm \times 120\,cm$, as shown in Figure 4c. The colour of the notes and the font matched those of the two other conditions. The chair-and-table arrangement replicated the one in the **R** condition and participants were free to choose their stance. Participants were free to modify the pre-printed sticky notes in the **P** condition, as they would in the other 2 conditions. All sessions were recorded using a video camera and a conference microphone. Participants expressed their consent to the recording prior to the study. In all three conditions, a pre-printed answer sheet was available along with a single pen which they were asked to fill out at the end. In all three conditions, the initial arrangement of notes was similar. Three piles were placed at same spots and in relative distance to each other. We controlled for the different table size by ensuring that when spread out, all the sticky-notes would require space proportionately greater than the available surface in all the 3 conditions. Consequently, all the experimental conditions had amount of sticky notes that would be equally hard to spreading across the surface, forcing the users to find strategies to effectively manage space if they wanted to have an overview of all the data.

Procedure

Each participant was individually greeted by the experimenter and then introduced to their partner for the study. A short demographics questionnaire was then administered. Next, the

| (a) Condition **R** — RAMPARTS | (b) Condition **T** — tabletop system | (c) Condition **P** — printed sticky notes |

Figure 4. The three experimental conditions used to evaluate RAMPARTS.

participants were introduced to the task, the functionalities of the system in the condition then were assigned, and they were then asked to play the role of analysts. A sample task was prepared with the same number of clues as the crime-solving tasks, but with far less difficulty. Participants were given as much time as they required to familiarise themselves with the functionality of the system and the experimenter was available to answer any questions.

Having assured that the participants were comfortable using the system, they were introduced to the task using the task source book [58]. Users had to juxtapose, combine, and eliminate cues to determine the murderer, the time of the murder, the location, and the weapon. The number of clues provided is intended to be large enough to warrant a discussion and require more than one person to solve effectively. There were redundant clues in the set and participants were supposed to agree to eliminate them. The experimenter then handed the participants the answer sheet and a pen. Participants were informed that the estimated time for completing the task was 25 minutes. However, they were welcome to take as much time as they required. We instructed participants to prioritise accuracy over speed and be as certain as possible about the answer before they decided they were finished.

The solution to the puzzle was then revealed. Next, each participant individually completed a questionnaire consisting of the "raw" NASA Task Load Index (NASA-TLX) [24] to measure the perceived workload. The study ended with a debriefing and a semi-structured interview where participants were asked to comment on their experience of the system, the perceived difficulty of the system, their strategy of solving the problem, and how the system supported the chosen strategy.

Measures

We used three data sources to evaluate RAMPARTS: Video and audio recording, answer sheets with name of criminal and associated details, and post-task survey responses about workload and team-experience.

Task Performance: Accuracy and Task Completion Time

As two indicators of task performance we use TCT and the quality of the answers. TCT is the time between when the question sheet was given to the participants and when it was handed back to the experimenter. The time was measured by the experimenter. The accuracy of the answers on the question sheet was measured by correct answers. Each of the four questions, name of criminal, location, time, and motive was rated binary as right or wrong.

Perceived Workload

Each participant rated the perceived workload of the study task with the six NASA-TLX questions, focusing on physical demand, temporal demand, performance, effort, and frustration [25]. In modification to the original NASA-TLX, we renounced weighting single questions. This modification is often applied and well known as raw NASA-TLX [24].

Sticky Moves

We measured how users manipulated the sticky notes over the duration of the sensemaking task, and how in particular they moved them around to create new solutions. One of the experimenters analysed the session video recordings to count how often the sticky notes were rearranged over two time intervals: first half, second half, and in total to understand the rhythm of sensemaking. A move was counted as a movement of one or group of sticky notes (with a swipe or drag) or moving paper. Moving multiple notes with a single move was only possible in the **P** condition (when they were glued together) and this was also counted as one move. The counting began after the first 5 minutes of the task, to avoid differences due to modalities and initial setup.

Results

Task Performance: Accuracy

Most participants delivered correct answers (4 out of 4 murder circumstances reported correctly). One participant pair in the **T** condition produced an entirely wrong answer (0 out 4 correct answers). Another group provided a partial answer (3 out of 4 answers, condition **T**). Overall, we saw no significant difference in the accuracy.

Task Performance: Task completion time

TCTs were extracted from the video recordings and the results are shown in Figure 5a. The lower the TCT, the better the Task Performance. Both, **R** ($M_R = 1320\,s, SD_R = 253\,s$) and **T** ($M_T = 1578\,s, SD_T = 275\,s$) system performed better than **P** ($M_P = 1941\,s, SD_P = 499s$) owing to the sensemaking features. A one-way ANOVA was performed to determine the significance of the mean differences between the three conditions. The main effect of experimental condition on TCT was statistically significant ($F_{2,22} = 6.97$, $p = 0.005$). Despite the unequal sample sizes, Levene's test of inequality was found to be insignificant (p = 0.128). Gabriel post hoc test for small variation in the sample size correction revealed that **R** performed significantly better than **P** ($p = 0.01$ after Bonferroni Correction). Results support our Hypothesis H that sensemaking features in **R** shortens TCT compared to **P**.

With regard to RQ, low cost **R** performs equally well compared to high-end **T**

Perceived workload
NASA-TLX questionnaire results are presented in Figure 5b. The three conditions reported similar aggregate scores: $M_R = 9.40$, $SD_R = 3.24$; $M_T = 8.61$, $SD_T = 2.63$; and $M_P = 8.16$, $SD_P = 2.08$. A Mixed Effects model with pair as the random effect and condition as the independent variable revealed no significant difference in the reported NASA-TLX scores ($F_{2,24} = 0.543$, $p = 0.59$).

Sticky Moves
We also recorded how often the sticky notes were moved by the participants for *relevance* or change existing *alignment*. In the first half of the TCT, users did not manipulate sticky notes any differently across the three conditions ($M_R = 41.11$, $SD_R = 39.20$; $M_T = 50.90$, $SD_T = 31.01$; $M_P = 44.86$, $SD_P = 17.79$; $F_{2,24} = 0.25$, $p > 0.05$), suggesting that users approached the task similarly at the onset. In contrast, a significant difference was observed for the number of sticky notes moved in the second half of the task ($M_R = 16.44$, $SD_R = 14.83$; $M_T = 94.2$, $SD_T = 55.04$, $M_P = 61.88$, $SD_P = 54.00$, $F_{2,24} = 6.98$, $p < 0.01$). Post hoc tests revealed a difference in the rhythm of sensemaking because RAMPARTS users moved significantly fewer notes around than the **T** condition in the second half of the task ($p < 0.05$). Additionally, a Pearson Product-Moment calculation revealed that there was no correlation between TCT and number of sticky notes moved ($r = 0.09$, $p > 0.1$).

Qualitative observations from RAMPARTS
Two researchers watched all the recorded video material from condition **R** and the videos were coded for participant position and device management. An additional discussion was then conducted and all coding discrepancies were eliminated. Overall, 3 pairs out of 9 decided to sit opposite each other. These three pairs chose to use one tablet per person as a "personal" device and put the remaining tablet in the middle of the table to share information. Six pairs decided to sit shoulder to shoulder and they, consequently, chose to employ different
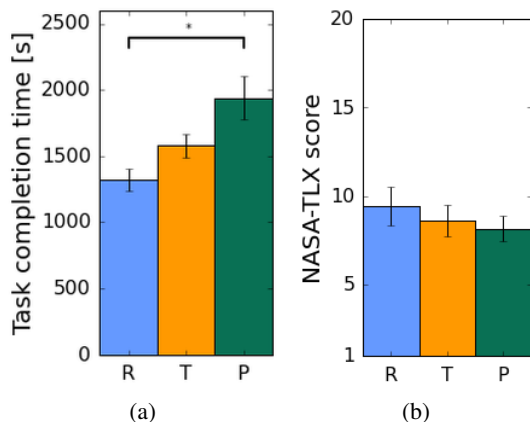

Figure 5. Mean values for task completion time (TCT) and NASA-TLX in the experimental conditions, the error bars representing the standard error. The statistically significant difference between R and P in TCT is marked with a *.
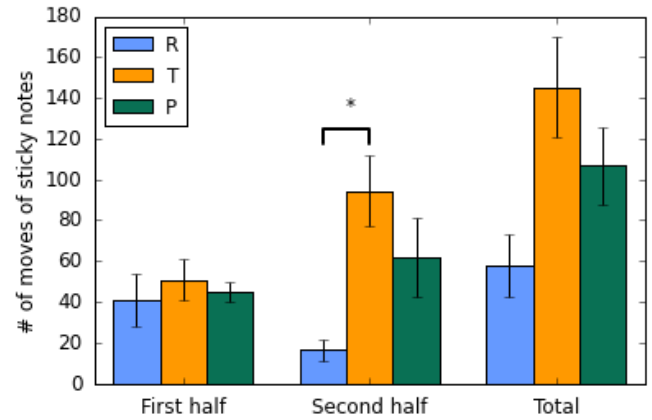

Figure 6. The number of sticky notes moved in the first half of the task, the second half, and in total for the three conditions. Statistically significant results are marked with *.

tablet arrangements. Five participants spread the three tablets horizontally or almost horizontally. These pairs would then initially process the information on each tablet individually, tablet by tablet before starting collaborative work. The users would then arrange information spatially, splitting it between the three devices. They used their finger or a pen to attract the attention of their partner. One of the participants commented positively on the ability to arrange the sticky notes spatially:

> The ability to arrange them spatially was really good, it makes the task easier. [Participant RA05]

Another pair used a strategy where one user dominated and led the discussion and controlled two tablets in a line and the other user provided relevant information from the third tablet. Users would also often move one of the tablets up to indicate on which device they were focusing at a given moment. One user decided to periodically remove one tablet from the line and move above a second one to compare information (Figure 7a) — whenever they felt two facts led to a conclusion or appeared to be contrary, the user would move one tablet out of the line to focus the discussion on resolving the issue. That movement would be then repeated each time a discussion was required to agree on a conclusion based on information from two tablets. Another pair placed an L-shaped (Figure 7b) tablet structure in the very centre of the table, interacting with the three devices as if they were a single large interactive surface. This happened once the group individually browsed the information on the three tablets, the L-shaped structure showed a transition between acquainting oneself with the data and beginning a discussion with the partner. The sensemaking support features like Highlighting for *Relevance* in RAMPARTS were reported as useful tools:

> I really enjoyed painting it with the green colour, I didnt have to look which one is about the same topic, with my partner we could just click on it. [Participant RB03]

One pair used a "three-dimensional" approach (Figure 7c). One user would often hover the tablet above the other tablets and "pour" sticky notes onto them. They would raise the tablets above the table to direct the partner's attention and compare information with a tablet laying on the table. They would also both hold their tablets up high to juxtapose their
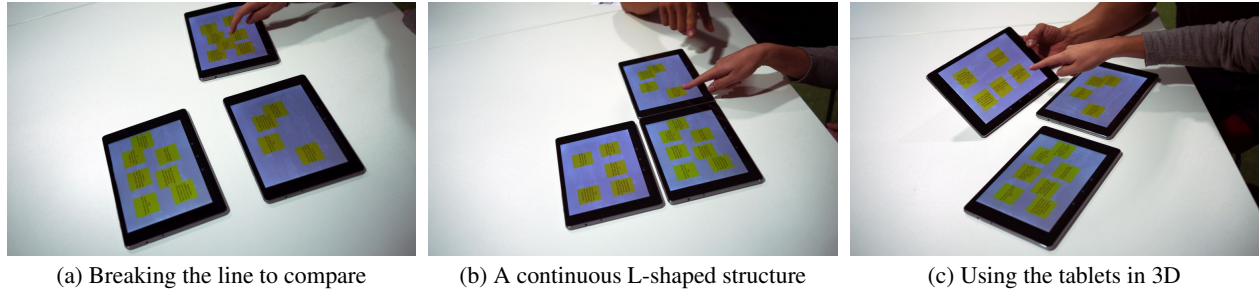
| (a) Breaking the line to compare | (b) A continuous L-shaped structure | (c) Using the tablets in 3D |

Figure 7. Excerpts of study footage showing the different spatial strategies employed by the participants to facilitate solving the crime mystery.

individual findings. Another group specifically planned individual and group work phases. They spread all the notes onto two tablets and then analysed individually, temporarily ignoring the third device. A discussion phase followed and the entire process was repeated three times with a final discussion. Users also reflected on the tangibility of the tools and the ability to distribute the content between the different tablets for *Alignment*. They also confirmed that spatial arrangements of the tablets were use to filter and combine information:

> I started assigning spaces to information, for example this is a pile of irrelevant information. [Participant RA04]

DISCUSSION

We found that both **R** and **T** performed better than **P** because sensemaking features implemented were indeed effective and supported our Hypothesis.

One possible explanation for **R**'s performance is that participants used the tablets as containers to categorise pieces of information (for example RA04). The affordance of display bezels to been seen as information containers is well described previously in literature [61]. Devices in our study allowed for crisp divisions between data sets, offering support for *relevant* information clustering. Furthermore, tablets themselves can be moved around like sticky notes. This is an advantage over the other 2 conditions where sticky clusters couldn't be moved conveniently. Our results suggest that the tangibility of individual tablets can provide extensive support for organising information. While this was hinted in Conductor [23], RAMPARTS shows that these affordances are also valid in a collaborative setting. The lack of significant differences in NASA TLX results shows that the technology used in all three conditions required a similar amount of effort from the users.

Surprisingly, we observed a significant decrease in the number of notes moved towards the end of the task with RAMPARTS. During the second half of the experiment, sticky notes were moved far lesser in **R** than in **T** and **P**. Based on qualitative observations, As note groups could be moved by manipulating tablets, fewer moves were needed to move groups in **R**. No such physical categorization was possible in **T** and **P**. On the other hand, even though users moved notes far lesser in **T** than **R**, they were equally effective in terms

of TCT. Determining the cause of that difference remains an open question.

Further, difference in the number of notes moved during the different phases of sensemaking points to different *rhythms of sensemaking* supported by different technologies. While it must be pointed out that all conditions moved approximately similar number of sticky notes throughout the task duration, some conditions involved higher note manipulation towards the end as opposed to earlier on. Perhaps, spatial awareness reduces the need for moving notes, because *relevant* sticky clusters represented by tablets acting as "bins" can be moved around and aligned in multiple styles to perform visual comparison.

In support of our RQ, while we observed no significant difference in TCT between RAMPARTS and tabletop, we believe that **R** has key advantage over **T**, because RAMPARTS supports creating ad-hoc environments by converting mobile devices into a multidisplay interface. As postulated by Fjeld et al. [11], further research is needed for turning everyday spaces into interactive discussion environments. In contrast to a bulky and expensive tabletop interface, RAMPARTS uses on-body mobile devices, ready for use in casual settings. On the other hand, we also show that the significant decrease in TCT confirms observations previously made by Hamilton and Wigdor [23] about multiple distributed devices being effective in supporting sensemaking.

We believe the insights presented here are not exclusive to crime solving. Our work generalizes beyond crime-solving tasks in other similar collaborative time critical tasks like crisis-informatics and medicals ensemaking in hospitals. Further, technology used in spatially aware mobile devices in RAMPARTS, would enable evidence collected by analysts (in the field) across domains like citizen science to be seamlessly shared for colocated analytics not depending on situated high-end infrastructure. For example, citizen scientists could gather soil samples data, and then use RAMPARTS to perform partial analytics, generate new insights and reduce workload, all in the field [45].

Furthermore, in domains beyond crime-solving, the specific sensemaking features of RAMPARTS could also be useful. For example, researchers reported temporal ordering as important for collaborative web search [48]. Overcrowding of hospitals requires better analysis by nurses [49] could be improved by visualizing algorithmically identified relevant data

as offered by RAMPARTS. Such scenarios are likely to be encountered in domains such as emergency response [37] and firefighting [9]. This illustrates a key advantage of RAMPARTS over tabletop — RAMPARTS can be an effective tool to proliferate digitally-supported sensemaking to new domains as it uses mobile devices that are likely to increase in number and availability. In contrast, tabletop interfaces are becoming less common. As a consequence, we interpret the lack of significant differences between **T** and **R** positive.

LIMITATIONS

RAMPARTS is primarily designed to simulate spatial awareness with multiple mobile devices for colocated collaborative sensemaking. However, RAMPARTS has been evaluated with a limited number of devices handled by a pair of collaborators in a relatively short-lived collaborative sensemaking task of a particular type. Scaling up the number of devices or users might introduce potential challenges like information management across the multiple devices. Longer term sensemaking might require provenance of analysis to ensure that analysis performed in the past is not lost in the future. Further, lab settings enable designers to vary design choices in controlled settings to understand the effects of each choice across multiple measure. Field research is needed to understand the impact of spatially aware mobile devices in real life crime solving teams with datasets of varying sizes. We hope that future work will address some of these challenges.

DESIGN IMPLICATIONS

The findings of our work have implications for designing colocated distributed collaborative sensemaking tools. Since the presence of spatial awareness had no negative effect on task performance compared to expensive bulky tabletops, we propose that tools should support spatial awareness to promote timely information sharing. We see spatially aware mobile device solutions like RAMPARTS as a part of the larger design landscape of colocated collaborative sensemaking tools. While at one end, one may design for sterile static environments like "war rooms" replete with interactive tabletops and large wall displays. On the other end, designers might need to support ad-hoc sensemaking tasks by analysts on the move while crowds-on-call aid them with sensemaking tasks [14, 15]. We locate RAMPARTS somewhere in the middle, where impromptu ad-hoc sensemaking is performed by the analysts themselves using devices on hand. By simulating and evaluating a *spatially aware system* that can effectively support sensemaking, we demonstrated that spatial awareness allowed users to organise information (transferring sticky notes between devices) and facilitate their collaborative sensemaking process (e.g. by moving devices to manage attention). Consequently, we believe that future systems should consider the spatial aspect of interaction and strive to support *relevance* and *alignment* through spatially aware gestures [53].

Within the larger design landscape, designers may choose to create solutions that interact only with other mobile devices, or might also integrate colocated non-digital artefacts into sensemaking processes. While RAMPARTS is designed closer to the former solution, our study revealed that some participants used mobile devices in the space above the table with *three-dimensional interactions* such as dropping post-it notes onto another device as a filter. While 3D interactions were used in past static systems (e.g. [56]), most designs have so far suggested treating the surface of the table on which the devices are placed as a continuous 2D interaction space (e.g. [65]). We believe that future work should provide extensive support for 3D interactions between mobile and non-mobile devices available in the environment to enable ad-hoc sensemaking. This design direction furthers the National Criminal Intelligence Plan [21] that suggests enabling novel technologies for colocated sensemaking between analysts.In crime-solving, investigators collect evidence in the field and hold that data privately in their mobile devices. RAMPARTS could enable them to share and analyze data in the field by providing an easy, accessible way to do sensemaking using technology they already have in hand. Consequently, we see an emerging need to investigate how multi-device systems could perform in crime-solving field work.

Further, designers should consider designing for different phases of analysis. We found that spatially aware mobile devices involve fewer movements of notes towards the latter half of the task. Future tools could appropriate user activity logs to identify different phases of analysis. Tools could help generate *relevant* recommendations when foraging, and support *alignment* for storytelling during the sensemaking. For example, foraging could be supported through recommendations based on Natural Language Processing of text. Alternatively, sensemaking could be supported through generating alternative storylines that could explain the events. Finally, identifying patterns of successful behaviour might help create tools that could train the analysts to best use the time at hand and potentially reduce the large number of unsolved crime cases, awaiting attention.

CONCLUSIONS

In this paper, we presented the design of RAMPARTS, a sensemaking tool that supports spatial awareness for mobile devices in colocated collaborative environments. We presented the findings from an experiment in which pairs of participants played the role of crime analysts collaborating to identify a criminal. We found that RAMPARTSs spatial-awareness decreased task completion time when compared to a paper-based system, without any adverse effect on task completion time compared to a tabletop, and without increasing perceived cognitive workload. We also discovered that using RAMPARTS resulted in significantly decreased note manipulation in the later stages of sensemaking, suggesting a different rhythm of sensemaking being pursued in RAMPARTS.

REFERENCES

1. Aruna D. Balakrishnan, Susan R. Fussell, and Sara Kiesler. 2008. Do Visualizations Improve Synchronous Remote Collaboration?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 1227–1236. DOI:http://dx.doi.org/10.1145/1357054.1357246

2. Rafael Ballagas, Michael Rohs, Jennifer G Sheridan, and Jan Borchers. 2004. BYOD: Bring Your Own Device. *Proceedings of the 2004 Workshop on Ubiquitous Display Environments* (2004).

3. Eric A. Bier, Stuart K. Card, and John W. Bodnar. 2010. Principles and Tools for Collaborative Entity-Based Intelligence Analysis. *IEEE Transactions on Visualization and Computer Graphics* 16, 2 (March 2010), 178–191. DOI:http://dx.doi.org/10.1109/TVCG.2009.104

4. Nicholas Chen, François Guimbretière, and Abigail Sellen. 2013. Graduate Student Use of a Multi-slate Reading System. In *Proceedings of the 2013 SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1799–1808. DOI:http://dx.doi.org/10.1145/2470654.2466237

5. George Chin, Jr., Olga A. Kuchar, and Katherine E. Wolf. 2009. Exploring the Analytical Processes of Intelligence Analysts. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 11–20. DOI:http://dx.doi.org/10.1145/1518701.1518704

6. Haeyong Chung, Seungwon Yang, Naveed Massjouni, Christopher Andrews, Rahul Kanna, and Chris North. 2010. Vizcept: Supporting synchronous collaboration for constructing visualizations in intelligence analysis. In *IEEE Symposium on Visual Analytics Science and Technology (VAST '10)*. IEEE, 107–114. DOI:http://dx.doi.org/10.1109/VAST.2010.5652932

7. Gregorio Convertino, Helena M. Mentis, Mary Beth Rosson, Aleksandra Slavkovic, and John M. Carroll. 2009. Supporting Content and Process Common Ground in Computer-supported Teamwork. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 2339–2348. DOI:http://dx.doi.org/10.1145/1518701.1519059

8. Beth Davey. 1983. Think aloud: Modeling the cognitive processes of reading comprehension. *Journal of Reading* (1983), 44–47.

9. Sebastian Denef, Leonardo Ramirez, Tobias Dyrks, and Gunnar Stevens. 2008. Handy Navigation in Ever-changing Spaces: An Ethnographic Study of Firefighting Practices. In *Proceedings of the 7th ACM Conference on Designing Interactive Systems (DIS '08)*. ACM, New York, NY, USA, 184–192. DOI:http://dx.doi.org/10.1145/1394445.1394465

10. Kristie Fisher, Scott Counts, and Aniket Kittur. 2012. Distributed Sensemaking: Improving Sensemaking by Leveraging the Efforts of Previous Users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 247–256. DOI:http://dx.doi.org/10.1145/2207676.2207711

11. Morten Fjeld, Paweł Woźniak, Josh Cowls, and Bonnie Nardi. 2015. Ad hoc encounters with big data: Engaging citizens in conversations around tabletops. *First Monday* 20, 2 (Feb. 2015). DOI:http://dx.doi.org/10.5210/fm.v20i2.5611

12. Darren Gergle, Robert E Kraut, and Susan R Fussell. 2004. Language efficiency and visual technology minimizing collaborative effort with visual information. *Journal of language and social psychology* 23, 4 (2004), 491–517.

13. Steven Gottlieb, Sheldon I Arenberg, Raj Singh, and others. 1994. *Crime analysis: From first report to final arrest*. Alpha Publishing Montclair, CA.

14. Nitesh Goyal. 2015. Designing for Collaborative Sensemaking: Using Expert & Non-Expert Crowd. *arXiv preprint arXiv:1511.06053* (2015).

15. Nitesh Goyal and Susan R Fussell. 2015. Designing for Collaborative Sensemaking: Leveraging Human Cognition For Complex Tasks. *arXiv preprint arXiv:1511.05737* (2015).

16. Nitesh Goyal and Susan R Fussell. 2016. Effects of Sensemaking Translucence on Distributed Collaborative Analysis. (2016). http://www.cs.cornell.edu/~ngoyal/Goyal_CSCW2016_preprint.pdf

17. Nitesh Goyal, Gilly Leshed, Dan Cosley, and Susan R. Fussell. 2014. Effects of Implicit Sharing in Collaborative Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 129–138. DOI:http://dx.doi.org/10.1145/2556288.2557229

18. Nitesh Goyal, Gilly Leshed, and Susan R. Fussell. 2013a. Effects of Visualization and Note-taking on Sensemaking and Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 2721–2724. DOI:http://dx.doi.org/10.1145/2470654.2481376

19. Nitesh Goyal, Gilly Leshed, and Susan R. Fussell. 2013b. Leveraging Partner's Insights for Distributed Collaborative Sensemaking. In *Proceedings of the 2013 Conference on Computer Supported Cooperative Work Companion (CSCW '13)*. ACM, New York, NY, USA, 15–18. DOI:http://dx.doi.org/10.1145/2441955.2441960

20. Saul Greenberg, Nicolai Marquardt, Till Ballendat, Rob Diaz-Marino, and Miaosen Wang. 2011. Proxemic Interactions: The New Ubicomp? *interactions* 18, 1 (Jan. 2011), 42–50. DOI:http://dx.doi.org/10.1145/1897239.1897250

21. Global Intelligence Working Group and others. 2003. National criminal intelligence sharing plan. *US Departent of Justice* 12 (2003), 2011.

22. Jonathan Haber, Miguel A. Nacenta, and Sheelagh Carpendale. 2014. Paper vs. Tablets: The Effect of Document Media in Co-located Collaborative Work. In *Proceedings of the International Working Conference on Advanced Visual Interfaces (AVI '14)*. ACM, New York, NY, USA, 89–96. DOI:http://dx.doi.org/10.1145/2598153.2598170

23. Peter Hamilton and Daniel J. Wigdor. 2014. Conductor: Enabling and Understanding Cross-device Interaction. In *Proceedings of the 2014 SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 2773–2782. DOI:http://dx.doi.org/10.1145/2556288.2557170

24. Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 50. Sage Publications, 904–908. DOI:http://dx.doi.org/10.1177/154193120605000909

25. Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Human Mental Workload*, Peter A. Hancock and Najmedin Meshkati (Eds.). Advances in Psychology, Vol. 52. North-Holland, 139 – 183. DOI:http://dx.doi.org/10.1016/S0166-4115(08)62386-9

26. Khalad Hasan, David Ahlström, and Pourang Irani. 2013. Ad-binning: leveraging around device space for storing, browsing and retrieving mobile device content. *Proceedings of the 2013 SIGCHI Conference on Human Factors in Computing Systems* (2013), 899–908. DOI:http://dx.doi.org/10.1145/2470654.2466115

27. Jeffrey Heer and Maneesh Agrawala. 2008. Design considerations for collaborative visual analytics. *Information visualization* 7, 1 (2008), 49–62.

28. Jeffrey Heer, Fernanda B. Viégas, and Martin Wattenberg. 2009. Voyagers and Voyeurs: Supporting Asynchronous Collaborative Visualization. *Communications of the ACM - Rural engineering development* 52, 1 (Jan. 2009), 87–97. DOI:http://dx.doi.org/10.1145/1435417.1435439

29. Tobias Hesselmann, Niels Henze, and Susanne Boll. 2010. FlashLight: Optical Communication Between Mobile Phones and Interactive Tabletops. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, NY, USA, 135–138. DOI:http://dx.doi.org/10.1145/1936652.1936679

30. Uta Hinrichs, Sheelagh Carpendale, and Stacey D. Scott. 2006. Evaluating the Effects of Fluid Interface Components on Tabletop Collaboration. In *Proceedings of the 2006 Working Conference on Advanced Visual Interfaces (AVI '06)*. ACM, New York, NY, USA, 27–34. DOI:http://dx.doi.org/10.1145/1133265.1133272

31. Petra Isenberg, Danyel Fisher, Sharoda A. Paul, Meredith Ringel Morris, Kori Inkpen, and Mary Czerwinski. 2012. Co-Located Collaborative Visual Analytics Around a Tabletop Display. *IEEE Transactions on Visualization and Computer Graphics* 18, 5 (May 2012), 689–702. DOI:http://dx.doi.org/10.1109/TVCG.2011.287

32. Jeroen Janssen, Gijsbert Erkens, Gellof Kanselaar, and Jos Jaspers. 2007. Visualization of participation: Does it contribute to successful computer-supported collaborative learning? *Computers & Education* 49, 4 (2007), 1037–1065. DOI:http://dx.doi.org/10.1016/j.compedu.2006.01.004

33. Sirkka L Jarvenpaa and D Sandy Staples. 2000. The use of collaborative electronic media for information sharing: an exploratory study of determinants. *The Journal of Strategic Information Systems* 9, 2 (2000), 129–154. DOI:http://dx.doi.org/10.1016/S0963-8687(00)00042-1

34. Tero Jokela, Jarno Ojala, and Thomas Olsson. 2015. A Diary Study on Combining Multiple Information Devices in Everyday Activities and Tasks. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3903–3912. DOI:http://dx.doi.org/10.1145/2702123.2702211

35. Ruogu Kang and Sara Kiesler. 2012. Do Collaborators' Annotations Help or Hurt Asynchronous Analysis. In *Proceedings of the ACM Conference on Computer Supported Cooperative Work Companion (CSCW '12)*. ACM, New York, NY, USA, 123–126. DOI:http://dx.doi.org/10.1145/2141512.2141558

36. Paul Keel. 2006. Collaborative Visual Analytics: Inferring from the Spatial Organization and Collaborative Use of Information. In *2006 IEEE Symposium On Visual Analytics And Technology*. IEEE, 137–144. DOI:http://dx.doi.org/10.1109/VAST.2006.261415

37. Jonas Landgren and Urban Nulden. 2007. A Study of Emergency Response Work: Patterns of Mobile Phone Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 1323–1332. DOI:http://dx.doi.org/10.1145/1240624.1240824

38. Ming Li and Leif Kobbelt. 2012. Dynamic Tiling Display: Building an Interactive Display Surface Using Multiple Mobile Devices. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia (MUM '12)*. ACM, New York, NY, USA, Article 24, 4 pages. DOI:http://dx.doi.org/10.1145/2406367.2406397

39. Andrés Lucero, Jussi Holopainen, and Tero Jokela. 2011. Pass-them-around: collaborative use of mobile phones for photo sharing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM Press, New York, 1787. DOI: http://dx.doi.org/10.1145/1978942.1979201

40. Andrés Lucero, Tero Jokela, Arto Palin, Viljakaisa Aaltonen, and Jari Nikara. 2012. EasyGroups: binding mobile devices for collaborative interactions. In *Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems (CHI EA '12)*. ACM Press, New York, 2189. DOI: http://dx.doi.org/10.1145/2212776.2223774

41. Andrés Lucero, Jaakko Keränen, and Hannu Korhonen. 2010. Collaborative Use of Mobile Phones for Brainstorming. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*. ACM, New York, NY, USA, 337–340. DOI: http://dx.doi.org/10.1145/1851600.1851659

42. Sebastian Marwecki, Roman Rädle, and Harald Reiterer. 2013. Encouraging Collaboration in Hybrid Therapy Games for Autistic Children. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. ACM, New York, NY, USA, 469–474. DOI: http://dx.doi.org/10.1145/2468356.2468439

43. Robert Morawa, Tom Horak, Ulrike Kister, Annett Mitschick, and Raimund Dachselt. 2014. Combining Timeline and Graph Visualization. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)*. ACM, New York, NY, USA, 345–350. DOI: http://dx.doi.org/10.1145/2669485.2669544

44. Miguel A. Nacenta, Mikkel R. Jakobsen, Remy Dautriche, Uta Hinrichs, Marian Dörk, Jonathan Haber, and Sheelagh Carpendale. 2012. The LunchTable: A Multi-user, Multi-display System for Information Sharing in Casual Group Interactions. In *Proceedings of the International Symposium on Pervasive Displays (PerDis '12)*. ACM, New York, NY, USA, Article 18, 6 pages. DOI: http://dx.doi.org/10.1145/2307798.2307816

45. Greg Newman, Andrea Wiggins, Alycia Crall, Eric Graham, Sarah Newman, and Kevin Crowston. 2012. The future of citizen science: emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment* 10, 6 (2012), 298–304.

46. Janni Nielsen, Torkil Clemmensen, and Carsten Yssing. 2002. Getting Access to What Goes on in People's Heads?: Reflections on the Think-aloud Technique. In *Proceedings of the Second Nordic Conference on Human-computer Interaction (NordiCHI '02)*. ACM, New York, NY, USA, 101–110. DOI: http://dx.doi.org/10.1145/572020.572033

47. Antti Oulasvirta. 2008. FEATURE: When Users "Do" the Ubicomp. *interactions* 15, 2 (March 2008), 6–9. DOI: http://dx.doi.org/10.1145/1340961.1340963

48. Sharoda A. Paul and Meredith Ringel Morris. 2009. CoSense: Enhancing Sensemaking for Collaborative Web Search. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 1771–1780. DOI: http://dx.doi.org/10.1145/1518701.1518974

49. Sharoda A. Paul and Madhu C. Reddy. 2010. Understanding Together: Sensemaking in Collaborative Information Seeking. In *Proceedings of the 2010 ACM Conference on Computer Supported Cooperative Work (CSCW '10)*. ACM, New York, NY, USA, 321–330. DOI: http://dx.doi.org/10.1145/1718918.1718976

50. Tommaso Piazza, Morten Fjeld, Gonzalo Ramos, AsimEvren Yantac, and Shengdong Zhao. 2013. Holy Smartphones and Tablets, Batman!: Mobile Interaction's Dynamic Duo. In *Proceedings of the 11th Asia Pacific Conference on Computer Human Interaction (APCHI '13)*. ACM, New York, NY, USA, 63–72. DOI: http://dx.doi.org/10.1145/2525194.2525205

51. Peter Pirolli and Stuart Card. 2005. The sensemaking process and leverage points for analyst technology as identified through cognitive task analysis. In *Proceedings of international conference on intelligence analysis*, Vol. 5. 2–4.

52. Roman Rädle, Hans-Christian Jetter, Nicolai Marquardt, Harald Reiterer, and Yvonne Rogers. 2014. HuddleLamp: Spatially-Aware Mobile Displays for Ad-hoc Around-the-Table Collaboration. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)*. ACM Press, New York, 45–54. DOI: http://dx.doi.org/10.1145/2669485.2669500

53. Roman Rädle, Hans-Christian Jetter, Mario Schreiner, Zhihao Lu, Harald Reiterer, and Yvonne Rogers. 2015. Spatially-aware or Spatially-agnostic?. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM Press, New York, New York, USA, 3913–3922. DOI: http://dx.doi.org/10.1145/2702123.2702287

54. Stephanie Santosa and Daniel Wigdor. 2013. A Field Study of Multi-device Workflows in Distributed Workspaces. In *Proceedings of the ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '13)*. ACM, New York, NY, USA, 63–72. DOI: http://dx.doi.org/10.1145/2493432.2493476

55. Stacey D. Scott, M. Sheelagh T. Carpendale, and Kori M. Inkpen. 2004. Territoriality in Collaborative Tabletop Workspaces. In *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work (CSCW '04)*. ACM, New York, NY, USA, 294–303. DOI: http://dx.doi.org/10.1145/1031607.1031655

56. Martin Spindler. 2012. Spatially aware tangible display interaction in a tabletop environment. *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces* (2012), 277. DOI: http://dx.doi.org/10.1145/2396636.2396679

57. Martin Spindler, Wolfgang Büschel, Charlotte Winkler, and Raimund Dachselt. 2014. Tangible displays for the masses: Spatial interaction with handheld displays by using consumer depth cameras. *Personal and Ubiquitous Computing* 18 (2014), 1213–1225. DOI: http://dx.doi.org/10.1007/s00779-013-0730-7

58. Gene Stanford and Barbara Dodds Stanford. *Learning Discussion Skills Through Games*. Citation Press. 75 pages.

59. Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. 2006. Collaborative Coupling over Tabletop Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. ACM, New York, NY, USA, 1181–1190. DOI:http://dx.doi.org/10.1145/1124772.1124950

60. James R. Wallace, Stacey D. Scott, and Carolyn G. MacGregor. 2013. Collaborative Sensemaking on a Digital Tabletop and Personal Tablets: Prioritization, Comparisons, and Tableaux. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 3345–3354. DOI: http://dx.doi.org/10.1145/2470654.2466458

61. James R. Wallace, Daniel Vogel, and Edward Lank. 2014. Effect of Bezel Presence and Width on Visual Search. In *Proceedings of the International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, Article 118, 6 pages. DOI: http://dx.doi.org/10.1145/2611009.2611019

62. C. Weaver. 2007. Is Coordination a Means to Collaboration?. In *Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV '07)*. 80–84. DOI: http://dx.doi.org/10.1109/CMV.2007.15

63. Sebastian Weise, John Hardy, Pragya Agarwal, Paul Coulton, Adrian Friday, and Mike Chiasson. 2012. Democratizing Ubiquitous Computing: A Right for Locality. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing (UbiComp '12)*. ACM, New York, NY, USA, 521–530. DOI: http://dx.doi.org/10.1145/2370216.2370293

64. Paweł Woźniak, Lars Lischke, Benjamin Schmidt, Shengdong Zhao, and Morten Fjeld. 2014a. Thaddeus: A Dual Device Interaction Space for Exploring Information Visualisation. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational (NordiCHI '14)*. ACM, New York, NY, USA, 41–50. DOI: http://dx.doi.org/10.1145/2639189.2639237

65. Paweł Woźniak, Benjamin Schmidt, Lars Lischke, Zlatko Franjcic, Asim Evren Yantaç, and Morten Fjeld. 2014b. MochaTop: Building Ad-hoc Data Spaces with Multiple Devices. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. ACM, New York, NY, USA, 2329–2334. DOI: http://dx.doi.org/10.1145/2559206.2581232

66. William Wright, David Schroh, Pascale Proulx, Alex Skaburskis, and Brian Cort. 2006. The Sandbox for Analysis: Concepts and Methods. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. ACM, New York, NY, USA, 801–810. DOI: http://dx.doi.org/10.1145/1124772.1124890

67. Kathryn Zickuhr and Lee Rainie. 2013. Tablet ownership 2013. *Pew Research Center report, pewinternet.com* (2013), 11. http://fullrss.net/r/http/pewinternet.org/~/media/Files/Reports/2013/PIP_Tabletownership2013.pdf