Investigating Awareness-Supporting Techniques in Co-located Sensemaking

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Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Computer Science and Applications

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June 27, 2019

Blacksburg, Virginia

Keywords: Collaboration, Sensemaking, Awareness

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(ABSTRACT)

Co-located sensemaking has benefitted from multi-user multi-touch devices such as tabletops and wall-mounted displays. Sensemakers use these displays to establish personal workspaces in which to perform individual sensemaking tasks, while preserving a shared space for the exchange and integration of findings. A large open interaction space allows multiple sensemakers to interact with the display at the same time and to communicate with partners face-to-face. However, collaborative systems must balance the tradeoff between working separately to complete individual work, and the need to communicate and maintain collaborative awareness. Dividing the tasks and working at the same time might encourage more alternative exploration paths, but reduced social exchange could also lead to weak mutual understanding and increased effort for work integration. Furthermore, close collaboration on the same task increases mutual awareness, but the tendency toward one-person dominance or turn-taking interaction underutilizes individual time and space, thereby reducing the benefits of divide-and-conquer. The four studies introduced in this dissertation investigated co-located space factors for notifications and shared visualization as two *awareness-supporting techniques* to assist individual contribution and teamwork. The research identifies *control*, *awareness*, and *communication* as key co-located space factors to balance cooperation, coordination, contribution, and communication. Knowledge on how notification and visualization techniques affect the co-located factors is explored and summarized. The findings identify design knowledge to better balance the individual work and styles of collaboration. Finally, this dissertation concludes by examining how awareness-supporting techniques affect the relationship between control, awareness, and communication.

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(GENERAL AUDIENCE ABSTRACT)

Co-located sensemaking has benefitted from multi-user multi-touch devices such as tabletops and wall-mounted displays. Sensemakers use these displays to perform individual sensemaking tasks, while preserving a shared space for the exchange and integration of findings. A large open interaction space allows multiple sensemakers to interact with the display at the same time and to communicate with partners face-to-face. However, collaborative systems must balance individual work and collaboration with other partners. Dividing the sensemaking tasks and working at the same time might encourage more alternative exploration paths, but reduced conversation could also lead to weak mutual understanding and increased effort for work integration. Furthermore, close collaboration on the same task increases mutual understanding, but the tendency toward one-person dominance or turn-taking interaction reduces the benefits of divide-and-conquer. Through four studies, this dissertation investigates notifications and shared visualization as two *awareness-supporting techniques* to assist individual contribution and team work. The research identifies *individual control*, *awareness*, and *communication* as key co-located space factors to balance cooperation, coordination, contribution, and communication. Knowledge on how notification and visualization techniques affect the co-located space factors is explored and summarized, to better design collaborative systems to support co-located sensemaking.

Dedication

Mom, Dad, and Yanshen, I made it!

Acknowledgments

Six years in Blacksburg can be so fast and so slow. The first day I arrived was like yesterday, and good and bad, happiness and sorrow, and confidence and confusion endured for days and nights. I appreciate everyone who held, loved, and encouraged me. This six-year Ph.D. journey couldn't have been so beautiful without you.

I wish to give my special thanks to my advisor, Dr. D. Scott McCrickard, my academic father, for bringing me into and educating me about the academic world. I couldn't have survived this journey without your patient guidance and support, as well as all the nice jokes and food you brought.

I also thank all my committee members – Edward A. Fox, Steve Harrison, Chris North, and Shahtab Wahid. Dr. Fox invited me to his project meetings and gave me much advice on collecting and retrieving Twitter data. Professor Harrison contributed many ideas in studying co-located collaboration. I took Dr. North's class, from which I gained much knowledge on data visualization. The card-based sensemaking idea originated from Dr. Wahid's dissertation work on PIC-UP. The input from all of you broadened the scope of this dissertation.

I wish to thank all my lab brothers and sisters who helped with the tedious but important work. Lindah, Tim, and Derek spent so many days helping me encode the video. Undergraduate students Sophia and Julia did an excellent job running the user studies. Kavin, Usman, and Sushant helped me implement and test the tabletop interface. I collaborated with Andrey and Seyam on the education approaches for mobile software development class.

I was lucky to have so many wonderful friends at VT. Hotpot-Fridays were the happiest time of the week. We ate, gamed, and laughed, sweeping all the tiredness and pressure away.

Last but not the least, I cannot be who I am today without my family. My father, Xiaoguang

Niu, and my mother, Rongge Jiao, always support me by my side and give me love, strength, and wisdom. My wife, Yanshen Yang, who married me at beautiful Mountain Lake near Virginia Tech, helped me so much when I was occupied by the work. I love you.

I will miss every single day I spent with my advisor, committee members, professors, and friends at Virginia Tech. Thank you for being with me in the six unforgettable years. The Hokie spirit is in my blood. It built a solid foundation for and will be the source of inspiration in my future life and career.

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List of Abbreviations

CSCW Computer Supported Cooperative Work

MDEs Multi-display environments

NLP Natural Language Processing

VIS visualization

VISGRAINS Visualize Group Activities in Sensemaking

NLP is a field of computer science, artificial intelligence, and linguistics concerned with the interactions between computers and human (natural) languages.

MDEs refers to the co-located workspace consisting of multiple interactive displays to allow several co-located people to work at the same time.

VIS in this dissertation refers to data visualization which uses shapes, colors, and other visual indicators to present data and interactions performed on the data.

CSCW refers to the research area which conducts studies in the design and use of technologies that affect groups, organizations, and communities.

VISGRAINS refers to the system designed and implemented in Chapter 6. It is a co-located sensemaking system to support retrieving, visualization, and organization of large social media datasets.

Chapter 1

Introduction

This research focuses on identifying key co-located space factors that balance individual and collaborative work. The design and evaluation of notifications and collaborative visualizations contribute to the understanding of how they affect co-located space factors, leading to different types of individual and team work. Furthermore, user studies deepen our knowledge of collaborative sensemaking and awareness-supporting in co-located sensemaking. This initial chapter provides an overview of the research domain, culminating in three key research questions and six sub-questions to be addressed in this dissertation.

1.1 Research Domain

Co-located sensemaking has benefitted from shared devices and multi-display environments (MDEs), which support multiple sensemakers collaborating in the same space at the same time. Sensemakers switch between working individually in personal workspaces and working collaboratively to exchange and discuss knowledge [161]. The present research examines **awareness-supporting techniques** in co-located sensemaking systems – designs that notify or connect related individual work on shared devices. Through a series of studies, this dissertation explains the effects of awareness-supporting techniques in balancing individual participation and collaborative activities through **control**, **awareness**, and **communication**. Shared displays improve the efficiency of collaboration and effectiveness in sensemaking

[48, 73, 79, 176], but a systemic understanding is lacking regarding how awareness-supporting techniques such as notifications and collaborative visualizations could present and relate group activities. Recent advancements in data processing and visualization offer new possibilities to automatically identify related items from individual work. This research explores the design of notification systems and shared overviews to inform group sensemaking activities and to affect individuals' control over data representations, awareness of each other's sensemaking activities, and face-to-face communication about the sensemaking tasks. The knowledge on how to raise awareness of related work contributes to the understanding of sensemaking collaboration and system design to support co-located sensemaking.

Sensemaking is a process in which sensemakers forage for key information and identify useful subsets, organize knowledge representations, and make high-level hypotheses [134]. Sensemaking tasks require people to visit the data to extract useful information, and to associate that information to generate knowledge. Co-located sensemaking systems providing individual clients for accessing data support sensemakers to exchange and integrate information. In co-located sensemaking, some activities are better performed individually to divide and conquer, while others require joint attention and discussion. Browsing and filtering the data can help identify useful subsets and collect information to answer different questions, which can be completed individually. In contrast, exchanging information about individual findings and discussing final outcomes necessitates close collaboration. The need for individual consumption of the data and eventual knowledge integration requires sensemaking systems to support simultaneous exploration and knowledge sharing and discussion. Notifications influence awareness in collaborative systems [47, 48, 54]. Displaying notifications in a shared workspace could support the awareness of others' activities when working individually, but may come with an attentional cost. Shared visualizations offer visual spaces for communication, but it is then necessary to consider how the task division and awareness maintenance are affected. System designers need to understand how different options of presenting group work could facilitate individual participation as well as joint attention.

Devices that support multi-user interactions benefit co-located sensemaking activities because they allow multiple people to work at the same time. Multi-display environments (MDEs) consisting of personal and shared displays enable co-located sensemakers to explore, organize, and discuss digital content in the co-located space. Earlier collaborative sensemaking systems in MDEs incorporated computers and projectors to present group work [92, 138]. Recent advancements in ubiquitous displays such as large tabletops and wall-mounted displays offer natural touch interactions and support multiple users interacting with data representations at the same time [70]. The open space also forms a face-to-face environment to communicate information and knowledge. Sensemakers can establish individual spaces to work simultaneously, and form a shared space to maintain awareness of others' work and communicate about findings (Figure 1.1). Multi-user multi-display environments can support simultaneous work, but the research on how surface-based systems can better notify sensemakers of each other's work and present integrated work is still in its infancy.

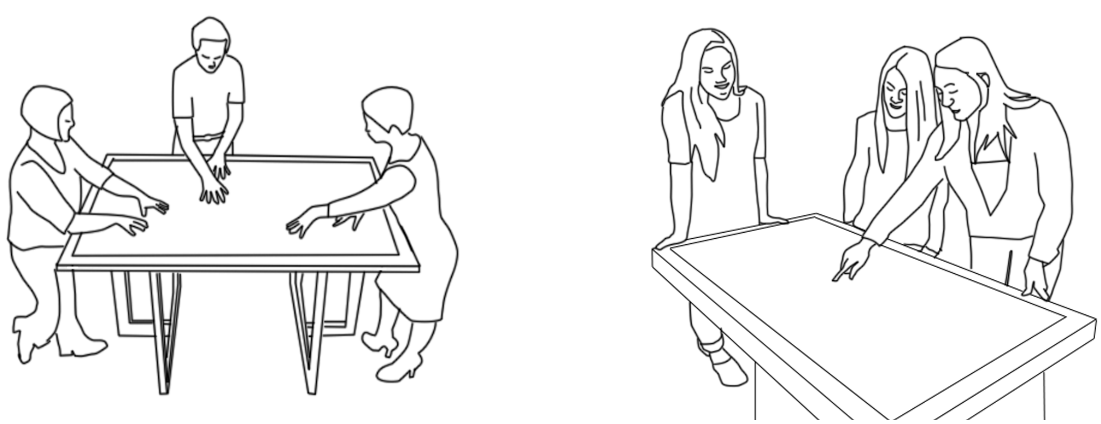

Figure 1.1: Sensemakers can establish personal spaces or focus on the same view with a shared tabletop display.

Designers of collaborative systems on large shared displays need to consider how sensemakers work with each other. Understanding whether, what, and how sensemaking activities should be connected or separated helps better design such systems. The division of the effort between individual sensemaking and participating group activities has been identified as a collaboration tradeoff [52]. Gutwin et al. described this tradeoff as follows:

> *"Individuals demand powerful and flexible means for interacting with the workspace and its artifacts, while groups require information about each other to maintain awareness."*

Sensemakers divide the labor to achieve personal sensemaking goals, and also collaborate closely on the joint task [161]. Though social communication and close collaboration could lead to better awareness of each other's activities [14, 75, 172], collaborators still prefer to keep individual workspaces open to interact at the same time [99]. Furthermore, dividing the task and working simultaneously could increase the coverage and diversity of the information [113, 154], but working in parallel also hinders the understanding of each other's findings and insights [172]. Sensemaking tasks with complex data could be divided and assigned to individual sensemakers [85], however, individual work must still be exchanged and integrated eventually. Considering the need for mixed-focus collaboration and group dynamics during co-located sensemaking [52], the design of collaborative systems with notifications and visualizations should consider how to allocate the visual space for individual and group information, and how to indicate related work from different sensemakers. Introducing widgets that indicate collaborative information in MDEs could boost sensemaking by generating higher awareness and tightened discussion; poorly designed shared views may also degrade sensemaking output by interrupting individual work and hindering coordination. Therefore sensemaking system designers need to understand how the presentation of group work affects different co-located space factors and how these factors lead to different styles of individual and collaborative work.

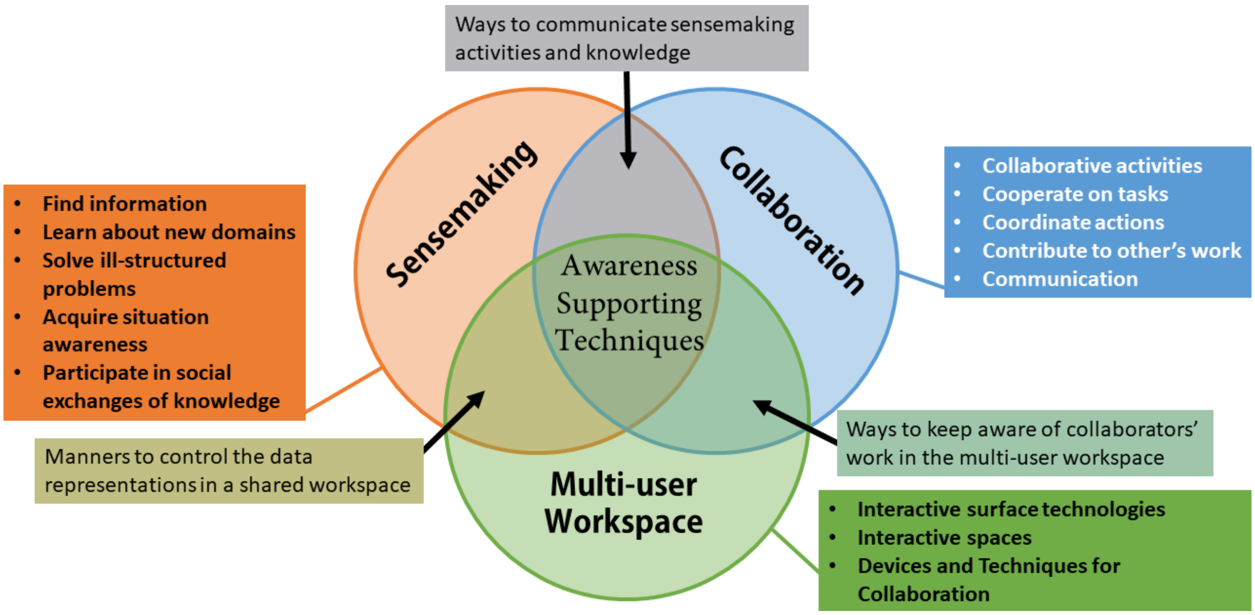

Figure 1.2: The domain of this research is at the intersection of sensemaking, collaboration, and multi-user workspace, with a focus on awareness supporting techniques. This research explores how awareness-supporting techniques affect manners sensemakers control the data representations in a multi-user workspace, ways sensemakers communicate sensemaking activities and knowledge during collaboration, and ways to keep aware of other collaborators' work performed in the multi-user workspace.

The domain of this research lies at the intersection between sensemaking, collaboration, and multi-user workspace. Sensemaking systems not only need to support finding information, but learning about new domains, solving ill-structured problems, acquiring situation awareness, and participating in social exchanges of knowledge [134, 135]. Collaborative technologies for information-intensive tasks consider how systems support communication, contribution, coordination, and cooperation [153]. Multi-user workspaces implemented with shared displays interactive surface technologies offer interactive spaces to support collaboration [75]. This research investigates notifications and collaborative visualizations as examples of awareness-supporting techniques in a tabletop-based workspace, to present and connect personal work and balance the tradeoff between individual participation and group activities. These techniques support awareness and affect sensemakers' manners to control the data representations in a shared workspace, ways to keep aware of collaborators' work in the multi-user workspace, and ways to communicate sensemaking activities and knowledge. Notification systems [20, 109] facilitate awareness by drawing attention and briefing workspace knowledge [54]. Notifications could inform all sensemaking actions, such as configuring a search key or annotating a set of data, but tracking partner's every single action may not be meaningful and efficient [20]. Furthermore, identifying changes and connections that are commonly important is challenging when there is a huge amount of data. With a massive dataset, conducting individual sensemaking and maintaining awareness could benefit from techniques such as visualization (VIS). VIS techniques could divide the data and present connections between individual work. To investigate the design space of presenting group activities while balancing simultaneous work and collaboration, this research addresses the following core problems:

- Tabletop technologies support simultaneous interaction, but it is still unknown whether and how the individual and collaborative work will be affected by a device which allows multiple sensemakers to work at the same time.
- Groups of people making sense of large datasets benefit from being aware of others' work. However, maintaining awareness or reacting to excessive notifications may hinder sensemakers' ability to work independently and simultaneously.
- Collaborative visualization helps people explore and make sense of the data together, but tends to focus on merging individual contributions. It is also imperative to understand how different shared overviews could balance the simultaneous work and social exchange.

Co-located sensemaking systems with notifications and shared visualization should support the division of the task and awareness of others' work, to achieve individual productivity and team collaboration. This research explores factors in co-located space that can balance the tradeoff between individual work and collaboration. Its main argument can be summarized as follows:

> *During collaborative sensemaking in multi-user co-located spaces, sensemakers can divide tasks and form individual workspaces to make sense of the data simultaneously. However, to support work integration and team productivity, notifications and collaborative visualizations can be used to manage the tradeoff between independent work and collaborative activities, to seek to support individual control, collaborative awareness, and knowledge communication.*

1.2 Research Questions

This dissertation examines how co-located sensemaking systems can help sensemakers to preserve individual workspaces and collaborate with each other. In a multi-user multi-touch workspace, good designs that properly inform users of each other's work and link it together encourage sensemakers to be aware of others' key sensemaking activities and to discuss findings, while still being able to work independently and simultaneously. To understand how the notification and visualization techniques affect the tradeoff between individual sensemaking and joint activities, this dissertation addresses the research questions of an understanding to the co-located workspace, notifications in a multi-user co-located workspace, and the collaborative visualization which presents common work in sensemaking.

- RQ1: How do sensemakers work simultaneously and collaboratively in co-located sensemaking, and what co-located space factors influence the two styles?

- RQ2: How do notifications highlighting related individual work balance individual participation and collaborative awareness?

- RQ3: How do shared overviews connecting related individual work affect individual control, awareness, and communication?

The research questions focus on design options to connect individual work in a co-located sensemaking workspace. This research examines co-located notifications and visualizations to indicate partners' work when each sensemaker works individually but also needs to stay aware of others' work and communicate findings. RQ1 explores the design space of supporting small co-located sensemaker groups collaborating with a large tabletop display. An exploratory study examines whether and how a shared device enabling simultaneous work encourages individual control and social communication. The findings for RQ1 summarize space factors and co-located space factors which form the design considerations for connecting individual work. RQ2 concerns the introduction of a notification system in a co-located workspace, to explore the effects of notifying partners of each other's actions in their own workspace. A comparative study is conducted to investigate a tabletop system with or without notifications. The results indicate how different types of awareness are affected by notifications through individual work, social norms, and team productivity. The findings for RQ2 point to the design direction of shared overviews. Finally, to address RQ3, a study is performed to investigate a collaborative visualization to overview group activities during a Twitter analysis task. This study compares different paradigms of collaborative visualizations to examine the benefits and costs of separating or connecting individual work in a shared overview.

1.3 Research Approach

This research identifies different styles of sensemaking collaboration to examine how awareness-supporting techniques affect co-located sensemaking. Key co-located space factors are identified to examine how awareness-supporting techniques lead to different styles of collaboration. Based on the primary research questions, the following sub-questions are formulated:

- S1. What co-located space factors determine the styles of collaboration?
- S2. How do sensemakers work individually and collaboratively with a shared tabletop?
- S3. What are the ways to connect and present related individual work?
- S4. How do notifications supporting awareness affect co-located space factors?
- S5. How do shared overviews presenting group work affect co-located space factors?
- S6. How do shared overviews lead to different styles of collaboration?

One research question is explored from multiple perspectives, including what collaboration components affect the design and how the co-located space factors lead to the individualness and collaborativeness in co-located sensemaking. The sub-questions help identify core collaboration factors and components that matter to different awareness-supporting designs. Some sub-questions denote the common design issues in different awareness-supporting techniques. The sub-questions are addressed in individual development efforts and user studies, which collectively serve to answer the main research questions.

The research questions are explored by answering each of the sub-questions through interface design and development, followed by a series of user studies. Figure 1.3 shows how the research questions and sub-questions are connected. RQ1 explores whether co-located sensemakers act simultaneously or in turns, two major ways to interact with a tabletop system, to

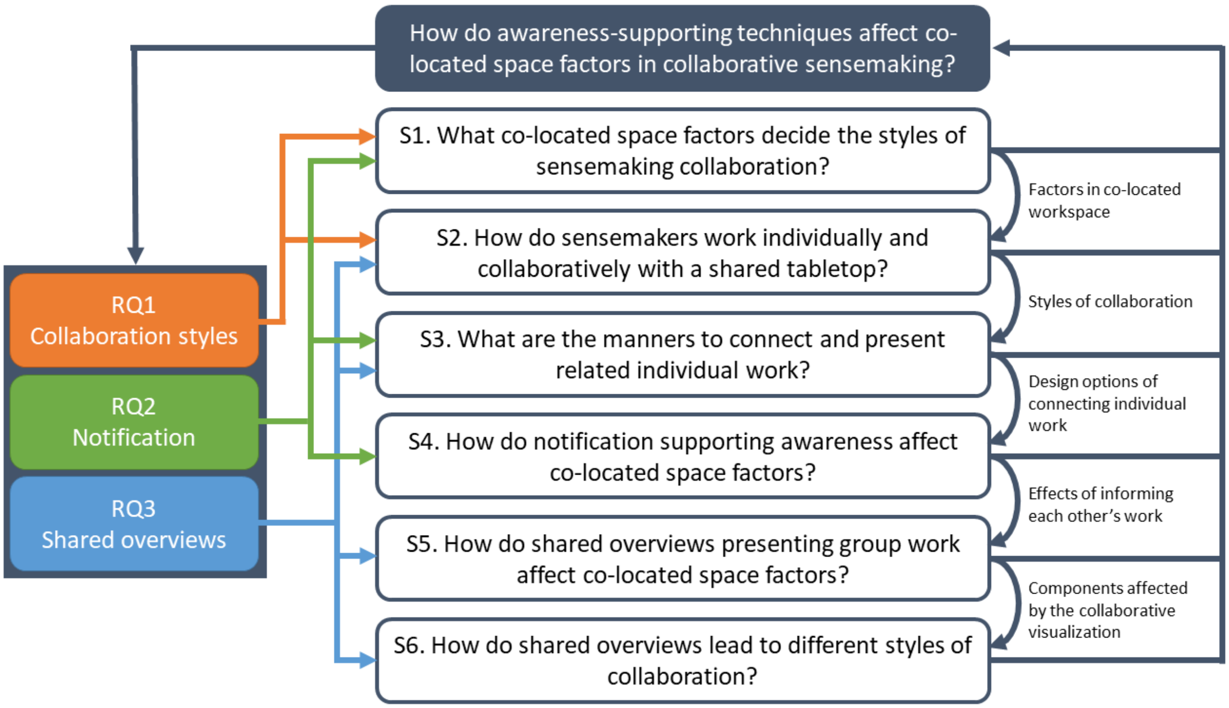

Figure 1.3: Research questions and their connections to the sub-questions. RQ1 is addressed by exploring how co-located space factors (S1) affect individual and collaborative work (S2). RQ2 is answered by examining how notifications connect individual work (S3) and raise awareness during co-located sensemaking (S4). Answering RQ2 leads to a deeper understanding of co-located space factors in co-located sensemaking (S1). RQ3 considers separating or connecting individual work in shared overviews to affect styles of collaboration (S2 and S3), and explores how co-located space factors (S5) and styles of collaboration (S6) are affected by collaborative visualizations.

identify key space factors and co-located space factors that affect the styles of collaboration. To address this question, an initial exploratory study is conducted on working individually or collaboratively in the co-located workspace. Sub-question 1 (S1) explores general co-located space factors identified in the literature, which are then used to examine the tradeoff between individual and collaborative work in S2. This research first identifies social, time, space, and interaction dimensions in co-located sensemaking (S1) and discusses how the styles of collaboration are affected by control, awareness, and communication (S2). The understanding of the two styles of collaboration builds a basis on which to design notifications to inform users of each other's work in individual workspaces.

RQ2 explores notifications in co-located sensemaking, identifying social exchange, individual work, and team productivity as the key co-located space factors affecting awareness. This question focuses on awareness and examines how a common awareness-supporting technique – notifications – influences styles of collaboration. The study of co-located notifications (RQ2) is addressed by S1 and S3, which are combined to answer S4. RQ2 incorporates the space factors identified from S1, and the answer to S3 concerns how co-located space factors are affected by connecting individual work with notifications. S4 examines the effects of notifications and leads to the consideration of shared overviews to visualize group activities in co-located sensemaking (RQ3).

By designing and evaluating collaborative visualizations, RQ3 is addressed in part by S2 from the perspective of the separation or connection of individual work, but also by S3 and S5, which examine options to present group work in co-located sensemaking. S3 for RQ3 considers parallel, connected, and merged individual work in a shared overview. S5 examines visualizations together with co-located space factors, exploring how individual and collaborative work are balanced by shared visualizations. Combining the answers for S1 to S6, this dissertation captures the knowledge in models, frameworks, and theories that summarize issues across the breadth of RQ1, RQ2, and RQ3.

1.4 Research Overview

This research consists of four individual projects, including analysis, design, development, and evaluation of co-located sensemaking systems. The systems implemented in this study focus on supporting co-located sensemaking with multi-user multi-touch displays. Different awareness-supporting techniques are examined, such as notifications and visualizations. Using four individual studies, this research explores (1) simultaneous and sequential interactions in co-located space, (2) notifications on multi-user displays, (3) the reflection of large amounts of personal data with a visualization, and (4) paradigms of shared overviews in supporting co-located sensemaking. Study (1) seeks to explore collaboration styles and addresses RQ1. Study (2) focuses on collaborative notifications and answers RQ2. Study (3) explores key activities in reading large datasets with a tabletop and visualization, leading to design considerations for Study (4), which examines collaborative visualization for co-located sensemaking and addresses RQ3.

Chapter 2 presents the background research which led to the research questions and design considerations. It reviews the literature on multi-user workspaces and co-located collaboration, and particularly sensemaking systems on tabletops and in multi-display environments. The chapter also reviews notification systems and collaborative visualizations proposed in prior studies and discusses problems with awareness-supporting techniques. The end of the chapter examines the relationship between the design, co-located space factors, and styles of collaboration.

Chapter 3 presents an observational study on simultaneous and sequential interaction, exploring styles of interaction with a shared tabletop. Two styles of collaboration are observed in the social, time, space, and interaction dimensions; this helps summarize key space factors that affect individual and collaborative work.

Chapter 4 introduces notification systems in the co-located sensemaking space. By comparing notification versus no notification conditions, this study explores how the awareness-supporting technique affects social, action, and activity awareness through individual control, social norms, and team performance. The study contributes an understanding of how to connect individual work with notifications and how sensemaking collaboration is affected.

Chapter 5 presents the necessary preparation to design awareness-supporting tools with data processing techniques and visualization. In this study, BlogCloud is designed and developed. BlogCloud is a tabletop-based system that incorporates visualization and natural language processing, to support re-visiting large amounts of personal data. The design experience with BlogCloud helps understand key sensemaking activities with a large dataset and actions performed on a tabletop with data visualization.

Chapter 6 reports a study on three different visualization paradigms. It explores the design options of separating or connecting individual work in a shared overview. Extending the system described in Chapter 5, VISGRAINS is implemented, which incorporates a collaborative visualization to present individual work in three different ways. Through a user study, this research explores how the collaborative visualization affects control, awareness, and communication as three key co-located space factors.

Chapter 7 summarizes the research findings addressing the three main research questions and six sub-questions. It discusses the importance of control, awareness, and communication in directing the styles of collaboration, and explains how the awareness-supporting techniques affect the balance between the three co-located space factors.

Chapter 2

Background and Related Work

In many life and work scenarios, people have to come together to make plans and decisions. This involves making sense of large volumes of data. For example, a small group of travelers plan trips based on what social media users like or dislike about places; a team of park designers discuss and decide what facilities to build by exploring visitors' comments; and a research group identifies topics and trends in public opinions by exploring a large social media repository. These collaborative sensemaking activities benefit from multi-user data exploration systems which support sensemakers in retrieving and organizing data at the same time. Collaborative devices such as multi-user multi-touch tabletops and wall displays allow people to establish a personal space to organize the data individually, along with a collaborative space to work together on complex shared tasks. Making sense of data collections together requires collaborators to shift between individual work and collaborative tasks, with the necessity to control individual data representations, maintain collaborative awareness, and communicate to synthesize knowledge.

This dissertation draws from and contributes to three major research areas. Co-located collaboration styles are examined during the same-time same-place sensemaking, with a specific focus on large multi-user displays. Notifications are examined on co-located groupware to enhance awareness in computer-supported collaborative work (CSCW). Collaborative sensemaking through visualization refers to multiple people using a shared visualization to achieve a common sensemaking goal. By examining awareness-supporting techniques that connect individual work during co-located sensemaking, this research contributes knowledge on the design of multi-user workspaces, sensemaking, and co-located collaboration. Techniques to raise users' awareness of each other's work are examined in a multi-user workspace, and different design options to connect individual contributions are explored. By comparing sensemakers' behaviors when using different awareness-supporting techniques, this research examines how to support collaborative behaviors by informing group activities and how the increased awareness affects sensemaking. This chapter reviews prior work on multi-user workspaces, sensemaking, and co-located collaboration.

2.1 Multi-user Workspace

The research community on interactive surfaces and spaces studies the design, development and use of new and emerging interactive surface technologies and interactive spaces. Studies on multi-user workspace explored devices and technologies for collaboration through interactive spaces [4]. A considerable amount of work has explored and designed interactions on multi-user tabletop displays. Early studies on multi-user digital displays were technologically limited by the number of detected touch points. Single-touch devices based on fingertip or stylus input only supported collaborators in turn-taking [15, 32, 90], which required coordinated actions to access digital content. This coordinated manner of interaction closely resembled turn-taking in traditional paper-based collaborative activities like affinity diagramming and mind mapping [26, 169]. Research on collaboration with these devices focused on understanding social protocols that coordinated the turn-taking [145]. Advances in touch technology and gesture recognition have brought more affordances to touch-sensitive displays to support simultaneous interaction. Projector-based [179] and multitouch-screen [61] devices have been developed, encouraging collaborators to manipulate digital objects at the same time [27]. Applications of these devices can been seen in many area-specified scenarios such as museums [12, 63, 106], games [5, 133], data analysis [76, 125], and assistive technologies [83]. Studies show that the walk-up-and-use nature of a public multi-touch display consists of both individual and collaborative interaction [61, 107, 131]. Information analysis and search tools on multi-user displays facilitate collaborative sense-making by supporting individual and collaborative use of digital materials [72, 117]. Furthermore, map and animation planning enforce individual operations with gestures that have to be performed together to enhance group awareness [38, 115]. Interaction techniques such as virtual hands or arms have been studied in terms of influences on the individual and collaborative interactions [28].

The configurations of collaborative space affect and structure interaction [58, 59]. Studies on multi-user systems and same-time same-place collaboration have distinguished key factors in workspaces to better support co-located activities [54]. *Who* is around, *where* actions are performed, *what* is the intent, *when* actions happen, and *how* things have been changed have been identified as key questions for the co-located collaborators to be aware of [54]. Harrison and Dourish argued that relational orientation, actions, partitioning, and awareness are features of the collaborative space [58]. Lee et al. investigated micro conversations in co-located collaboration, and identified cognitive space, social space, and digital space as channels to tune attention and manage tasks [91, 92]. Coupling styles capture how collaborators engage in mixed-focus collaboration [161]; these styles reflect the degree to which people become aware of others' presence and identity. Modes of loose- and close-coupled collaborations indicate social aspects of collaboration [79, 149, 161]. Close-coupled collaboration has shown advantages in building common ground and achieving shared goals [14, 99, 172]. Territoriality spatially probes how collaborators divide shared interaction space to organize ideas [150]. Individual ideas are engendered in personal space, while shared space is for idea exchange and integration [103]. Control and availability of digital objects in territories influence the arrangement of users and how individuals engage in personal and shared tasks [92, 103].

As large displays are prominently used for collaborative sensemaking to support joint attention and discussion [77], it is important to understand how co-located space factors are affected by different information presentations on a shared display. Prior research has explored the use of a shared display to mediate individual work and collaboration. Overviews of on-going collaboration are examined with tablets [16, 137], laptops [99, 138], tabletops [13, 49, 80], control or conference room settings [39, 100, 171], and wall-size displays [2, 105]. Individual control over interactive space, awareness of group activities, and communication between sensemakers could be enhanced or hindered by different shared views [153]. The large interactive displays offer benefits to support collaboration, but only a small amount of related research has explored the social aspects of such systems [77]. It is vital to understand how multi-user displays could incorporate data processing techniques to associate group activities, in order to support data-intensive activities such as sensemaking.

2.2 Sensemaking

Sensemaking is a common life and work activity in which people seek and obtain knowledge. It could benefit from data visualization [43, 134]. Pirolli and Russell argued that sensemaking involves finding information, learning about new domains, solving ill-structured problems, acquiring situation awareness, and participating in social exchanges of knowledge [135]. Pirolli and Card proposed a notional model of sensemaking, in which sensemakers iterate between the loops of foraging and sense making, to eventually develop mental and conceptual models [134]. Research investigated models and frameworks to describe collaborators' information seeking and interpretation behaviors [23, 153, 157]. Studies have identified patterns in how collaborators retrieve and make sense of data in medical work [60, 130], intelligence analysis [85, 172], and web-page searching [116, 156]. Furthermore, recent studies have investigated visualization in co-located space to support collaborative sensemaking [77].

Chirag Shah examined collaborative information seeking and identified *communication*, *contribution*, *coordination*, *cooperation* and *collaboration* as five different group activities to demonstrate the styles of working individually or collaborating intensively [153]. Communication centers the group activities and serves as the main channel for information exchange. Contribution encourages offering information to other sensemakers to benefit collaboration work. Coordination connects different agents in harmonious actions, and requires awareness of the group plan and activities. Cooperation is when sensemakers agree on the plan and divide the task to work at the same time. Finally, collaboration umbrellas communication, contribution, coordination, and cooperation [153]. Effective collaboration requires sensemakers to work together towards a common goal of sensemaking. Similar theories have also been proposed regarding co-located collaboration with tabletop displays. For example, Tang et al. identified *loosely-coupled* and *close-coupled* as two major styles of collaboration in co-located tasks [161]. Control, awareness, and communication are three key components accepted in the literature as affecting sensemaking collaboration. Control is the individual power to interact with the interface with which sensemakers obtain and organize sensemaking materials. Communication establishes channels for knowledge exchange and supports the coordination of the group. Awareness is the understanding of others' actions and activities in the context of one's own work. The three co-located space factors are essential to close collaboration. Framing co-located space factors such as individual control, awareness, and communication directs people's ability and willingness to contribute, coordinate, and cooperate [58, 161].

To support diverse collaborative behaviors, sensemaking groupware on computers, tablets, tabletops, and wall-mounted displays forms a collaboration space that supports individual work as well as group collaboration [58, 71]. For example, Lark incorporated visual encodings of individual operations in a shared visualization [165], and ScatterBlogs used extra tablets to enable individual interaction with the display [96]. KTGraph supported asynchronous collaborative analysis by providing visual cues for knowledge hand-off [183]. Furthermore, Reiterer et al. studied how small teams use visualizations on individual and shared devices [137, 182]. Collaborators divide the workspace and interact with a personal device [137], or in a personal territory on a shared display [14, 150], to perform sensemaking in a simultaneous manner. However, due to the tendency to work together, sensemakers pause individual tasks to observe, communicate, or even engage in others' work [161], reflecting the need for social exchange [77]. Sensemakers maintain awareness by tracking others' actions, communicating goals and plans, and connecting individual work to the team's work, to achieve team productivity [98]. Working closely together and always engaging in the same task enhances their awareness of each other's activities, but the less independent work may lead to underutilization of individual time and space [154]. On the other hand, organizing large amounts of information in individual space costs time, which also increases others' effort to maintain awareness [72, 118].

Studies on multi-display environments have investigated the supporting of collaborative sensemaking with data visualization as well [70, 75, 99, 172, 176]. Early research found that collaborative visualization facilitates knowledge integration [104] and error correction [102]. Isenberg proposed a research agenda in visualization on large interactive displays, and raised social challenges as one of the key questions to be addressed in the design of surface-based visualizations [70, 72, 74, 77]. North et al. explored visualizations on high-resolution displays for collaborative sensemaking and suggested that social configuration affects people's way of using space [14, 172]. Furthermore, Melanie investigated visualization with multiple device settings and reported that externalization and awareness are key to the effectiveness of group work [99]. These studies imply that social factors like awareness influence people's conversation and interface utility, and further affect the integration of individual work. Hence, it is imperative to understand how the configuration of shared visualization affects social factors such as awareness, and how this influence leads to different collaboration outcomes [77, 132].

2.3 Collaboration

The CSCW community have considered supporting collaboration in different scenarios with different time-space settings. Johansen's time-space matrix classifies tools for collaborative activities as "same time, same place," "same time, different place," "different time, same place," and "different time, different place" [75, 81]. This research centers on the awareness-supporting techniques in the "same time, same place" collaboration. Sensemakers need an increased awareness of each other's work to encourage knowledge exchange and communication, thus supporting collaboration [35, 102, 147, 148]. An understanding of personal workspaces helps determine how team members make decisions and takes action [34].A high degree of team shared awareness implies collaborators' understanding of shared elements, which is core to common ground [25, 112, 147]. Protocols to develop common ground are a part of social conventions in exchanging awareness information [20, 103, 103]. As such, maintaining awareness of others' actions has long been a topic of interest, including in Gutwin's framework for exploring workspace awareness [54] and Fussell's exploration of how visual cues help conversational grounding and reduce the efforts to maintain situation awareness [47, 48].

Many awareness-supporting techniques are designed to enhance the social exchange of sensemakers' situations. Studies on team situation awareness have suggested that group activities

Table 2.1: Time-space matrix of CSCW systems adopted from [81]

	Same place	Different place
Same time	Co-located synchronous collaboration	Co-located asynchronous collaboration
Different time	Distributed synchronous collaboration	Distributed asynchronous collaboration

such as communication and planning contribute to the common understanding of the collaborative situation [147, 148]. Early works investigated how the configurations of the shared displays and the interactive objects affected co-located activities, including group and table sizes [146], object distribution [116], space allocation [87, 150], and control types [106, 143]. Recent studies have focused on issues such as cross-device interaction [62, 137, 182], social regulation [36, 37], screen orientation [166], and shared overview [16]. These studies have explored the possibilities for multiple users to work at the same time and in the same place [40]. Building on the findings from prior research, the present study explores how notification systems and shared overviews could connect related individual work to affect individual control, maintaining awareness, and communication during co-located sensemaking.

2.3.1 Notifications

Among the many techniques to support awareness and deliver information, notifications have been widely used [13, 20, 128, 170]. When working in a shared interaction space, people allocate attention to incoming notifications to maintain awareness of collaborators' presence, speech, and activities [52, 54]. The design of notifications for collaborative systems considers tradeoffs between utility benefits and attention costs [20, 22, 111]. For instance, studies have shown that introducing notifications in groupware may heighten awareness of group work, but restrict individual progress [20, 30]. However, with the emergence of novel collaboration technologies such as large tabletops, notifications and awareness remain under-explored.

Problems with awareness-enhancing techniques are pertinent to individual and team work, and particularly the effectiveness of communication. Carroll et al. drew from situation awareness, common ground, and workspace awareness to suggest that social awareness, action awareness, and activity awareness are the core of notification design [20].The model provides awareness breakdowns and suggests practical design strategies for notification systems. While Carroll et al. explored how notifications may affect group activities, the large interaction space [146], face-to-face communication [182], dynamic work styles [161], and multi-touch interactions afforded by multi-user displays introduce other factors unique to collaboration. These new contextual elements influence how collaborators perceive and react to notifications [34, 159].

Large multi-touch displays allow co-located people to maintain individual workspaces and perform individual work (e.g., [87, 97, 122]). Studies have investigated awareness support indicating others' activities to raise mutual understanding, but at the cost of degraded individual work. For example, WeSearch and Cambiera integrated "marquee" widgets to inform collaborators about searches and to enhance their awareness of activities; however, studies of both tools suggested that these widgets lacked sufficient communicative benefits to support close collaboration [72, 118]. Navi Badgeboard and Navi Surface used digital badges to increase the awareness of personal achievements and group activities, but a study showed that these badges made the students hesitant to participate in collaboration without others' confirmation [21]. Many prior studies on multi-user co-located collaboration have faced the dilemma that though working simultaneously could improve system utility, the need for awareness drives people to the single thread of tasks rather than divide-and-conquer [99, 161]. This contradicts the need for labor division in many sensemaking tasks: when dealing with large data collections, sensemakers prefer to have full control over their individual workspace and process the data in parallel [52, 84, 85].The divided processing of information leads to better coverage of the data and improves the diversity of the considered information [154].

2.3.2 Collaborative Visualization

Notifications deliver awareness information directly to others' workspace. Another way to inform group activities is to incorporate collaborative visualizations which can be viewed by multiple sensemakers at the same time [24, 138, 158, 175]. Isenberg proposed the research agenda in visualization on large interactive displays, and raised social challenges as one of the key questions to be addressed in the design of surface-based visualizations [70, 72, 74, 77]. Studies have found that collaborative visualization facilitates knowledge integration [104] and error correction [102]. Interactive maps OrMis and Canyon used secondary views to support mutual awareness in collaborative exploration; however, study results indicated that people often worked in turn-taking instead of simultaneously [13, 69]. North et al. explored visualizations on high-resolution displays for collaborative sensemaking, and found that social configuration affected people's way of using space [14, 172]. Melanie investigated visualization with multiple device settings and suggested that externalization and awareness are key to the effectiveness of group work [99].

These studies imply that social factors like awareness influence people's conversation and interface utility, and further affect the integration of individual work. It is imperative to understand how the configuration of shared visualizations affects social factors such as awareness, and how this influence leads to different collaboration outcomes [77]. Prior research has suggested that overview settings affect sensemakers' individual control, awareness, and communication. Some studies support separated individual work to enable task distribution [116, 138, 172], while others suggest connecting related parts to trigger discussion [16, 72, 99, 118]. However, the design choices of separating or connecting group work still require knowledge on how each choice affects sensemaking activities and outcomes. Grounded in prior research, this dissertation also seeks to provide a deeper understanding of how three overview design options affect co-located sensemaking.

2.4 Chapter Summary

This chapter focuses on the interaction between multi-user workspaces, sensemaking, and collaboration (Figure 1.2). Supporting collaboration has drawn attention in prior research on systems for information seeking and sensemaking [75, 104, 153]. Multi-user systems incorporating tabletops [149], wall displays [175], and multiple tablets [16] enable sensemakers to work at the same time and share information and knowledge [149]. Studies have examined the opportunities to support individual work and collaborative activities with shared displays [54, 77, 149]. This work considers the intersection between multi-user devices, sensemaking, and collaboration, with a focus on exploring how notifications and shared overviews could connect individual work.

Styles of collaboration influence the effectiveness of sensemaking. Many prior designs have sought to promote close-coupled collaboration, in which sensemakers focus on the same problem, actively keep awareness, and discuss findings [16, 72, 161, 172]. There is growing consensus that sensemakers who collaborate more closely yield better sensemaking outcomes [72, 172, 176]. While supporting sharing and discussion is key to the design of collaborative sensemaking systems, individual control is still demanded for simultaneous work [124], achieving individual sensemaking goals [116, 149], and dividing sensemaking roles [14]. The tradeoff is between keeping awareness of others' work and dividing the tasks to maximize individual time and effort. This is one of Grudin's problems: that users must obtain value out of the extra effort they put into collaborating with others [51].

2.4.1 Styles of Collaboration

It is necessary to consider the benefits and costs to collaboration of relating individual work in a shared workspace. Shah identified situations in which collaboration could add burden rather than efficiency to information-intensive tasks [153]. Collaborative sensemaking systems need to consider how the design supports effective *communication*, *contribution*, *coordination*, and *cooperation* to achieve the goal of *collaboration* [153]. Shah's collaboration model suggests five types of group activities, which emphasize individual work and collaborative work in different ways. **Collaboration** is the activity of working together to gain benefits that could not be yielded from individual work [155]. Shah defined **communication** as a "process of sending or exchanging information", which requires collaborative activities and may interrupt individual work [155]. Exchanging information with multi-user devices could be achieved through looking at a shared view and discussing, or using notifications of others' work delivered to one's own workspace. **Contribution** is "an informal relationship by which individuals help each other in achieving their personal goals" [155]. Contribution is still collaborative, but emphasizes benefiting one party's work by paying joint attention to one's individual workspace. **Coordination** is a process in which people work harmoniously at the same time and place; it involves shared resources, responsibilities, and goals [155]. Coordinated work could achieve individual goals, but because the resources or digital artifacts are shared, sensemakers need to take strategies to coordinate the use of the system. Finally, **cooperation** is when collaborators follow some rules to work simultaneously and complete individual tasks [155]. This style of group activity requires dividing the task and working individually to finish different parts of the task. Based on Shah's model, this study summarizes how different group activities reflect different levels of importance of individualness and collaborativeness, as illustrated in Figure 2.1.

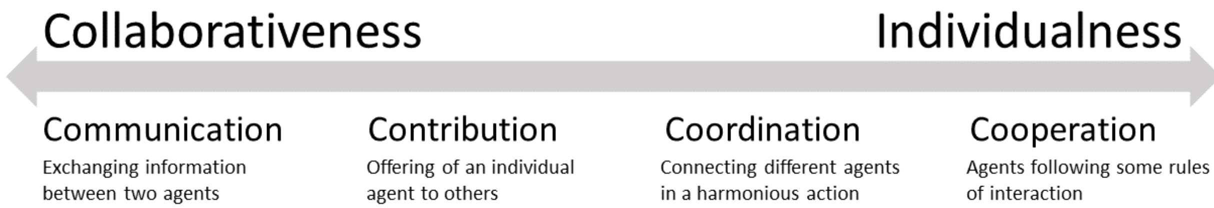

Figure 2.1: How communication, coordination, coordination, and cooperation reflect individualness and collaborativeness during co-located sensemaking.

2.4.2 Control, Awareness, and Communication

To understand how notifications and visualizations promote or hinder group activities, it is important to study collaboration aspects affected by awareness-supporting techniques. Shah's theory identifies *control*, *communication*, and *awareness* as three key co-located space factors in sensemaking tasks [153].

Control is the individual power to interact with the shared interface. When relating each others' work, sensemakers pay attention to other's activities and may withdraw from interacting with personal representations. Individual power over the shared data representations determines individual ability to participate in the sensemaking task. . Gutwin argued that individuals demand powerful and flexible means for interacting with the shared interface in co-located collaboration [55]. Yuill and Rogers defined *control of action* as the extent of the user's control over actions and decisions [181]. Multi-user multi-touch devices such as tabletop displays add flexibility to support users in gaining more individual control over their actions [181]. Morris argued that division of labor is important to sensemaking tasks, especially when dealing with large amounts of information [113]. Supporting individual control guarantees individuals' ability to access the data and make contributions to the co-located sensemaking task.

Awareness is the understanding of others' actions and activities. The design of notifications and shared overviews could bring in different understandings of partners' work and affect different styles of collaboration. Supporting awareness is a critical issue in collaborative sensemaking systems [153]. Dourish defined awareness as *"understanding of the activities of others, which provides a context for your own activity"* [30]. Gutwin and Greenberg noted that workspace awareness – the up-to-the-moment understanding of another person's interaction with a shared workspace – needs to be supported by co-located systems [53, 54]. When notifying users of collaborators' interactions, action, social, and activity awareness could be supported by notification system [20]. Paul and Reddy suggested that action awareness leads to particular sensemaking activities [130]. Awareness of each other's work helps coordinate actions over the shared artifacts and maintain consistency of the task goals and plans [20].

Communication establishes channels for knowledge exchange and supports the coordination of the group. When supporting communication, it is necessary to consider what information is delivered by awareness-supporting techniques, and how sensemakers discuss the connected individual work. Encouraging communication is an important way to promote close collaboration [46], which relies on effective communication between sensemakers and generally leads to better sensemaking outcomes [72, 161, 175]. Large interactive displays offer an open space to support face-to-face discussion [55]. Prior studies have noted that face-to-face conversation is still the major way to communicate findings and coordinate actions [72, 100]. However, besides conversation, sensemakers could also leverage awareness-supporting widgets that indicate others' work to exchange information [92, 123]. The awareness-supporting techniques not only present other's work, but could also trigger conversation [72, 118]. Effective communication encourages close collaboration and facilitates the synthesizing of findings

[99, 161].

To better understand awareness-supporting techniques, this study examines notifications and shared overviews in co-located sensemaking. It discusses the ways in which awareness-supporting techniques affect co-located space factors, which affect different styles of group activities.

Chapter 3

Simultaneous and Sequential Interaction in Co-located Collaboration

In co-located sensemaking, collaborating with multi-user devices such as large multi-touch tabletops allows sensemakers to establish individual workspaces and work at the same time. On the other hand, the need to exchange and integrate information requires sensemakers to coordinate actions and make changes. Prior studies on the contextual use of multi-user touch displays have provided an understanding of interaction and collaboration styles [149]. However, the design of the interface on a shared tabletop should take into account that some interactions are performed at the same time while others are done in turns. To understand how sensemakers work simultaneously and collaboratively on a sensemaking task, it is important to investigate what factors in the co-located space determine the forms of collaborative interaction and how to design for different styles of collaboration.

To gain an initial understanding of individual and collaborative use of a multi-user multi-touch display, a card-based tool is deployed on a 55-inch tabletop, and a collaborative ideation task of sensemaker pairs or trios creating a technology solution is observed. The system allows two to three sensemakers to organize digital cards on the tabletop and create a solution poster as a sensemaking outcome. By observing 10 groups of sensemakers search for and make sense of information represented by 98 digital cards, this study explores what co-located space factors influence simultaneous and sequential interaction.

This study [124] explores questions S1, *"what co-located space factors determine the styles of collaboration?"* and S2, *"how do sensemakers work individually and collaboratively with a shared tabletop?"* Two categories of interaction – simultaneous and sequential – are differentiated during collaborative use of virtual spaces [72, 79, 115, 131, 142, 150]. The two styles of collaboration are working individually and working collaboratively with a shared tabletop display. This study explores simultaneous and sequential interactions from social, time, space, and interaction dimensions, examining sensemakers' ways and preferences when collaborating with a shared sensemaking space. In simultaneous interaction, more than one person touches the display at the same time to manipulate data objects – for tasks that can be divided and completed in parallel [131], or for collaborative tasks that require multiple users to complete them individually [118]. In contrast, sequential interactions are guided by social protocols in which people negotiate and take turns using the device [133]. The turn-taking guarantees the awareness of each other's activities and helps the team avoid conflicts in using the data objects.

Clearly, simultaneous and sequential interactions entail certain tradeoffs. Simultaneous interactions support the distribution of tasks among people, opening possibilities to finish the task more quickly. However, this task distribution may weaken awareness of others' actions. On the other hand, sequential interaction can enhance awareness and build a sense of group cohesion by encouraging collaborators to observe and participate in actions, but it is unclear whether this sequentiality is the best use of time and device interaction capability. Investigating factors that influence people's decisions to work simultaneously or sequentially – and the roles and impacts of technology in encouraging their behaviors – will broaden our collective knowledge about ways in which technology can support collaborative sensemaking.

To better understand simultaneous and sequential interaction in collaborative sensemaking with multi-user touch tabletops, an observational study was conducted in which pairs and trios completed an ideation task on a tabletop touch display.

3.1 Abstract

Large-scale multi-touch displays are widely used in real-world practices to support various types of collaborative work [61, 122, 131]. These displays detect concurrent multi-user touch inputs on a large space for information exploration and organization. They are targeted for workplaces that involve design and analysis activities [57, 67, 86, 125, 168]. In these contexts, the multi-user touch displays serve as platforms to facilitate sensemaking activities, such as information exploration, knowledge generation and exchange, and decision-making.

To better understand simultaneous and sequential interaction in creative collaboration with multi-user touch tabletops, this study conducted an observational study of pairs and triads completing an ideation task on a 55' tabletop touch display. Ten design sessions are observed to investigate the patterns of the collaborative interaction. Four collaboration factors gleaned from prior research are investigated as factors in collaborative idea synthesis: *coupling style*, *interaction stage*, *territoriality*, and *semantic actions*. The four factors reflect workspace awareness knowledge [54] identified by Gutwin et al. and provide a platform for understanding how designers engage in collaborative tasks. Our research seeks to learn how users collaborate to foster future design of software and technology leveraging large multi-touch displays. This study focuses on four contributions:

- Present four collaborative factors that influence simultaneous and sequential use of tabletop displays

- Explain when and how interaction style influences collaborative factors
- Identify how knowledge of simultaneous and sequential styles drawn from each collaborative factor provide recommendations for system design

3.2 Simultaneous and sequential Interaction

Simultaneous and sequential interactions play different roles in the collaborative interaction with multi-user touch displays. Simultaneous input techniques support collaboration by giving each person equal opportunity for information access, and, accordingly, enhancing equality of participation across the group [63] and increasing cooperation [115]. In addition, when the interaction task consists of distributable work, simultaneous interactions allow collaborators to work on different parts of the task in parallel. However, simultaneous interaction may also result in interaction errors. Sequential input coordinated by social protocols is another collaboration approach with multi-user displays. Benefits lie in avoiding conflicts from simultaneous interaction [61], and sequential interaction also can enhance group awareness by leaving users sufficient time to observe each others' activities [63]. But requirements of sequential use by a system or method might reduce efficiency by cutting down on opportunities for parallel activities [107, 131]. To provide a better understanding of the two interaction styles with the multi-user touch display, this study focuses on an ideation task to probe the patterns of collaborative activities in the four examined factors.

3.3 Collaboration Factors

This study investigates two interaction styles through four collaboration factors in tabletop workspace. This section details the identification of these factors and discuss the subcategories in each category (Table 3.1).

Table 3.1: Collaboration factors observed in this study

WA Info	Collaboration Factors	Observed Categories
Who(social)	Coupling Style	Loosely-coupled, close-coupled
When(time)	Interaction Stage	Browsing, organization, specification
Where(space)	Territoriality	Personal territory, group territory
What(interaction)	Semantic Actions	Emphasizing, sorting, grouping, linking, deleting

3.3.1 Coupling Style

A group's collaborative coupling style describes the social manner in which individual collaborator participates the work. In collaborating through a multi-user display, some tasks benefit from joint attention and/or the joint action to complete, while other tasks can be done in parallel. Focused attention involves more verbal communications, usually centered on one or more digital objects. With distributed attention, communication is more occasional, and manipulations by different collaborators are not necessarily related. The group transits between focused and distributed attention, influencing manner of interaction with the display. This study examines two types of coupling styles, *loosely-* and *close-coupled* collaboration [52, 72, 79, 161]. Communication and attention are the main indicators to distinguish coupling style. In close-coupled collaboration, the group has active discussions that focus on the same digital objects. In loosely-coupled collaboration, each group member focuses on objects in parallel without significant communication. Observing sequential and simultaneous interaction within each style will help understand how attention and conversation factors influence collaborative interaction.

3.3.2 Interaction Stage

This study leverages three temporal stages of interaction which outline the design sensemaking process, drawing primarily from the PIC-UP card set and the design tool [174], but prevalent across much of the design activities. This study uses browsing, organization, and specification as three interaction stages to observe the temporal changes of simultaneous and sequential interaction. Browsing resembles the foraging stage of sensemaking, during which initial data are collected and explored [134]. Organization are activities to make sense of the collected information, during which relationships between digital content are specified [134]. Specification is a period of time clarify the final knowledge deliverable [134].

Browsing Stage

Browsing stage is the initial step in using the interface to understand content in working space. When browsing, the group may not have a clear idea about the tool or task. Browsing gives users a perspective that helps to explore ways to use the system and understand the information provided by digital objects. Interactions when browsing are tentative and less coordinated, since attention and action of different users generally focus on their own interests. Parallel work helps users learn information and quickly identify initial sensemaking ideas.

Organization Stage

Organization Stage is associated with the arrangement of sensemaking materials toward deeper assessment of ideas from the browsing stage. The evolution of sensemaking ideas from browsing to organization lie in relationships identified among digital elements. The group exchanges ideas and tries different combinations of the elements, to collaboratively make decisions on which elements to use. The shared display at this stage serves as a space to exchange the idea, so the interactions usually incorporate sharing or evaluating digital objects. These types of activities usually attract group attention, and the joint attention influences the manner of collaborative interaction.

Specification Stage

Specification stage involves refinements of the structure of the digital objects that comprise the sensemaking outcome. As ideas are focused, details of digital elements and relationships among them are made more definite and clear. Activities in this stage include arranging elements and specifying relationships and interactions. Compared to organization, the arranging of the digital elements within this stage are no longer an attempt to find possibilities; they represent more certain and finalized modifications. As such, most interactions at this stage happen to nearly finished design through sequential access that help collaborators avoid mutual interference.

3.3.3 Territoriality

It has been widely observed that collaborators create *personal territories* and *group territories* in interacting with multi-user displays [28, 150, 168]. Personal territory is an area where an individual participant obtains digital resources and explores solution alternatives. This area leaves collaborators a private space to clarify personal ideas before introducing them to the group. Group territory is a shared space to assemble ideas from each individual that serves as a space in which the group exchanges ideas and resources. The segmentation of the interaction space influences the manner of interaction. To further explore how territory influences the simultaneous and sequential interactions, this study observes the two modes of collaboration within two types of territory. Personal territory interactions include activities within personal space, namely interactions to organize individual idea, or move interesting cards into the personal space. Group territory interactions consist of activities that happen in the group space, which are the modifications made to the ongoing sensemaking results.

3.3.4 Semantic Actions

From creating a diagram to organizing data files with a multi-user touch display, collaborators need to annotate, sort, group, link and delete digital objects to make sense of the materials [44, 61, 63, 125]. This study examines five semantic actions with the multi-user display – emphasizing, sorting, grouping, linking and deleting – gleaned from prior studies with interactive information synthesization that cover most sensemaking actions [111, 125, 141]. When a user observes the object set and the elements are especially inspiring, the user may *emphasize* that object and share it with teammates with actions that include moving the object, pointing at it, and elaborating on an idea. After the user collects ideas, it is necessary to *sort* the digital objects and select suitable ones, perhaps by *grouping* similar or relevant information. By clustering digital objects, an data group is used as an integrated entity to further connect to other materials. For key connections, collaborators *link* the feature pair by drawing lines between digital objects, or by positioning them closely. During organization of elements, if digital objects appear to be less important or relevant, users *delete* these elements through gestures such as moving them to the corner of the display.

3.4 Observational Study

This section describes our observational study of simultaneous interaction and sequential interaction in a small group design activity. Leveraging a card design system implemented on a multi-user tabletop display, 10 small groups of two or three collaborators created designs with digital materials. This study chose a design task because it reflects the need to experience different coupling styles, to shift between creative design stages, to manage space utility, and to perform gestural actions, thereby fulfilling the goals of our observation.

The observational experiment was conducted with 19 undergraduate students between 18 and 30 years of age. Participants worked in a team of two or three people, and they could take part in the study either once or twice. To help ensure diversity of ideas in the sensemaking process, no two participants could collaborate in a group more than once.

3.4.1 Multi-touch Supported Design Tool

The card-based multi-touch supported design tool used in this study is a design sensemaking application [56] running on the Microsoft Perceptive Pixel (see Figure 3.1). The Microsoft Perceptive Pixel is a 55-inch multi-touch display enabling simultaneous finger operations of different users like touching, pinching and dragging. The design application running on it consists of a blank working area in the center and design cards along each side (Figure 3.3). Each design card can be moved, rotated and resized by different designers simultaneously with the fingertips. A toolbox, located on each side of the table, provides a drawing tools and a commenting tool. Using a pencil tool, users can draw lines of different colors and thicknesses with the finger. An eraser tool and an undo tool are provided for correction. A commenting tool creates a textbox and a virtual keyboard for editing the typed comments. Each textbox can also be moved, rotated and resized.

Figure 3.1: Using the collaborative design tool on a Microsoft Perceptive Pixel system.

3.4.2 Collaborative Task and Digital Card Creation

The design task is to design a novel technology solution to help five - seven year old children manage their emotions, such as anger and anxiety. The digital cards used in this study are created based on three workplace factors-social context, activities and artifacts-as described in the design requirements. Accordingly, this study designed three types of cards corresponding to each of the dimensions: problem cards, activity cards and technology cards (Figure 3.2). The 30 problem cards include emotional problems summarized from the Preschool Anxiety Scale (PAS) [160]. The problem cards aim to provide hints on the context of the design and help the designers understand the emotional problems of the children. 31 activity cards show common activities like reading, walking and listening to music with which the children can alleviate negative emotions. The technology cards have 37 popular digital devices like tablet, smartphone, and Google Glass.

Figure 3.2: Examples of the three types of design cards. From left: problem card, activity card, technology card.

3.4.3 Process

19 participants formed five groups of three members and five groups of two members. Each group used the sensemaking system to complete the sensemaking task. First, the task was described to the group. The method to manipulate the design card and draw the lines was demonstrated to the participants. Each participant then tried the system. After the participants became familiar with the tool, the group was informed that the sensemaking outcome should be presented in a form of design poster, and an example poster was shown and explained. An overhead camera looking the tabletop display (Figure 3.3) recorded video of the entire sensemaking process. After finishing the design poster, each participant completed a six-item questionnaire probing aspects of the experiment: using the interface, exploring the digital cards, organizing ideas, completing the design, collaborating with teammates, and general feedback. The questions include an open-ended writing portion to let participants leave their comments on each aspect.

During recruitment, participants were allowed to take part multiple times in the study. Six students participated the study twice and the rest participated once. Repeated participation sought to explore whether participating multiple times would lead to dominance and other changes in coupling styles, but the data and questionnaire shows that participants engage

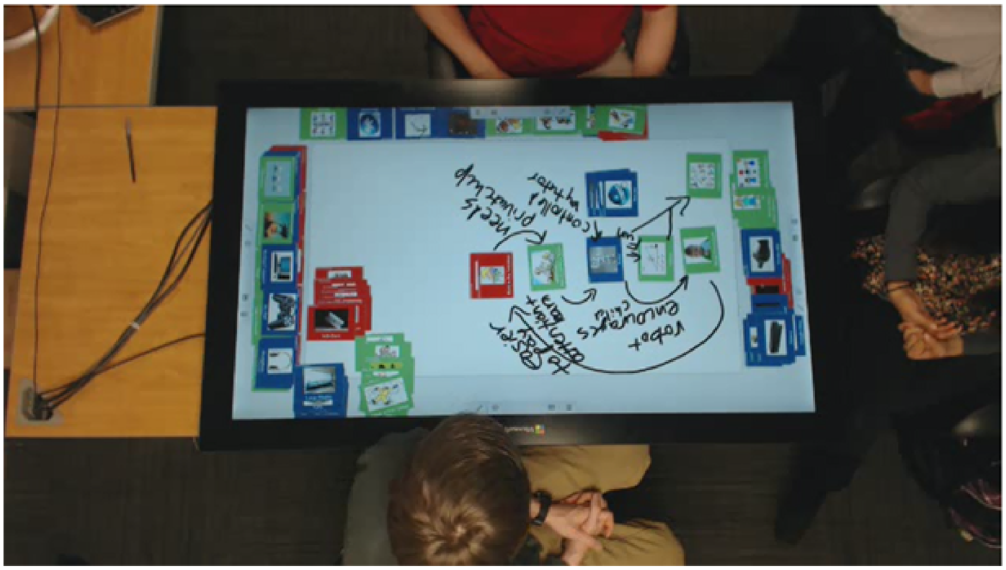

Figure 3.3: Video screenshot of the investigation.

similarly each time, suggesting social conventions still guide the manner of collaboration [13].

3.4.4 Coding Method

To examine the relationships between the four collaboration factors and the simultaneous and sequential interaction, the research investigators first coded the video. Simultaneous and sequential interactions are determined by whether the participants touch the display at the same time. If two or more participants touch the display at the same time, that interaction period is tagged as simultaneous, otherwise as sequential.

The video clip was first divided into three parts according to three interaction stages. In the browsing stage of card-based groupware, the main task is observing the card set and discussing ideas over single or a small subset of the cards. This study defines the browsing stage as the period during which the most of, if not all, cards are browsed, ideas are brainstormed and useful or relevant design cards are selected. This study uses the time after which no cards being observed for the first time as the end of the browsing stage. The organization stage is a process of evaluating the initial ideas, make selection, and arrange the desired cards. A reversed observation method is applied to dissect this stage: the design result is referenced first, and second is the time when the final design plan is used, thus separating the organization stage and the specification stage.

We then used an event-based method to code the other three factors. Two research investigators reviewed the entire video separately. If the status of any factor changed, the investigator recorded the time stamp and the statuses of coupling style, territoriality and semantic actions according to the definition described above. For the coupling styles, if the participants communicate with each other (or keep silent) more than a short while (two to three seconds), we consider them to be switched to close-coupled style (or loosely-coupled style, respectively). For territoriality, if a card is being or has been shown to all participants, and no user moves it back to his side, we consider this card to be in group territory. Interactions with shared cards are categorized as group territory activities. Otherwise the card is considered as personal card and interaction with it is categorized as personal territory activity. As mentioned previously, four semantic actions are coded based on the purpose of the interaction.

Emphasizing actions include pointing, scaling, or mentioning a single card to explain an idea. *Sorting* actions compare and select among cards and pick useful ones. *Grouping* actions move several cards together to form a card cluster. *Linking* actions align two cards together or draw lines between cards to show relationships. *Deleting* include actions which move the cards from the center to the corner.

Comments from the post-experiment questionnaire were analyzed with affinity diagramming. Comments were extracted from the questionnaire and placed on note card (181 cards in total), with one focused point on each card. Three researchers, all with affinity diagramming experience, sorted the cards as a group, clustering and labeling related sets of cards as they emerged. The clusters of feedback are discussed in relation to the core themes of this work.

3.5 Results

All groups successfully finished the tasks and created a design poster, taking between 17 and 55 minutes. Average time taken was 33.12 minutes (SD=11.26). Collectively, sensemaker groups showed good understanding of the content on the digital cards, with only two groups inquiring about two of the technology cards during the design period (about the MYO armband and the FuelBand). There were no major usability issues that interrupted the collaborations. Though several participants perform the task twice, they still followed similar progresses in the sensemaking task, suggesting that the influence did not significantly impact the results.

Overall, participants are far more frequently interacted with the display sequentially than simultaneously. 10 groups spent an average of 1474.10 seconds (SD = 564.53) on sequential interaction and 513.10 seconds (SD = 214.84) on simultaneous interaction. The results revealed that the time on sequential interaction is longer than on simultaneous interaction.

Despite knowing that they can interact with the device simultaneously, the tabletop is used more in a turn-taking manner [142]. A typical sensemaking procedure is that the participant teams spent some time placing the cards around the table for better visibility, and spent the majority of the time discussing the cards, selecting useful elements, and taking turns organizing the cards. Results of each category are presented in Figure 3.4.

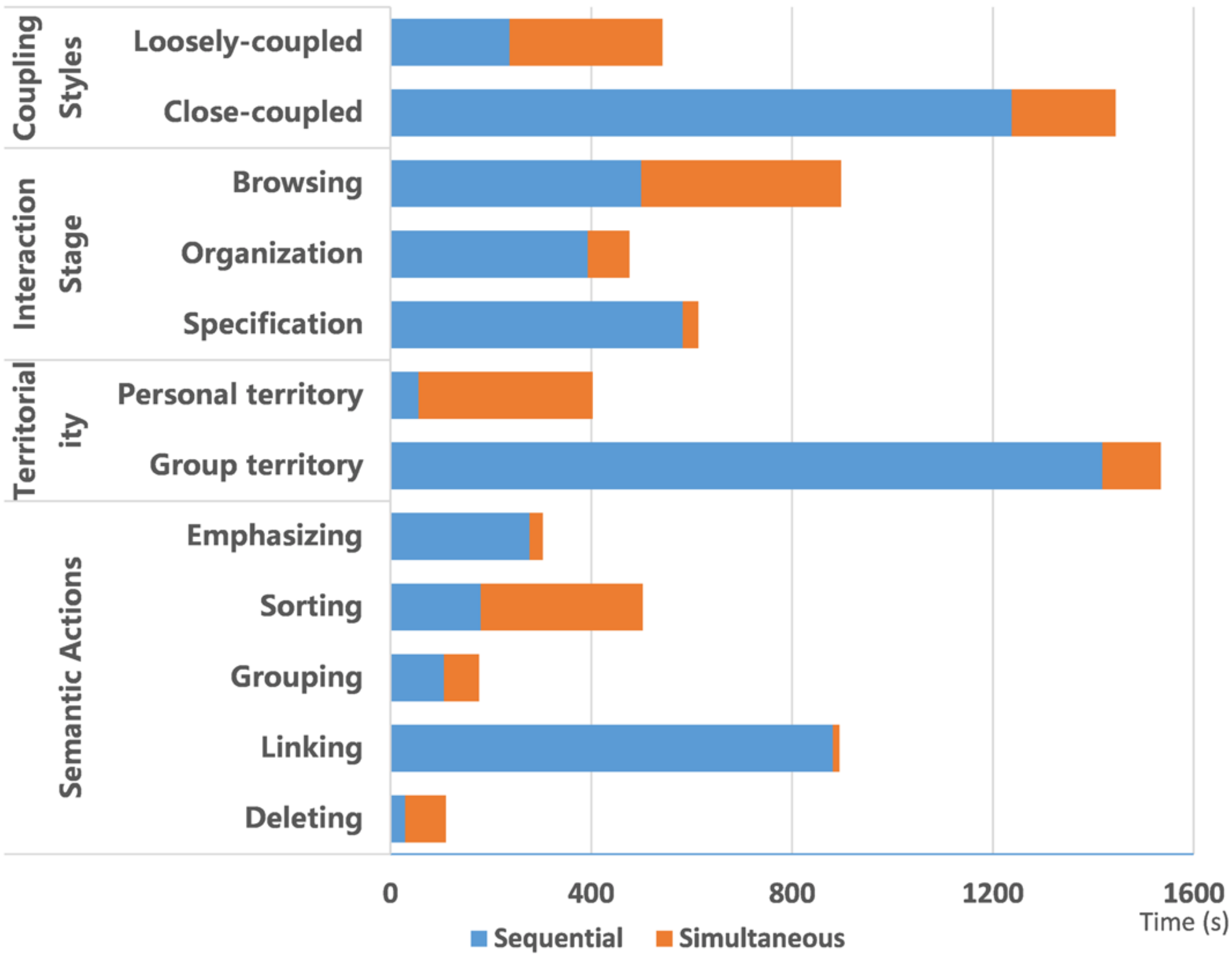

Figure 3.4: Time of sequential and simultaneous interaction for four observed factors.

3.5.1 Interaction Modes with Coupling Styles

On average, the participant groups spent 24.08 minutes (SD = 12.67) designing closely together and 9.04 minutes (SD = 6.92) working independently. When focusing on the same set of digital objects (close-coupled), groups spent 1237.2 seconds (SD = 647.02) turn-taking with the table. The average time for simultaneous touch during close-coupled collaboration is 207.60 seconds (SD = 144.86), smaller than sequential. When groups focus on different objects and work in parallel (loosely-coupled), average times are 236.90 seconds (SD = 270.02) for sequential and 305.50 seconds (SD = 196.59) for simultaneous interaction.

In closed-coupled collaboration, collaborators often have tense communication and pay attention to the same sensemaking issue. These conversations are usually about suggesting and selecting ideas with the cards. Therefore it benefits participants to keep aware of each others' thoughts and behaviors to reach common ground. Compared to simultaneous interaction, sequential interaction results in more time to observe others' activity and evaluate ideas. Since simultaneous interaction with shared materials also might bring interference to conversation and action, participants generally apply sequential interaction to avoid potential conflicts. In loosely-coupled collaboration, participants deliberate and modify different parts of the design. Less mutual influence reduces the chance of conflict; therefore participants can use the card at the same time. We noticed that in loosely-coupled collaboration the sequential interaction time has similar range with the simultaneous interaction. From our observation, participants sometimes look at and think about different cards in parallel without actively moving the cards. The sequentially in this case is due to coincidental touch.

Results of the post-experiment questionnaire also imply that participants appreciate being able to access the table simultaneously, but still desire a close partnership found in sequential turn-taking. Regarding simultaneous access of the table, a participant in Group 6 (G6) noted *"I thought that the interface had a lot of options and free space which made me feel like I could do whatever I wanted."* A participant in G9 wrote *"I like how we were all able to stand up around the table and interact simultaneously on a single platform rather than individual screens."* The openness and equality of using the design table benefits the collaboration, since simultaneous use of the cards gives the participants room to think and work individually, while not blocking the channel for communication.

We also note a common concern on how cards scaffold idea exchange. For example, a participant of G1 commented on the system *"hard for some people to see cards of the people sitting opposite to them."* A G4 participant mentioned *"sharing cards with other group* *members is sometimes tedious due to having to rotate and re-rotate cards.”* These concerns reflect that participants wish to know what others are doing and when they are willing to share ideas. These activities mirror the turn-taking observed in card processing. Though there could be a better method to share cards, the close-coupled collaboration helps the team share ideas and maintain mutual understanding of the task.

3.5.2 Interaction Modes in Three Stages

The average time span of the browsing, organization and specification design stages are 897.60 (SD = 390.58), 476.00 (SD = 286.71) and 613.60 (SD = 373.13) seconds. In the browsing stage, the times for sequential and simultaneous interaction have relatively close mean values of 499.30 seconds (SD = 297.95) and 398.30 seconds (SD = 145.37). However, in the organization stage, the average times for sequential and simultaneous interaction are 392.70 seconds (SD = 279.98) and 83.30 seconds (SD = 86.29), with the former higher than the latter. Moreover, in the specification stage, sequential interaction time (m = 582.10s, SD = 351.41) is longer than simultaneous interaction time (m = 31.50s, SD = 47.07).

The simultaneous interaction mostly happens at the browsing stage. This finding furthers the observation in [142] that simultaneous interactions were conducted merely at the beginning of the task. The exploration of the digital materials is the preparing phase through which collaborators become familiar with the materials and collect initial ideas. Participants need time to browse the cards in parallel to clarify individual ideas, which leads to the simultaneous use of the cards. But when interesting ideas are identified, participants need time to briefly communicate and evaluate the idea; therefore sequential interaction also happens for similar time. In the organization stage, participants take turns proposing and evaluating ideas. The participant who suggests an idea usually takes control of the cards, and passes control of the cards to the next solver when finished. The specification stage has a clearer common goal in design. The changes and decisions made to the cards are important and definite. Therefore the simultaneous interaction in this stage is even less-collaborators need to pay attention when an idea is finalized; unexpected moves will distract the team and interfere with decision-making.

In completing the sensemaking task, interactions with cards reflect participants' thoughts on design. A participant (G5) commented on the browsing stage *"I felt cards on the table helped throw out a bunch of ideas, and the layout/tools along with the cards helped create an environment to nurture creativity and outside the box thinking."* Another participant (G6) noted during idea organization *"I was inspired to think of new ideas, by seeing all of the possible problems and technology that could detect such problem at once. It allowed me to quickly decide on a path to take."* But the number of the cards sometimes highlights problems with idea organization, since *"with all the cards however, sometimes the screen was a little bit chaotic and we would lose track of some of the cards"* (G10). Seeing and using the cards is a process of clarifying ideas [136, 163]. The phases of idea generation, synthesization, and specification reflect how participants use the design elements. Collecting possible ideas tends to be done in parallel, so cards are touched simultaneously in the browsing stage. Organizing and specifying relationships between ideas need joint attention, so card manipulations happen more in a turn-taking manner.

3.5.3 Interaction Modes in Different Territories

For the interaction in different territories, the average time participants spent in personal territory and group territory are 1584.60 (SD = 521.38) and 402.6 (SD = 197.89) seconds. The average time for sequential interaction and simultaneous interaction are 1417.90 (SD

= 514.39) and 116.70 (SD = 112.57) seconds in group territory, with the former longer than the latter. When focusing on digital objects in personal territory, the average time is 56.20 (SD = 72.29) seconds for sequential interaction and 346.40 (SD = 167.53) seconds for simultaneous interaction. The simultaneous interaction in personal territory is longer than sequential interaction.

In personal territory, participants have free access to the cards and usually interact with them without concern for other participants. The simultaneous interaction in personal territory reduces the time to finish the parallel. Being able to work independently on different cards helps designers generate rich and diverse ideas. Another case of simultaneous use in personal territory is removing the less useful cards. Considering the number of the cards, the affordance of removing the card simultaneously reduces the time to narrow down the design options. The cards in group territory are shared by all members. The co-ownership of the design materials makes individual participant tend to acquire others' attention or consent before making changes. When working simultaneously in the group territory without proper awareness of each others' action, errors might be caused due to the conflict of operations.

Regarding transitions between two territories, the dragging and dropping feature of the digital cards gives the participants an easy way to integrate ideas. *"Integrating and changing our ideas was very simple, as we just had to drag cards around"* (G6) and *"it is easy to add/remove ideas and integrate them to the poster by moving the cards... we can have a better view of all the technologies we want to use, so that we won't miss/forget something during the process."* (G8) However, some other features hinder free use of personal space. Some participants noted that the tools' moving and drawing modes block simultaneous use of the table: *"However, when drawing or commenting, it put the whole table in that mode (drawing mode) and the other person had to just watch. It would be great if one person could comment or draw, and the other people could still do other activities"* (G10) and *"if* *the group started working with one tool, and idea requiring the previous tool may be put on hold."* (G8) Participants wish to have the personal space always available even when others occupy the shared space to help quickly record ideas.

3.5.4 Interaction Modes with Semantic Actions

Five semantic actions are observed with different frequency of use. Linking of cards takes the longest time (m = 894.1s, SD = 363.81), and deleting is the least performed action (m = 110.6s, SD = 133.51). The average time for emphasizing, sorting, grouping are 303.6 (SD = 257.72), 502.6 (SD = 298.88), 176.3 (SD = 122.8) seconds. The five actions also show differences in terms of two modes of interaction. The result indicates that emphasizing and linking are performed more in turn-taking mode than simultaneous mode. Grouping and deleting, which are the two least used actions, show no significant differences with interaction mode. For the sorting, we noticed that average time in simultaneous interaction seems higher than that in sequential interaction. This is perhaps due to that group 7 spent nearly 15 minutes taking turns to evaluate and sort every one of the 98 design cards.

Our observation shows that different semantic actions are conducted with different interaction modes. Emphasizing one card denotes the discovery of an interesting idea. Linking a pair of cards suggests designers identify or confirm an important relationship. These two actions usually involve pivotal ideas or decisions that inspire the team and push forward the design. As such they ask for joint attention and consensus from other members in the group. The necessity of group awareness makes the emphasizing and linking actions being conducted in a sequential manner. Different from emphasizing and linking, card sorting means ranking several cards based on some user-defined criteria. From our observation, most group members pick their own interesting cards and make the rest of the design grounded on the selected cards. So the sorting process is generally conducted in parallel in which participants can locate cards of individual interest very quickly. We also note that group 7 discusses and evaluates every card to decide which cards to use. The sequential reading and discussing of the cards increases the time to sort the ideas. Grouping and deleting are used less than the former three actions and are conducted both simultaneously and sequentially. Grouping was used to complement an idea by adding one or more cards to an existed card cluster. On the contrary, deleting happens when cards added previously appear to be less useful or irrelevant as the design evolves. In our study, the simultaneous adding or removing of cards usually happens when the target card does not impact the current design very much, while the sequential interplay of these actions usually involves cards of certain importance.

One noteworthy technique to emphasize and sort digital cards is enlarging or shrinking card, because *"the resizing ability makes it easy to assign important/priority for each card"* (G9) and *"being able to resize them gave us the ability to make certain cards appear as more important than other, which may be a desired ability in designing."* (G7) The resizable digital cards offer a unique affordance in contrast to paper cards: different sizes represent different importance, and the better visibility makes key elements easy to capture. Also, we observed that when a participant zoom the card to take up more screen space, the intentional or unintentional intrusion draws the group's attention, triggering a shift from simultaneous exploration to a turn-taking conversation.

The simultaneous dragging and dropping expedite creating card groups to cluster similar elements. The participants agreed that *"it was very easy to share the cards or create groupings by dragging"* (G3) and *"it was incredibly easy to create groupings, by simply dragging cards to their desired group."* (G6) But when the card group grows large, *"it would be great if there was a way to select cards and make them into a group, whenever you wanted to move a group of cards that you had related, you had to do it one by one".* (G10) These comments suggest that the participants adopt the provided touch interaction intuitively, but still wish the system to support new semantic actions for manipulating a group of digital artifacts.

3.6 Discussion

To expand the understanding of simultaneous and sequential interaction with multi-user touch display in co-located sensemaking, our observational study examined interaction within a goal-oriented sensemaking task. The observation of simultaneous and sequential interaction in co-located sensemaking explored the RQ1 *"how do sensemakers work simultaneously and collaboratively in co-located sense-making and what co-located space factors influence the two styles?"*. Our findings suggest that simultaneous and sequential interactions are influenced by group activities including the deliberation, exchange, and integration of the group ideas, which form the main body of the collaborative task. Build on many previous studies on the collaboration over shared multi-touch devices (e.g., [74, 79, 122, 168]), our observation further looks into when and how people interact sequentially and simultaneously, particularly from social, spatial, temporal and gestural perspectives. Building on the analysis in the previous section of simultaneous and sequential interaction within the four collaboration factors, this section puts forth observations based on the findings.

3.6.1 Supporting Collaboration Techniques

Sequential interaction is the dominant collaboration technique for design-related sensemaking with multi-user touch display. Participants spent more time on sequential interaction with the display compared to the simultaneous. The digital collaborative space is used as a supporting tool to help explain and exchange ideas. However, the conversations during the design, which mostly happens in a turn-taking fashion, influence the physical interactions.

Prior studies focus on the form of coupling styles [79, 161] or technology support for both close-couple and loosely-coupled collaboration [28, 74, 168]. This study further explores how coupling styles affect simultaneous and sequential use of the device. When closely collaborate with each other and have tense conversation, the participants tend to use the multi-user display in a sequential mode to avoid interference. But when working in distributed attention, collaborators are more flexible suggests that though the multi-user touch-sensitive device provides the ability to handle concurrent user inputs, the interaction manner does not totally lie on the affordances in selecting interaction manner. This implies that the influence of the awareness and conversational factors to the physical interaction is considerable.

The participants in our study perceive the openness and freedom of the interaction space as useful to forage information. The equal and simultaneous access to the touch table motivates participation, thereafter encourage making contributions. Also, the participants are ready to show their findings and learn what others are doing. Though resulting in the sequential interactions with the table, the close-coupled collaboration enhances the mutual awareness to each others' activities, and therefore builds the common ground to the collaborative task.

3.6.2 Supporting Task Change in Interaction Stages

Prior research gave general descriptions of when the simultaneous and sequential interactions happen in different contexts [38, 63, 142]. Grounded in these findings, this study conducted a deeper investigation of the two interaction modes in three interaction stages. Upon our observation, we notice that more frequently the simultaneous interactions happen at the browsing stage. In the organization and specification stage when the idea is getting more and more certain, collaborators do not interact with the display at the same time. This suggests that the simultaneous browsing helps collaborators quickly acquire enough information through exploration, and generate many potentially interesting if yet unclear ideas. Sequential interaction helps collaborators pay attention to each other and maintain the same understanding towards the decided plan.

Implications from this finding include the design of the groupware on the multi-user touch display should supports simultaneous foraging and sequential sensemaking. The interactive objects should be available to all collaborators for exploratory manipulation and the spatial interferences between them should be avoided. As the design becomes clearer, mechanisms to coordinate the turn-taking idea exchange and decision-making should be considered to facilitate mutual awareness.

Our participants took the digital cards as a media to forage and make sense with the design information. Building on prior knowledge on sense-making process [134] and reflective practices with the design materials [136, 163], our study suggests that different constitution and different interaction modes of the digital materials influence the path of design throughout the three design stages. When collaborating through groupware, providing abundant while simultaneously accessible materials at the beginning will expand the idea inventory. In completing the design, methods such as highlighting important objects and taking turns will encourage collaborators to focus more on the key thoughts and not diverging with too many unrelated ideas.

3.6.3 Supporting Interactions in Territories

Prior work has explored how collaborators work in personal and shared territories, and how technology can help and hinder work activities. When working on shared tasks, participants seemed to avoid touching the display at the same time, while when working separately they interacted with digital objects simultaneously. This observation of territoriality suggests that sequential use of the objects dominate interactions within group territory and the simultaneous interaction dominates personal space.

These interaction patterns suggest that collaboration tools should support transition between personal and group work, including by reflecting recent changes to assist collaborators in observing, evaluating, and responding to modifications [22]. Technology should enable collaborators to distribute work in the space and finish simultaneously to increase efficiency of collaboration and encourage balanced participation.

Control and availability of shared objects are critical for collaborative systems [150, 181]. In the context of co-located collaboration technologies, operations that interfere with personal control (e.g., mode switching) can cause interaction issues. Our observations showed that users might switch mode during personal work, ignoring global effects on others. Yet participants need availability of personal space: it facilitates idea organization, and allows the participants to work on their own subtask when others are editing the shared space. In crafting or choosing a collaborative digital table and software, one should consider ways to ensure an always-on personal space for each collaborator; or when the personal space is not available there should be proper support for awareness.

3.6.4 Supporting Semantic Actions

Some actions are better performed simultaneously, while others may be only suitable in turns. In the observation of the semantic actions, we noticed that activities like emphasizing one card or linking a pair of cards are conducted in turns. Some actions such as sorting the cards are usually performed in parallel. Other actions include grouping and deleting can be sequential or simultaneous, based on the content and importance of the target card.

Regarding relative utility, it would be beneficial to take the interaction mode into consideration when designing the interaction technique for the multi-user touch display. For example, in the gesture based collaboration system, gestures for sorting personal objects might be preferred to be performed simultaneously, so the system should be able to handle the simultaneous gesturing during these actions. Gestures for emphasizing or connecting the digital objects should be designed in a more noticeable manner to ensure group awareness of personal thoughts [178].

The digital cards capture most affordances of the paper cards, such as moving, rotating and clustering, but the malleable and distributable feature further enhance the co-located collaboration by helping idea exchange and integration. In our observational study, the resizing and the drag-and-drop action are used to communicate interesting cards and integrate group ideas. In addition to the semantic interactions that designed for object manipulation [33, 44, 115, 122], our study suggests that leveraging the communicational meaning of the semantic actions can also increase the mutual awareness of individual ideas and therefore reduce the effort to integrate group opinions. Other semantic actions on digital objects, such as the batch operations, should also be considered to facilitate organization and simplification of the design ideas.

3.7 Chapter Summary

This chapter presented an observational study focused on collaborative interaction with a multi-user touch display. Simultaneous interaction and sequential interaction during the sensemaking activity were examined with four collaboration factors: coupling style, interaction stage, territoriality, and semantic action. The results suggest that in design-focused co-located sensemaking, sequential use of the digital objects is the major method of interaction with the multi-user touch display. Other results point to the understanding of the simultaneous and sequential patterns in different interaction stages, among different territories, and in actions with different semantic meanings. The following are the main conclusions regarding S1, *"what co-located space factors determine the styles of collaboration?"* and S2, *"how do sensemakers work individually and collaboratively with a shared tabletop?"*

- S1: The personal and collaborative spaces have their own characteristics of simultaneous or sequential access – personal control over the workspace is preferred to always be simultaneously available, while the awareness maintenance and communication lead to sequential interaction.
- S2: Although technology and encouragement were provided in support of simultaneous interaction, in this study sequential interaction was the dominant collaboration technique used with the multi-user touch display.
- S2: Rich and simultaneously manipulable digital materials are preferred and facilitate idea generation, but the organization and synthesis of the ideas require a less interruptive and distractive approach to collaborate over the shared materials.

Some actions are better performed simultaneously for efficient collaboration, while others may only be suitable to execute in turns to better communicate ideas. Attaching communicational meanings to the interaction enhances mutual awareness and mutual understanding. With the prevalence of large-scale multi-touch displays, increasingly more collaborative work has the potential to be supported by technology-enhanced materials and approaches.

Chapter 4

Notifications and Awareness in Collaborative Sensemaking

Display technologies such as multi-user tabletops and wall displays offer face-to-face environments for sensemakers to monitor each other's actions and activities. However, when dealing with large amounts of data representations, sensemakers have to decide between working separately to explore more individual data or participating in others' work to maintain awareness. Incorporating awareness-supporting techniques such as notifications could simplify awareness maintenance, but their effects on collaboration with multi-user tabletops are under-explored. Our first study on simultaneous and sequential interaction suggests that simultaneous interfaces are not fully utilized by co-located sensemakers due to the need for social exchange and avoidance of conflicts in shared space [124]. However, participants still prefer the openness of personal space for ad-hoc foraging to consider and contribute new possibilities. Prior studies have also found that the ability to divide the task and work at the same time is imperative to the effectiveness of collaboration [113, 154].

Awareness-supporting techniques such as notification systems [20, 109, 128] have historically been used in CSCW systems to assist distributed users in tuning awareness information. Design of awareness-enhancing techniques is pertinent to individual and team awareness, and particularly to the effectiveness of communication. This study examines notifications on tabletops and explores how they affect sensemaking collaboration. A card-based system is designed and implemented with which two sensemakers can work together on two sides of a tabletop display. Travel information is represented by a series of digital cards on the table, and sensemakers can sort the cards into virtual boxes in the middle of the display. The system offers the option to trigger notifications when the cards are drag-and-dropped into the category box.

TThis study extends the understanding of S1, *"what co-located space factors determine the styles of collaboration?"*, and also explores S3, *"what are the ways to connect and present related individual work?"* [123] and S4, *"how do notifications supporting awareness affect co-located space factors?"* This study initially addresses S3 by adding in-workspace notifications; this question is then further explored in Chapters 5 and 6. Utilizing notifications to reduce the effort of awareness maintenance could help balance simultaneous and sequential interactions. We leverage the model identified by Carroll et al., expanding it into a framework that describes the effect of notification in the tabletop-based co-located context.

4.1 Abstract

Recent advances in multi-user multi-touch displays enable support for rich and complex simultaneous co-located collaboration. Multi-touch tabletop displays and wall-mounted displays provide collaborative spaces where people simultaneously interact with the digital content while being able to see and talk to each other, but use of these large displays introduce issues regarding how to support multi-person sensemaking interaction. Distinguishing characteristics of tabletops, compared to other shared large displays, relates to the increased physical size and the support for multiple simultaneous touches. These differences allow users to establish their own personal spaces within the display and work on complex multi-handed tasks, with added potential to ignore the sensemaking activities of

others-necessitating awareness-support such as notifications.

Prior studies have explored how visual designs and notifications influence awareness in collaboration [47, 48, 54]. Shared display notifications seek to address awareness problems, but studies suggest that incorporating notifications comes with attentional cost. Understanding and balancing such tradeoffs center the design and evaluation of notification techniques. Carroll et al. aggregated knowledge from prior studies on collaborative awareness (e.g., [34, 45, 54]), concluding that collaborators' social, action, and activity awareness must be balanced by notifications [20]. This study considers those three types of awareness, expanding their definitions to encompass the unique nature of multi-user tabletops – highlighting the importance of awareness of shared activities in multi-user tabletop use.

We leverage the model identified by Carroll et al., expanding it into a framework that describes the effect of notification in tabletop-based co-located sensemaking. Individual work, social norms, and team performance are three collaboration factors in the framework, for which notifications have significant influence in social, action, and activity awareness. The framework provides an understanding of the effects of notifications-both benefits and costs – in influencing collaborative awareness over the multi-user tabletop display. The research outcome provides knowledge for multi-user tabletop designers to better use and evaluate notifications in supporting co-located awareness for sensemaking tasks.

The framework is examined in a laboratory study with 61 participants. The study focused on a collaborative card-sorting task, exploring whether notifications that show collaborator activities affect sensemaking awareness. The results consider two metrics for each of social, action, and activity awareness. The study demonstrates an increased awareness of the actions of others when using notifications, highlighting differences in social norm, task performance, and individual work. The results suggest a research agenda that encourages further investigation toward understanding not only how notifications affect social, action, and activity awareness, but also how notifications can be designed and used to encourage sharing and enhance communication.

4.2 Multi-Tser Tabletops and Collaborative Awareness

Staying aware of others' sensemaking activities is a secondary but valuable part of co-located collaboration [20, 30]. When collaborating using a multi-user tabletop display, people monitor others' activities through multiple communication channels: listening to what others are saying, observing others' body gestures, seeing others' touch actions, and revisiting changes. Awareness on tabletop applications can be augmented with notifications showing others' sensemaking activity, e.g., visual effects highlighting digital items. Notifications in the co-located workspace inform collaborators of prior group activities, but may influence individual activities and the manner in which collaborators participate group work. To connect prior work on notification design with practical application of multi-user tabletop notifications, we examine the use of co-located notifications with Carroll's awareness model. Carroll's model incorporates three high-level awareness types with a knowledge structure about notifications in collaborative systems. Action, social and activity awareness are refined from prior research on collaborative awareness, including situation awareness [34], workspace awareness [54, 55] and visual-based grounding process [45]. The model is rooted in practical use of collaborative notifications and clarifies the awareness categories that must be supported through notifications.

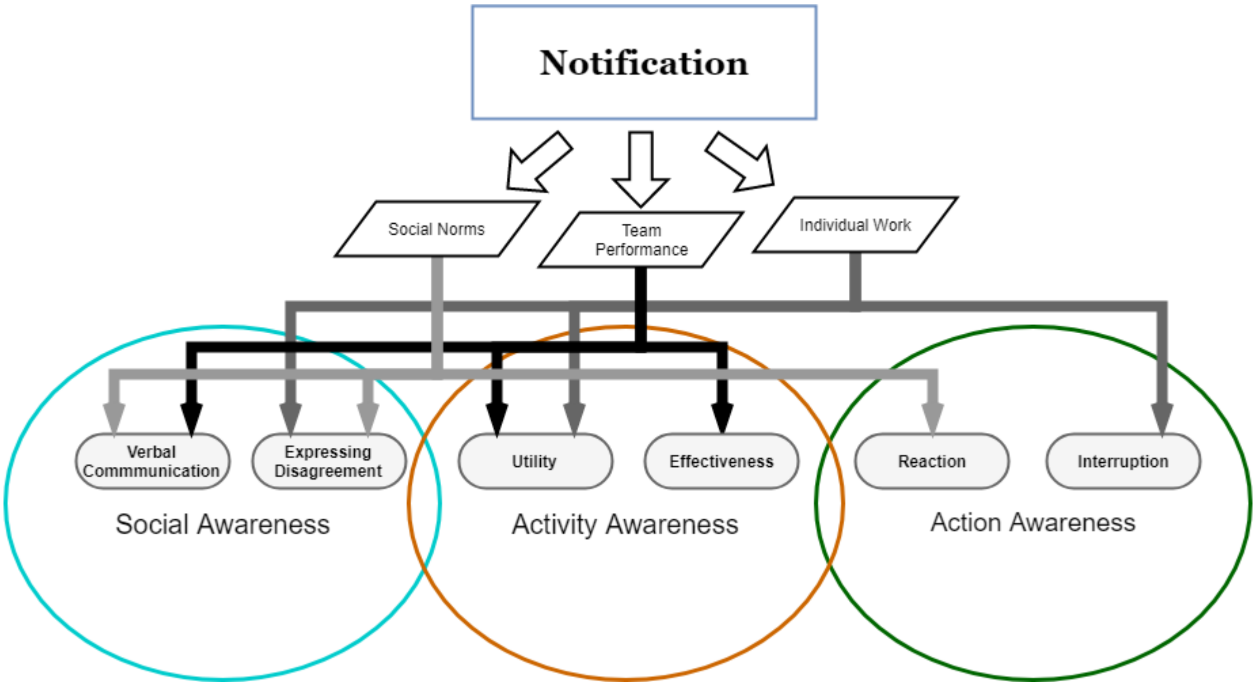

Figure 4.1: Framework showing how notifications influence different types of awareness.

4.2.1 Action Awareness

Action awareness refers to the understanding of the ongoing actions carried out by sensemakers. In collaborative applications for sensemaking, people know what objects are shared with others and who is modifying them through indicators on the screen. As a part of workspace awareness, these indicators reflect immediate and synchronous actions to the shared artifacts (e.g., *what* questions addressed by workspace awareness information), which influences one's own decision about the next action [34, 54]. multi-user tabletop displays provide large interaction space, enabling collaborators to work at different screen position while being able to see what others are doing. The division of screen space, referred as *territoriality* [150], reflects the space need for both individual and collaborative tasks. However, when observing actions in another's territory, awareness might be restricted by the form factors of the display [28, 89]. multi-user tabletop affordances influence factors such as *reaction* to the other's activity and *interruptions* to individual work. Direct touch affects how people react to others' actions, since responding in face-to-face collaboration is preferred to be timely, and body cues may attract others' attention. Due to large screen size, reacting to a notification and moving attentional focus requires cognitive effort. People usually defer or even completely leave their own ongoing work when they react to the notified item on the other side of the display [131]. The immediate reaction is a source of breakdowns and may cause interruptions to individual workflow.

4.2.2 Social Awareness

In CSCW, social awareness refers to knowledge of the presence of collaborators. Particularly in remote collaboration, people want to know about collaborators: anyone is available, who is around, who is doing the actions, and other social factors not visible to collaborators [54, 108]. These questions form people's understanding to the presence and identity of other collaborators, as well as the authorship of the actions [54]. Collaborators use language and other visual medium to maintain social awareness, which is a part social interactions for building common [25, 47, 48]. When collaborating using a tabletop display, however, issues of existence and engagement is different. The large interaction space affects social interaction. For example, recent study suggests that communication reduces with larger size of the shared display [182]. The introduction of multi-user tabletop technology for co-located presence makes mood-related factors such as *verbal communication* and *expressing disagreement* more important [74, 133]. In addition, social presence in a co-located context also encourages collaborators to react to each other or their digital representations (e.g., notifications) [139]. For example, responding to another's action with utterances or body cues shows awareness of other's thoughts and activities [63]. Giving an appropriate response can not only move forward the task, but also increase connectedness and build a closer working relationship. Asking about actions verbally helps capture others' purpose and plan in the collaborative task [54]. Awareness of the social context also influence the exchanging and merging of the individual awareness to develop common ground [147]. In co-located sensemaking with tabletops, the awareness to the other's social presence might influence people's willingness to consider different possibilities and express disagreements.

4.2.3 Activity Awareness

Activity awareness is the perception of sensemakers' plans and motivations [20]. Activity awareness includes not only many aspects of social and action awareness through an understanding of the overall situation, but also a deeper understanding of the current and past workspace information throughout various collaborative events [54]. Activity awareness established from communication and shared views highly influence the effectiveness of collaboration [47, 48]. Higher activity awareness may simplify conversation and coordinate actions in the workspace [48, 54]. Establishing effective activity awareness on multi-user tabletops is challenging. Collaborators are usually involved with others' work in different *coupling styles* – working separately in a *loosely-coupled* style or intensively with a *close-coupled* style [162]. Closer relationships improve collaboration outcomes, but people still need to work independently [72, 162]. Collaborators might be working in parallel during the collaboration, though the size and multi-touch capabilities can result in people not understanding others' activities. But others' activities in the collaborative task can affect individual work [75]. Awareness of the team situation influences the *utility* of the digital artifacts and the *effectiveness* of group work. Although most multi-user tabletops are simultaneously accessible to all collaborators, people need to monitor other's actions on the shared items to decide the appropriateness one's own actions [147]. This understanding, which can be obtained from reading notifications, affects the utility of personal items. Failing to understand others' activities might lead collaborators to perform spurious work. Notifications indicating other's activities have promise in avoiding these problems and boost collaboration, but only if appropriately used.

4.3 Notification and Awareness

A *notification* is a way to "deliver the current, important information to users in an efficient and effective manner, without causing unwanted distraction to ongoing tasks" [110]. Notifications can heighten awareness of collaborators' activities, though they also introduce costs. Collaborative notification in our research has two characteristics: it presents an immediate alert after the partner makes an important change, and it provides enduring information about past activities. Previous knowledge of notification design and the unique form factors of multi-user tabletops reveals three areas for which notifications affect awareness – individual work, social norms, and team performance – that help clarify the manner in which notifications affect collaborative awareness.

4.3.1 Individual Work

Individual situation awareness is the understanding to the status of the collaborative environment and leads to sense making and action execution [35]. Acting on items used by others, expressing diverse ideas, and pausing individual work to give responses are consequences of awareness to one's own responsibilities. During individual work, the degree for which each collaborator understands the impact of other's activities modifies the individual utility of the shared items. In multi-user tabletop collaboration, utility is embodied by which and how touch items are visited. An incoming notification distracts a sensemaker's attention from the current focus area to the notification. Given the large interaction space of multi-user tabletops, moving attentive focus might interrupt individual actions, causing breakdowns in workflow. Disagreement may also be limited when notified that a different decision has already been made, for better or worse. Notifications in the face-to-face context heightening awareness of other's activities might enhance mutual understanding, but may also discourage individual thoughts.

4.3.2 Social Norms

Social Norms reflect conventions that affect the *grounding* process in which sensemakers communicate and exchange awareness information [25, 46, 48]. With multi-user tabletop notifications, sensemakers obtain a way to acknowledge and respond to others' activities in the co-located space. Notifications serve as an embodiment of others' presence and activities. In addition to body cues, people can also acknowledge and react to others through interaction with notifications. But higher awareness of social presence may reduce verbal conversations. Notifications manifesting collaborators' past decisions may affect people's willingness to make changes, especially for items changed by others. These influences imply that notifications impact awareness of co-located social context and alter the social norms that guide co-located group work.

4.3.3 Team Performance

Notifications showing other's activities may potentially influence the performance of the collaborative task. Team performance in this study focus on how team situation awareness influence the overall utility and effectiveness of collaborative interaction. Notifications indicating the key changes assist the understanding of other's behavior. With higher awareness of other's actions and activities, people may simplify the face-to-face conversation to make the interaction more efficient [54, 92]. Notifications are also a part of the information upon which people make decisions on the next-up activities. Better understanding of others' activities helps people monitor the progress of the collaborative task, thereby increasing potential effectiveness of the collaboration. Notifications indicating the status of the digital objects help people decide which one to use and influence overall utility of the digital items on the multi-user tabletop display.

4.3.4 Framework of Notification and Co-located Awareness

Figure 4.1 summarizes how notifications impact different types of awareness, with individual work, team performance, and social norms as factors affected by notifications. The manner in which notifications influence social, action, and activity awareness comes from connections among factors and aspects in multi-user tabletop collaboration for each type of awareness. To better understand the role of notifications in co-located collaboration, a laboratory study is conducted with a collaborative card-sorting task on a multi-user tabletop display.

4.4 Supporting Card Sorting

Card sorting is a common method for organizing information in sensemaking activities [66]. In this collaborative information organization activity, people explore a set of cards and sort them into categories. Each card contains an item, and cards in the same category share characteristics. In a card-sorting task, collaborators communicate to share thoughts, manipulate cards to explore the card content, and observe the card status to track the overall task progress. Analogous exploration and decision-making activities on multi-user tabletops can be found in other examples [29, 61, 72, 118].

A card-sorting system is developed with Windows Presentation Foundation on a multi-user tabletop display. For our study, the system uses two identical sets of digital cards on two sides of the tabletop. Cards consist of text and pictures representing items to be sorted. Any card can be moved, rotated and zoomed with common multi-finger touch operations [177] by multiple people simultaneously. The system was designed with the guidelines proposed by Morris et al. [114] and Scott et al. [149, 150], replicating controls in each collaborator's personal space. Similar interface layouts can be seen in many other studies [72, 142, 182]. The color-coded category bins are in the center of the table. Users can drag and drop a card onto a bin to categorize it. The card background turns the same color as the bin when sorted. The notification used in the tool consists of an animation and a background color change (Figure 4.2). When one user sorts a card into the bin, the card with the same content on his partner's side will shake for one second and then its background changes color. The animation informs the collaborator of an change, with the color indicating card category. Animated notifications have been shown to better attract user's attention compared to other generic notifications [7], which should help raise awareness when using large tabletop displays.

4.5 Indicators of Awareness

There is no complete collection of metrics that fully reflect the different types of awareness, but we sought to identify a number of awareness indicators that reflect their core aspects [63] (Table 4.1). Carroll et al. defined social awareness as *people's understanding of the current social context*. The co-presence of users in tabletop collaboration affects the communication as well as recognition of communication between people. In the context of our experiment, we identify *verbal response* as the most indicative of social awareness more so than gaze, gesture and other social interaction. Verbal response implies the realization of the social presence of others, which may lead to ad-hoc communications as a part of grounding process

[48]. No or few verbal responses in the co-located context suggests that participants are less ready to give feedback, or perhaps even a failure to realize a partner's decisions [139]. A second social awareness indicator, *category change*, is more indirect but interpretive, tying to the core activity of categorizing cards as required by this experiment. Awareness of social presence influences collaborator feelings about the card category. Understanding to the social context of the face-to-face collaboration indicates high social awareness, but may also discourage activities of individuals, such as expressing the intent to change the card sorted by another [20].

Action awareness refers to immediate reactions to others' actions on the shared objects categorized by a collaborator. In co-located sensemaking, the moment-to-moment awareness of others' actions influences one's own decisions. Too much information about actions may tax users' ability to comprehend and excessively interrupt one's own activities. *Touch reaction* and *touch distance* were used as indicators of action awareness. Gestural behaviors on touch-enabled items reflect collaborators' cognitive flow [142, 162]. The immediate touch response to other's sorting actions indicates the perception of other's activities. Increased awareness of actions performed in the collaborative space enables participants to more easily identify changed items and understand how they influence their own tasks [54]. Touch distance is used to evaluate interruption and distraction. We describe it as the accumulated spatial distance between every adjacent touch movement. Higher touch distance implies that the collaborator shifts attentional focus from one region to another. It might interrupt deliberation on the current card and break down card exploration.

Activity awareness influences the level of coordination in collaborative sensemaking. Higher activity awareness suggests that sensemakers accurately perceive others' goals and actions, and therefore adjust their own activities for higher teamwork effectiveness. Collaborators with higher activity awareness coordinate their own actions in accordance with the others' actions, not only lending more effort to unfinished tasks but also avoiding duplicated work. In this study, we examine activity awareness as it is reflected in item utility and number of times a collaborator sorts previously sorted cards to the same category (called redundant sort). Number of times the collaborator moves the cards reflects overall utility of the multi-user tabletop interaction space. With increased awareness of others' activities, we assume collaborators have less concern about interaction conflicts; therefore more efforts can be spent on exploring the unused items [116]. Duplicating the sorting actions reflects people's knowledge about overall task progress. With low awareness of other's activities, a collaborator may not realize a card has been sorted and may perform a redundant action. Extraneous sorting behavior increases task burden and suggests low activity awareness, reducing task effectiveness.

Table 4.1: Evaluated GA types and indicators

	Factor	Description	Examples
Social Awareness	Verbal Response	Collaborator gives feedback after seeing partner's activity	Acknowledgement of changes; Indicating awareness of other's presence and involvement; Verbal responses that initiate ad-hoc conversations and establish common ground
	Category Change	Number of times a collaborator sorts previously sorted cards	Modifying others' sorting results; Reflecting level of concerns on other's past decisions; Category changes that indicate lower awareness of the authorship of actions or fewer concerns on changing other's decisions
Action Awareness	Touch Reaction	Collaborator identifies sorted card location and moves it to category	Reacting to or showing comprehension of other's actions through one's own actions; Touch reactions that influence one's own future actions on the shared items
	Touch Distance	Accumulated distance between touch actions	Interruptions by the collaborator; Making effort to respond to other's actions; Increased hand move on the tabletop
Activity Awareness	Item Utility	Number of card movements per minute	Frequency of accessing different items; Stating or otherwise indicating knowledge of the item category
	Redundant Sort	Number of times collaborator sorts previously sorted cards	Statements reflecting lack of knowledge of other's repeated actions and implied intentions; Overlap in activities with collaborator

4.6 User Study

Study participants were recruited from a community and university participant pool at our institution. During the experiment, a 55-inch Microsoft Perceptive Pixel Display tabletop is placed in the center of a laboratory room with the participants standing on opposite sides (Figure 4.2).

4.6.1 Research Setup

Each participant was assigned to an experiment group: the notification group or the control group. The notification group performed the card sorting task with notifications (see Figure 4.2). The control group worked on a system without notifications – card-sorting actions were not reflected in the partner's cards. The task asks participants to sort up to 36 different travel destinations into three different categories representing three levels of visiting priorities: definitely visit, probably visit, possibly visit. The destinations are presented on 36 digital cards. Each card represents a well-known U.S. city (e.g., Boston, New York) with suggested days of travel and projected cost. See Appendix A.1 for example cards.

The participants were asked to sort the cards collaboratively with their partner, evaluating destinations as a team. To categorize a card, a participant drags and drops the card to a color-coded category bin. Each card can only be in one category. Once a card is sorted, the matching card on the partner's side reflects the new category. To measure the category change, the participants were notified that after the partner sorted a card and it is not necessary to sort it sorted again if there is agreement with the card category. For the notification group, sorting results in a highlighting notification on the same card on the partner's side and changes its background color. For the control group, sorting a card has no visual effect on the partner's card.

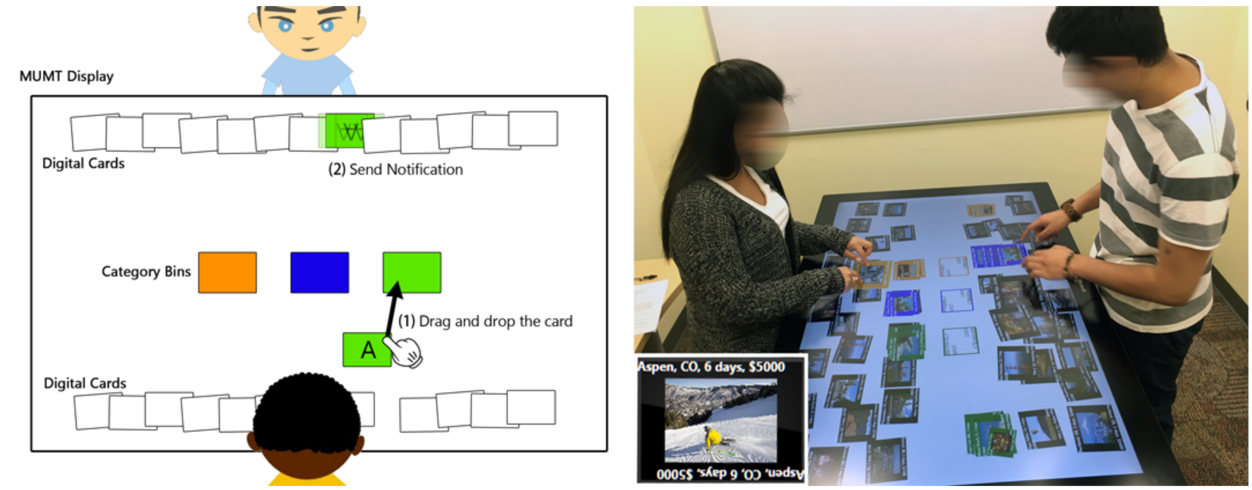

Figure 4.2: Left: Interface and a notification in the card-sorting tool. Collaborators stand on two sides of the table and sort cards by dragging and dropping into category bins. Right: The experiment setup and an example card (inset).

Participants were informed of the task requirements and system use and practiced with the system by moving and sorting an unrelated set of cards. The participants were told to sort around 15 cards based on the provided information on the card. They were also instructed that each category should contain at least one card, the task terminates if lasts longer than 20 minutes and one should not use the card on the partner's side. 61 participants (60 undergraduate and one graduate student, 37 females, mean age 19.9, SD 1.5) took part in the experiment. The participants had various majors: computer science (N=9), psychology (8), biology (5) and neuroscience (4). 30 participants (19 females) were in the notification group and 31 (18 females) in the control group.

4.6.2 Experiment Confederate

Variables related to personality, aggressiveness, and preferences can greatly influence study results [167]. Because we were interested in comparing reactions to partner actions and system notifications, we chose to incorporate a research confederate. A *confederate* is a member of the experiment team who pretends to be a participant but who follows a pre-defined script. The confederate was instructed to perform identical actions for all participants. The confederate's script was developed with the following criteria to measure awareness factors: (1) For both groups, the confederate sorts the equal and reasonable number of cards (Verbal and Touch Response). (2) The participants' touch actions should not be greatly interfered by the partner (Item Utility and Touch Distance). (3) The partner sorted each designated card to the same category so that the two groups have the same situation to make changes (Category Change). The variable-controlled study influences the observation of the awareness indicators in two ways. First, since the confederate performs identical sorts for all participants, each participant receives same number of notifications, therefore the participants have equal chance to give verbal responses and touch reactions to the partner, with equal likelihood of interruption by sorting actions. This helps avoid cases of low notification count. Secondly, personal preference influences choices; use of a confederate ensures the two groups experience similar conditions. This helps avoid situations of participant reluctance to change category because the partner dominates collaboration.

Table 4.2: Confederate script. Column 1: time for each sort. Columns 2 & 3: card destination and category for each time. Column 4: whether confederate gives verbal explanation.

Time (MM:SS)	Card	Category	Verbal Description
01:00	Boston	Definitely Visit	Yes
01:00	Boston	Definitely Visit	Yes
01:30	Annapolis	Probably Visit	Yes
02:00	Washington	Possibly Visit	No
03:00	Charleston	Definitely Visit	No
04:00	Miami Beach	Probably Visit	Yes
04:00	Napa Valley	Possibly Visit	Yes
04:30	New Orleans	Definitely Visit	No
05:00	Myrtle Beach	Probably Visit	No
05:30	Richmond	Possibly Visit	Yes
06:00	San Francisco	Definitely Visit	No
06:30	San Antonio	Probably Visit	No
07:00	Raleigh	Possibly Visit	Yes

An undergraduate research team member served as confederate and performed the card-sorting task with all participants. Participants did not know they would be working with a confederate before the study. If the participant asked questions or made a comment, the confederate gave brief feedback, but she did not engage directly with the participant's sorting activity. For example, if the participant asked "Do you want go to Boston?" The confederate will reply, "Yeah, you can sort it to whatever category you like." Before the actual experiment, the confederate practiced the task for fourtimes with different persons for timing and quality.

To examine the awareness indicators under the same condition, the confederate followed the same pre-defined script across all sessions. A timer is provided at the corner of experiment room to let the confederate monitor the time. At the beginning of the task, the confederate suggests that they look at all the cards. Then after a period of time the confederate sorts one card to one category. The confederate sorts 12 cards in total. The order of the card sorting and categories where the cards were sorted were same with all participants, as showed in Table 2. When sorting six of the 12 cards, the confederate gives a verbal explanation. When sorting the other sixcards, the confederate does not say anything (see column 4 in Table 4.2). If the confederate's sorting action conflicts with the participant's ongoing speech or actions, the confederate will delay her action a few seconds to let the participant finish. Since the confederate always sorts the same set of cards with the approximately same time interval, participants' verbal and gestural reactions to the confederate's sorting actions can be compared between groups.

4.6.3 Data Collecting Method

To quantify the awareness indicators in the study, we use two sources of data. An overhead camera over the center of the tabletop captured and saved all actions. The system also tracked and logged each touch movement performed on the multi-user tabletop display. Card movement records start at a touch on the cards and end when all fingers on that card leave the display, with collected attributes of each record including the card content, owner, current category, start and end point timestamps and pixel coordination, and whether the card is dragged and dropped into a bin and the category of the bin.

Video Data Analysis

The *verbal response* for the social awareness is reflected in reactions to confederate card sorting. We focus the video analysis of *card-sorting* events. Five research team members independently transcribed card-sorting events in the video records. 12 events were identified in the video track first, then the research members took records of participant verbal feedback. Two team members transcribed the notification group and another two transcribed the control group, while the lead researcher transcribed all videos in both groups. Each person worked individually without interaction. Thus, each record has three transcription records from three different team members. To ensure reasonable agreement, for each card-sorting event the participant is considered to give a verbal response if at least two records indicate an interaction.

Touch Data Analysis

The other five awareness indicators were quantified from touch logs. Each card movement performed by the participants were categorized into one of three touch categories – *moving* *touch* (MT), *sorting touch* (ST) and *awareness touch* (AT). MTs are the card movement before the card is sorted. STs are the actions of dragging-and-dropping the card into a category bin. ATs are the touch actions of moving the cards that already be sorted. Touch reaction is measured as the number of events for which the confederate sorted a card and the participant moved that card within 10 seconds. Item utility is the number of touch movements performed by the participant, measured in touches per minute. The item utilities of the three touch types were measured separately. The card touching frequencies in each of the 12 card-sorting events intervals were calculated (from the beginning to the 1st card-sorting, and all 11 intervals between the 12 card-sorting events). Touch distance is calculated as the total distance between the start points of every pair of adjacent touch movements within the 10 seconds. 12 touch distance records are recorded for each of confederate card-sorting event. Category changes and redundant sort are the card-sorting events in which a participant sorts a card that has already been sorted, when the card is dragged-and-dropped into the different and the same category, respectively.

4.7 Results

One participant in the control group who did not work collaboratively as instructed and whose data was not considered in the analysis. Average task time for the notification group and the control group are 8.72 (SD=9.55) and 9.55 (SD=2.49) minutes, respectively. The participants in the notification group sorted 18.00 cards on average (SD=7.64) and the control group sorted 18.83 cards on average (SD=8.63). Since the two groups do not differ in task involvement, we focused on how notification affects the social, action and activity awareness. Differences for ANOVA tests for each of the awareness indicators is considered significant at a $p<0.05$ level.

4.7.1 Verbal Response and Touch Reaction

Verbal response indicates participants' social awareness of giving feedback to the confederate and touch reaction indicates the action awareness of confederate's actions. These two awareness factors both measure immediate reactions to confederate's actions. The verbal response and touch reaction form fourconditions: (A) the participant does not have any response behavior. (B) The participant gives a verbal response, but does not touch the sorted card. (C) The participant does not give a verbal response, but has an action to move the sorted card to a storage place. (D) The participant touches the sorted card and gives verbal response. Figure 4.3 shows the average numbers and standard deviations (in parentheses) of events in each condition.

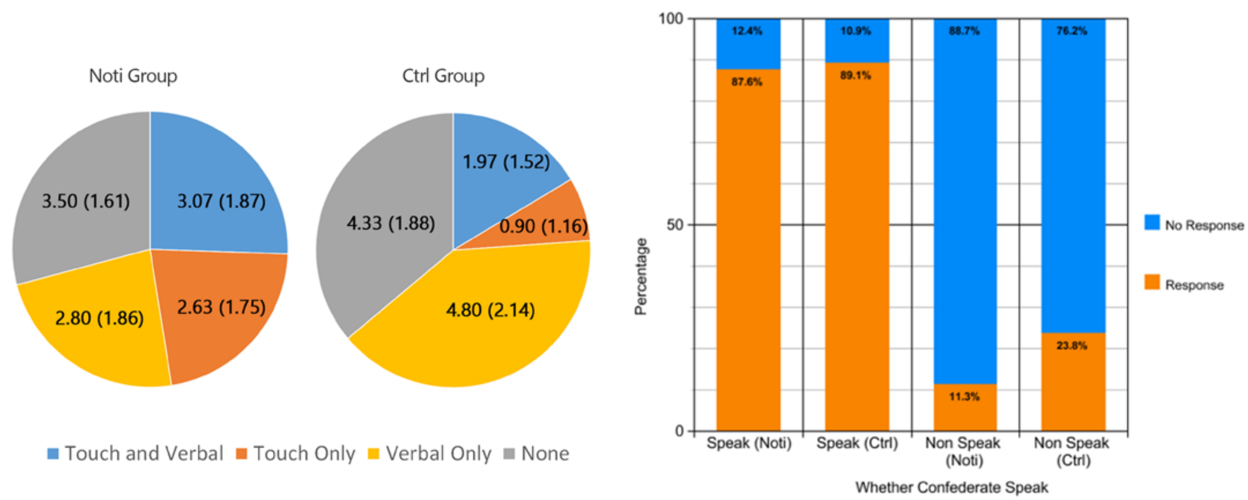

Figure 4.3: Left: Numbers of confederate card-sorting events in fourfeedback conditions. Right: The two bars on left show percentage of events when the participant gives a verbal utterance in response to confederate verbal reasoning upon sorting. The two bars on the right show the percentages when the confederate sorts the card without saying anything.

When neither giving a verbal response to the confederate nor touching the card that was just sorted (condition A), the participant is less likely to notice nor is care about the confederate sorting behavior. In contrast, responding to the confederate's behavior and having some touch reactions (condition D) suggests that the participant paid attention to the confederate and acknowledges the idea or intent. In the study the notification group gives no response and both responses 3.5 times and 3.07 times respectively, compared to 4.33 and 1.97 for the control group in these conditions. The notification group responds significantly more times with both responses ($p=0.0078$) and fewer times giving no response ($p=0.0354$). The results suggest that the noti group has higher awareness of confederate's sorting behaviors than the control group.

Participants in the control group make a verbal utterance an average of 4.8 times, higher than the notification group's 2.8 times ($p=0.0001$). The control group touches a card sorted by the confederate 0.9 times without a verbal reply, less than the notification group's 2.63 times ($p<0.0001$). Considering events with both touch and verbal response, the notification group gave a verbal response 5.87 times and a touch reaction 5.7 times, compared to 6.77 and 2.87 times for the control group. The difference in condition (B) and (C) for the two groups suggests that the notification group was more likely to respond by moving a card rather than speaking to the confederate.

We further examined verbal communication based on when the confederate sorts a card. Figure 4.3 illustrates events when the confederate speaking resulting in participant verbal response. When the confederate said something while sorting the card, verbal replies were given almost 90% of the time regardless of group (two left bars in Figure 4.3). The notification group gives fewer verbal responses (11.3%) when the confederate did not say anything, while the control group speaks to the confederate in 23.8% of the confederate's card-sorting events, a significant difference ($p=0.0146$) (see Figure 4.3, two right bars). This indicates that the notification group is less likely to initiate a conversation after capturing confederate's action. Comparing differences in immediate reactions between the two groups, the notification group has higher action awareness than the control group, but lower social awareness in giving verbal feedback.

4.7.2 Item Utility and Touch Distance

Item utility reflects activity awareness, influencing action performance. Touch distance reflects the effort participants spent in reacting to confederate's actions. Both indicators relate to action flow during sorting. Figure 4.4 shows average item utilities between confederate's card-sorting events. The two groups move cards at similar frequency until the confederate sorted the third card, when the control group moves unsorted cards at a lower frequency. The average moving frequency for the notification group is 19.72 (SD=6.23) and control group is 16.14 (SD=6.92), with former significant higher than latter (p=0.0218). It implies that participants without notification were less effective in visiting unsorted cards, suggesting low activity awareness.

Figure 4.5 shows average touch distance 10 seconds before and after each of the 12 confederate's card-sorting events, with notification group (52.31 in., SD=3.20) larger than control group (41.28 in., SD=3.20, p=0.0188), suggesting that participants in the notification group have higher action awareness and are more likely to shift focus. After a notification, participants stop exploring the current area to focus on the highlighted card, and then resume work near the highlighted card. The cognitive breakdown resulting from high action awareness may interrupt ongoing thoughts and ideation.

4.7.3 Category Change and Redundant Sort

Changing a card's category that was previously sorted by the confederate reflects either disagreement or lack of awareness, while unnecessarily sorting to the same category reflects low awareness. Figure 4.6 illustrates all category change and redundant sort instances. Only fourparticipants in the notification group re-sorted cards after the confederate sorted them, with only two changing the category. In contrast, the control group has many more

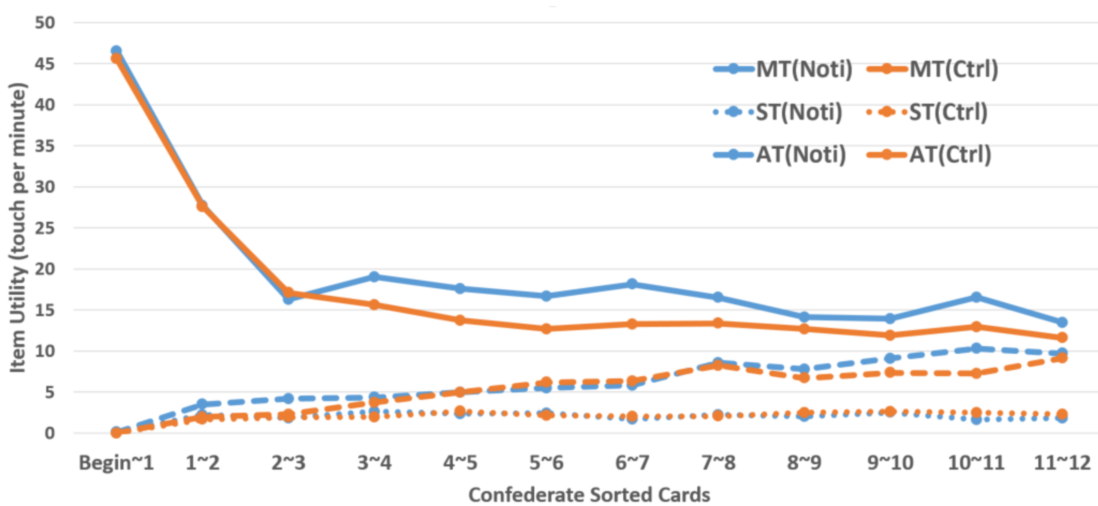

Figure 4.4: Item utility of each touch type between the confederate card-sorting events.

instances of re-sorting: 19 participants in the control group re-sorted at least one card to the same category, and nine participants changed at least one card to another category. The notification group had higher awareness but also performed fewer category changes.

4.8 Discussion

This study extends Carroll's model to examine how multi-user tabletop notifications affect individual work, social norms, and team performance for social, action, and activity awareness [20]. By examining notifications in co-located sensemaking, we explored the RQ2 *"how do notifications highlighting related individual work balance the individual participation and collaborative awareness?"*. Examining our results through the lens of key concerns of the research community, this section explores these research concerns to further the understanding of the benefits and costs in using notifications.

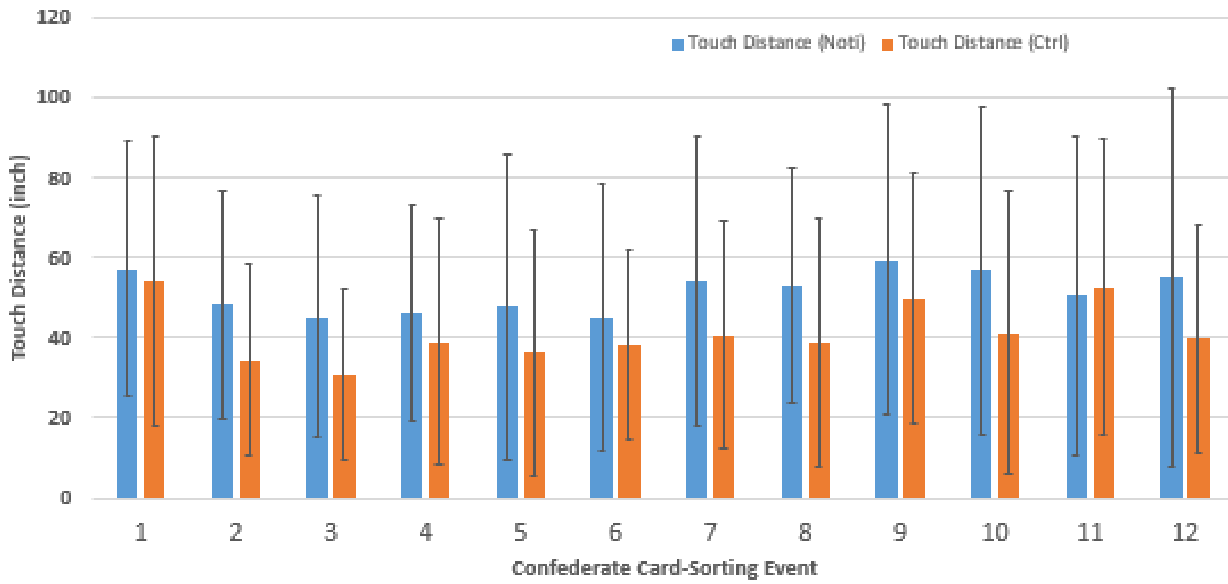

Figure 4.5: The touch distances 10 seconds before and after each confederate card-sorting event. The distance is measured in inches. The error bars show ± one standard deviation.

4.8.1 Influencing Individual Work

Awareness of others' behaviors affects decisions about work [30, 148]. In activities like collaborative card sorting, workers may need to clarify decisions and express opinions. Our study shows how notifications can redirect individual work by affecting item utility, expressing disagreement, and causing interruptions. Notifications deliver awareness information into the personal space, resulting in others' actions exerting influence on individual work. In co-located teamwork, perceiving and understanding others' behaviors is indispensable to individual work [150]. Historically, this occurs through observation and conversation, but notifications provide an alternate awareness path. Our study reveals how connecting with others is important in raising awareness, drawing attention to others and their personal space [150]. With notifications, it is possible to recognize others' actions within one's own interaction space. Closer indicators of other's behaviors blend with items in the individual space, affecting individual task performance. Notifications influence how awareness informa-

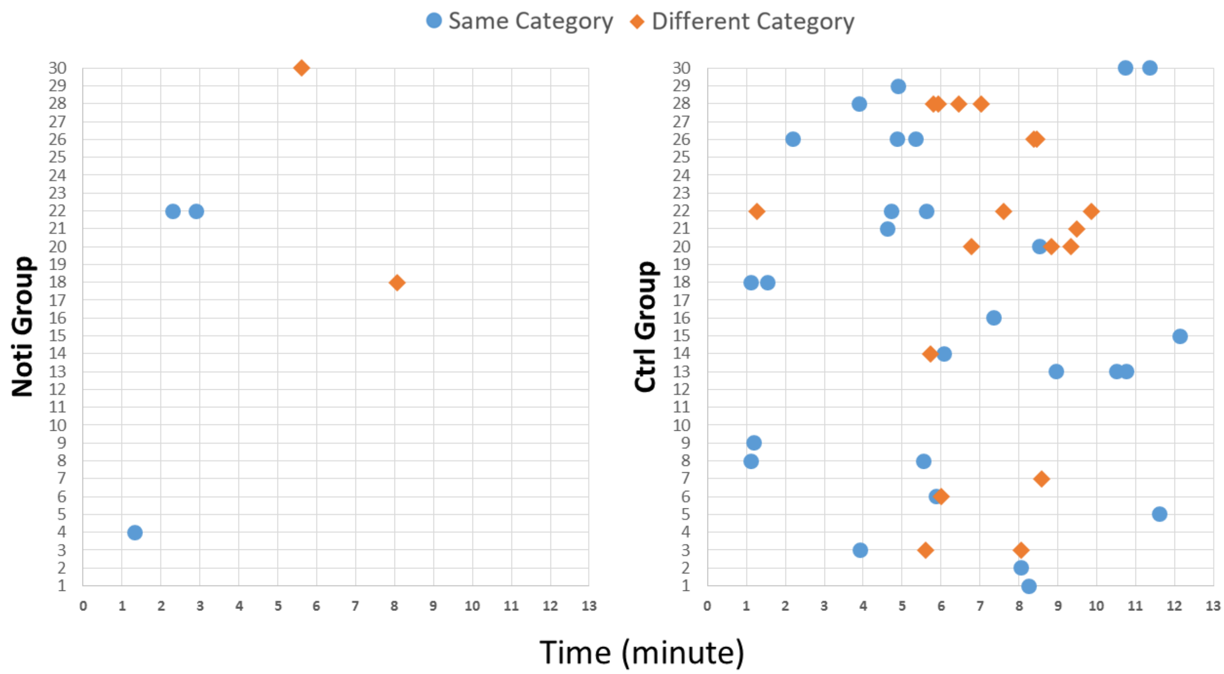

Figure 4.6: Category change and redundant sort for notification (Noti) and control (Ctrl) groups.

tion is delivered, necessitating decisions on how to craft notifications to encourage behavior. The attention-attracting nature of notifications encourages mental shifts – risking workflow breakdowns by redirecting attention and action.

When using notifications on tabletop displays, designers can employ notifications to complement collaborative awareness and intensify mutual influence between individual work, especially when sensemakers engage in the personal space and risk awareness problems (e.g., opposite orientation [89] and long referring distance [29]). Users are likely to classify the items and tasks as "completed-by-others" and "to-be-finished", therefore lean more considerations and actions on the latter. Benefits include more attention on the unfinished work and better item utility, but it could weaken consideration of alternatives and interrupts personal work. **Designers need to consider appropriate ways to present notifications, realizing the tradeoff between intrusiveness to the individual's on-going task and**

increased understanding to alternatives and new possibilities brought by others' actions.

4.8.2 Influencing Social Norms

Social norms play an important role in managing co-located sensemaking for multi-user tabletops [1, 103]. In face-to-face design activities like card sorting, participants follow social conventions and protocols to communicate and conduct joint activities. Collaborators using tabletops become aware of others' actions in two ways: by observing another person perform an action and by observing the results of the action. Our results suggest that notifications heighten awareness of partner actions, changing participant behavior – though without discussion or comment as is the norm. Instead, reactions are directed toward the shared screen via lightweight touches. Even though the instigator of an action is present, people focus on technology rather than the collaborator.

This social norm finding furthers knowledge of grounding in co-located collaboration [25, 112]. Notifications can result in reluctance to express contrary thought: since they manifest others' activities, they may increase negotiation and persuasion costs. Contrary to the notion that face-to-face communication is considered a low-cost way to build common ground [112], understanding others through notifications may supersede a need to communicate – regardless of whether it leads to optimal outcome.

Notifications facilitate development of common ground, informing sensemakers of others' activities. However, the ability to react by touch rather than verbally can result in an inability to gain confirmation [112], lessening connection found in verbal responses. When employing notifications, multi-user tabletop designers must consider the effects on face-to-face communication. As sensemaking benefit from verbal communication, our work suggests that notifications may create negative norms that discourage sensemakers from talking about key issues. **Designers should leverage notifications to incite desired verbal communication while realizing the costs of the notifications: users working in parallel with notification-supported communication can increase efficiency of the collaborative task exchanges, but notifications may cause degradation in performance toward individual task goals.**

4.8.3 Influencing Team Performance

In face-to-face collaboration, perceiving and processing verbal and touch actions in co-located space is time-consuming. With notifications, sensemakers have a path to recognize collaborators' thoughts and intentions, lessening perceived need to discuss the action. This can decrease time communicating with partners, smoothing the move to the next action and avoiding performing extra work. Our notifications seemed to reduce this need – though we acknowledge that other types of notifications might encourage verbal communication [118].

Salas et al. identify effects between individual and team situation awareness [147]. Awareness depends on environmental elements and collaborator communication [35, 147]. In tabletop-supported collaboration, these activities might be depressed by larger interaction space [182]. Notifications add flexibility to awareness management of co-located interaction. Instead of relying on body cues and conversation, well-designed notifications can tailor visibility and availability of information, providing more freedom to sensemakers in identifying others' activities. Flexibility in awareness management smooths simultaneous interaction by reducing conflicting actions (e.g., sorting a card to different category) so sensemakers can work independently without intrusion [161].

Managing concurrent activities in co-located space influences participation and mutual awareness of collaboration [28, 41, 63]. In simultaneous interactions with multi-user tabletops, availability of multi-touch interactions mean sensemakers withdraw from interpersonal interactions and avoid conflicts by engaging in individual interactions – with the danger of reducing performance and awareness. Though interpersonal communication has long been recognized as the core to building common ground, notification-based understanding may provide enough grounding information in multi-user tabletop collaboration. **Tabletop designers could utilize notifications to improve sensemakers' ability to work independently, especially for collaborative tasks that are suitable for divide-and-conquer, therefore improving team efficiency through simultaneous and synchronized work.**

4.9 Chapter Summary

Notifications have been widely employed in supporting collaboration – they deliver current and important events in the collaborative space and heighten the awareness of others' sensemaking activities [20, 108]. Prior work on awareness-enhancing designs and tools on multi-user tabletops has focused on supporting the awareness of a single workspace element. This chapter expands previous knowledge by providing a critical understanding of using notifications in tabletop-supported collaboration. Through a user study, three types of awareness are evaluated: action awareness, social awareness, and activity awareness, which are pertinent to individual control, communication, and collaborative awareness. The findings are grounded in contextual differences between traditional computer-supported collaboration and action-highlighting collaboration on a shared tabletop display. Benefits and costs of using notifications are presented to foster future notification design for tabletop-based groupware. The findings of this study are used to address sub-questions S2, S3, S5, and S6:

- S1: Notifications affect social, action, and activity awareness through individual control, a new awareness acquiring path, and more efficient communication and better team performance.

- S3: When presenting notifications to connect related individual work, designers need to realize the tradeoff between intrusiveness to the individual's on-going task and the need to discuss alternatives and new possibilities brought by others' actions.

- S4: Sensemakers working in parallel with notification-supported communication can increase the efficiency of the collaborative task exchanges, but notifications may cause degradation in expressing alternative ideas due to awareness of others' decisions.

- S4: Notifications improve collaborators' ability to work independently, especially for collaborative tasks that are suitable for divide-and-conquer, thus improving team efficiency through simultaneous and synchronized work.

Chapter 5

Sensemaking Activities when Re-visiting Large Personal Blogs

Today, sensemaking tasks are increasingly involving the exploration and understanding of large datasets. Blog data, for example, offers repositories for people to re-visit and make sense of long-term experience. In Chapter 4, notifications connecting individual work were found to improve activity awareness and team performance, but they did not provide obvious benefits in fostering conversation. This awareness-support technique also degraded sensemakers' willingness to express alternatives. To explore solutions to these problems, this study considers the use of natural language processing (NLP) and visualization techniques to mine useful information and encourage conversation. A peripheral visualization on a secondary display could overview sensemaking activities without directly affecting individual work. Visualizations incorporating data processing techniques could mine and present information that is not directly identifiable, which could trigger reflection and conversation about different topics. This study and the one in Chapter 6 explore the effect of shared overviews on co-located sensemaking.

Before designing shared overviews to visualize group activities, it is necessary to determine the key sensemaking activities with a tabletop interface that allow information to be retrieved from a large data collection. In this study, a blog re-visitation system – BlogCloud – is implemented. BlogCloud allows sensemakers to re-explore their personal content from a tabletop interface. It is an interactive blog exploration tool implemented on a dual display setting, and it allows bloggers to search for, read, and organize blog segments. The tabletop display contains digital cards to show blog paragraphs. A vertical display shows a word-cloud visualization, which indicates high-level topics reflecting the searched keywords and re-visited experience records.

This study and the next one (Chapter 6) address RQ3 regarding how shared overviews affect collaborative sensemaking. BlogCloud supports exploring and making sense of a large blog collection with a tabletop interface. The system uses NLP technique and data visualization to reorganize the data stream. Three long-distance hikers are observed as they re-visit their personal content and share with others, to extract key interactions and visualization components that lead to the sensemaking outcome. This study partially answers S3, *"what are the ways to connect and present related individual work?"* and S5, *"how do shared overviews presenting group work affect co-located space factors?"* The results of this study show that searching for words from memory, presenting high-level topics, and connecting related topics need to be supported by the collaborative visualization.

5.1 Abstract

Digital personal archives log life materials chronologically, necessitating the identification of novel user experiences in re-visiting them and generating new ideas [42, 126, 152]. Interaction designs supporting reading one's own life-logs seek to regenerate prior experiences by encouraging meaningful interaction with photographs [126], videos [152], and geo-locations [164]. However, personal textual content such as blogs has long been under-studied in re-visitation [42] and generation of new perspectives about self [78]. The textual content takes time to read, especially when it grows massively large but minimally organized [9, 68]. When

bloggers need to re-visit and share stories from blogs, for example during themed conferences or meetings, the massive volume and textual nature of blogs makes it hard to understand core themes and capture an overview and connections.

People spend time crafting blogs, recording moments in life, and capturing essences of thoughts [121]. In 2017, blog authors on the WordPress crafted over 80 million new blog posts each month [1]. Around 80% of the regular bloggers posted at least once per month, and over 90% of blogs had more than 500 words [2]. Bloggers write about experiences over time, generating a temporally-ordered flow of experience [82, 121]. Many blog authors have a desire to reflect, but generally do not wish to re-read the entire collection [9]. Given the massive volume of content in many blogs, retrieving and organizing information about experiences cost effort of memory and time [120], while combination and reorganization of materials generates new ideas [8]. To support novel blog interaction, natural language processing (NLP) and visualization (VIS) provide opportunities to reorganize large blog content. Large touch displays can present the representations of personal contents dynamically to support multimodal interaction with blogs.

NLP and text visualization (VIS) offer new design materials to build multimodal experiences with large personal texts. This research reports our experiences inviting three long-term bloggers to re-visit their large personal blogs with *BlogCloud*, a system which implements blog **reorganization** – breaking the temporal order of blogs and recombining experience segments by natural language processing (NLP) techniques. Reorganization depicts a new design opportunity to utilize text processing techniques to support multimodal interaction with personal blogs, in contrast to their original forms of long textual information on web pages. To obtain an early understanding of user's reaction to the new form of personal

[1] A live look at activity across WordPress.com. (09 2018). https://wordpress.com/activity/

[2] Blogging Statistics and Trends: The 2017 Survey of 1000 Bloggers. (09 2018). https://www.orbitmedia.com/blog/blogging-statistics/

content, we designed and implemented a blog re-visitation system, *BlogCloud*. We report our experiences taking a walk-through of the interaction in use context and report users' open-ended experience stories, which helped us collect meaningful feedback and identify new design opportunities with the reorganization [88, 180]. We consider the blog re-visitation during themed public events, to probe how the new re-visitation modality created by NLP and VIS could encourage re-discovery of one's own themed experiences. Concluded from our experience with BlougCloud, we identify that the *reorganized topics* – sets of related or similar content from personal blogs – offer new materials for reflection and new paths for re-visitation, enabling multimodal interaction with symbolic memories. This paper organizes as follow: we first review prior work on re-visitation and reflection on large personal content, with identification of key factors and theories in life-logging and re-visitation. Following we introduce the opportunities to utilize natural language processing techniques to reorganize large personal blogs. Then we introduce BlogCloud, a multimodal interactive system which operationalizes blog reorganization with natural language processing and visualization technologies. Next, we focus on our experiences with three long-term blog authors using BlogCloud during themed public event, to describe new blog re-visitation manners with the reorganized content. Finally, our discussion and conclusion seek to suggest new design opportunities to enable interaction with the reorganized blog topics.

5.2 Blog Reorganization for Re-visitation

This study seeks to explore the *reorganization* of large personal blogs with text processing and visualization technologies, with the goal of understanding their roles in creating new modalities from re-visitation. Temporally organized personal blogs contain rich life experiences, but their temporal order, textual form, and large content volume limit generating high level ideas and memorizing particular experiences. While experiences from reading one's own blogs benefits from technologies to prompt explanation and see more perspectives [42], reading large personal blog calls for better approaches to break their original order and reorganize experiential items. Natural language processing (NLP) and visualization (VIS) are promising approaches to store and retrieve large textual data [42]. However, little is known about the opportunities of re-visiting one's own NLP-processed and VIS-presented long blogs, to engender new ideas about past experiences and open multimodal pathways for re-visitation.

The NLP reorganized content and the visualization of topics offer new potentials to engender novel blog reading experiences. Our conceptual approach of *reorganization* with NLP reduces the effort to identify and retrieve related experiences. Exploring the computer reorganized contents and topics offers a high level view of the experiences. NLP and VIS support re-visitation by reducing the effort of organizing and exploring the large blog volume. The derived topics may provide new perspectives from the massive data, which potentially increases the expressiveness of blogs and the enjoyment of re-visitation.

We examine two blog reorganization approaches to support re-visitation: NLP techniques break the original order of blogs; users can search keywords among blogs and re-visit blog sections that are similar to a particular experience (Figure 5.1). NLP techniques are applied on personal blogs to raise awareness of similar experiences, which match a symbolic word or relate to a particular section. NLP makes it technologically possible to search large blog texts and recognize relevant content by computing document similarity. Common NLP technologies provides methods to filter less meaningful words (i.e., stop words), identify keywords, vectorize textual data, and compute similarity. The processed blogs can be indexed to enable searching. NLP techniques can also automatically identify and group the blog content that are similar to a re-visited blog section. Contents that are identified from searching or grouped by NLP-calculated similarity constitute a new content group, which breaks the original order and reorganized into a new topic. A visualized topic contains similar or related experiences, which could illustrate the context of a past experience and offer a new interaction modal [144]. Interactive text visualizations can present inferential information of the topics, such as the number of similar segments and keywords of the topics, to inspire new perspectives and connect related experiences [8, 68].

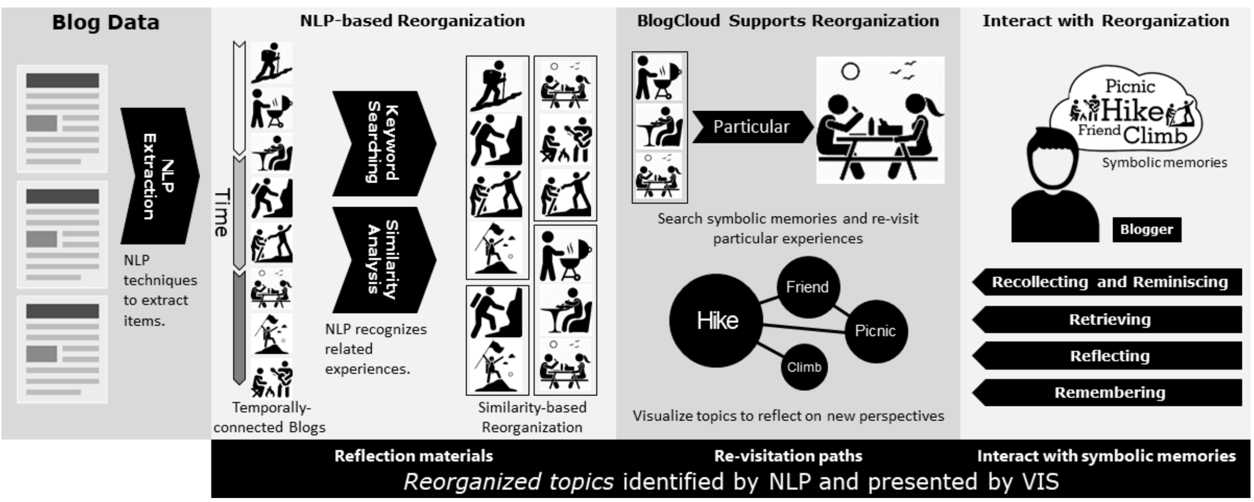

Figure 5.1: The conceptual description of *reorganization*. NLP breaks the original temporal order of blogs by keyword searching and similarity-based grouping. Bloggers can re-visit particular experiences and reflect on the visualized high-level topics. Reorganization leads to new manners to re-visit personal blogs.

5.3 BlogCloud: Blog Re-visitation Tool

To explore the *reorganization* ability of natural language processing (NLP) and visualization (VIS) in supporting blog re-visitation, we designed and implemented *BlogCloud* (Figure 5.2). BlogCloud is an interactive blog exploration tool which allows the bloggers to search, read, and organize blog segments. BlogCloud seeks to extract keywords which indicate experiential items from blogs, support reorganization of experiences, and interact with symbolic memories from blog data.

5.3.1 BlogCloud on Large Interactive Displays

We consider re-visiting one's own personal blogs during public events, when bloggers interact with a walk-up-and-use tool [107] to reflect on the NLP- and VIS- augmented blogs. To explore the multimodal design for this context, BlogCloud is implemented with large interactive displays: a multi-touch tabletop and a vertical display (Figure 5.2). We choose large interactive displays as the platform since they feature content manipulation with natural touch interaction [177]. Large displays also benefit reading activities by expanding visual and interaction space [3]. As blogs may contain multiple entries of the same topic, presenting related content in one interaction space affords comparison and reflection. Large displays allow users to allocate spaces to facilitate organization and comparing details [3]. With multi-display design, bloggers can shift between visiting particular blog entries and viewing high-level topics, with possible better perception to the NLP results.

5.3.2 System Implementation

Though there are other ways to reorganize large blog collections, we choose to use keyword searching and similarity analysis as two common methods to explore the design benefits of reorganization. BlogCloud reorganize blogs (Figure 5.1) and support re-visitation by:

- Using natural language processing techniques to chunk the temporal blog stream and identify potentially important keywords.
- Allowing bloggers to denote symbolic memories and retrieve blogs by searching keywords.

- Supporting generation of related topics connected to the re-visited blog sections, by visualizing keywords and presenting inferential information of topics.

BlogCloud incorporates natural language processing (NLP) techniques to break the temporal stream of blogs, which allows searching and similarity-based grouping. To instantiate the concept, we choose three generic but common NLP techniques in text processing: keyword extraction, term-frequency based vectors and cosine-similarity clustering. Though other high-level NLP and machine learning techniques could be used, extracting key information and grouping documents reflect core functions of many NLP and machine learning based approaches.

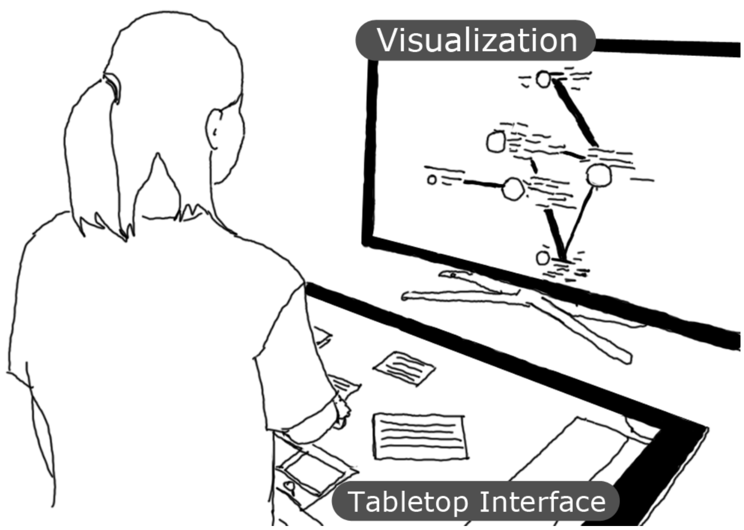

Figure 5.2: The BlogCloud system. The tabletop supports blog searching and viewing. The vertical display shows a visualization of the NLP-processed content.

A paragraph is used as the basic reflection section (see Figure 5.3) since paragraphs usually focus on a few interrelated experiential items that are lexically self-contained and map well for natural language processing. Text processing is running on a paragraph based collection. BlogCloud segments the words by spaces and punctuation. Stop-words (e.g., “a”, “an” and “the”) are eliminated from further processing. For each paragraph, nouns, verbs, adjectives

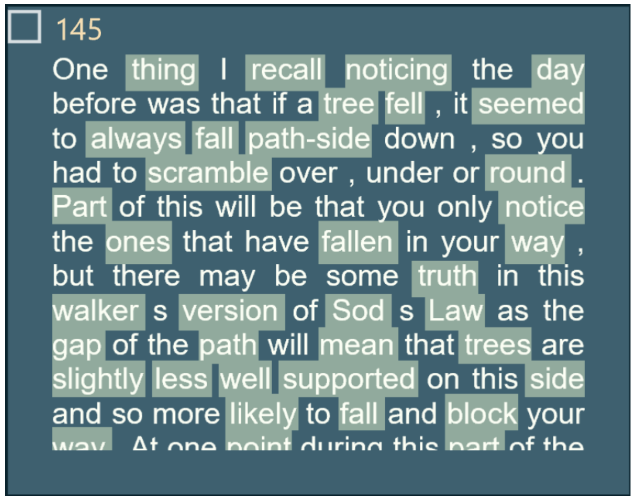

Figure 5.3: A paragraph card on tabletop interface. Words with background color are recognized keywords. This card illustrates an experience of mountain climbing (A1). Showing actual content allows re-visit experience details.

and adverbs are extracted as keywords with coreNLP [101]. The weight of each keyword in a paragraph is calculated using term frequency-inverse document frequency (TF-IDF) [95], through which the importance of words are estimated. Segmentation and term weighting techniques enable the system to process words and prepare for blog reorganization. BlogCloud stores the weight of each keyword for each paragraph.

The text processing segments the blog stream, so that the users can search memories and

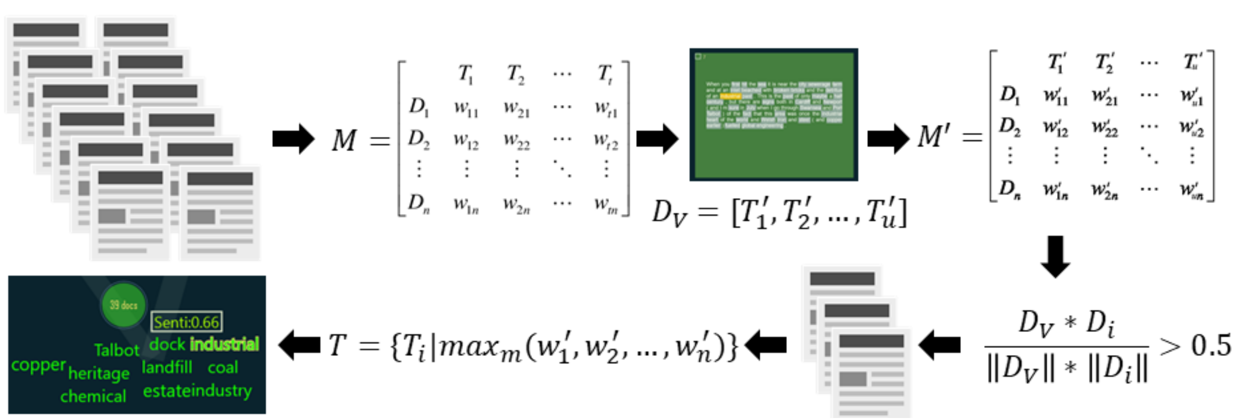

Figure 5.4: Blog processing pipeline to generate word cloud in the BlogCloud visualization.

read matched blog paragraphs (Figure 5.4). Grouping similar paragraphs makes a topic that is related to the re-visited blog section. The system first converts the entire blog set into a document-term matrix M. w_{ij} is the TF-IDF weight [95] of T_i in paragraph D_j. When one blog paragraph (VP) is viewed on a card, BlogCloud creates an array of terms D_V, which only contains the keywords that appear in VP. Then the system creates a sub-matrix M' from M by selecting columns whose corresponding terms also appear in D_V. The similarity comparison method used by BlogCloud is based on paragraph vectors and cosine similarity. For the re-visited paragraph (VP) and a paragraph (CP) that is being compared, the system decides similarly through two generic steps: (1) For VP, create a vector $\vec{V_u} =< w'_1, w'_1, ..., w'_u >$ where w'_1 to w'_u are the weights of the u unique keywords in D_V. The row c in M' is CP's vector $\vec{V_c} =< w'_{1c}, w'_{2c}, ..., w'_{uc} >$. Since M' is extracted from D_V, $\vec{V_u}$ and $\vec{V_c}$ have the same size and each element represents the TF-IDF weights of the same word. (2) Calculate the cosine similarity [94] between $\vec{V_u}$ and $\vec{V_c}$, if the similarity score is above 0.5, the system determines CP is a paragraph that is similar to VP. All similar CPs form a *paragraph group*. For all paragraphs in this group, the system choose top m words with highest TF-IDF weights to generate the word cloud for VP. m varies between 10 and 20, with larger paragraph groups contain more words. To indicate the relatedness between a pair of paragraph groups, BlogCloud tracks the number of paragraphs that co-appear in both paragraph groups. The NLP methods and parameters are decided by multiple trials on a test blog set.

The BlogCloud interface supports breaking the original time order of blogs through keyword searching and visualizing similar content, to present the *reorganization* of blogs. Users can search words with BlogCloud to retrieve a list of matched paragraphs. To support re-visiting particular experiences, digital cards presenting the paragraphs can be created and manipulated on the multi-touch tabletop (Figure 5.3). The cards can be moved, rotated and zoomed with multi-finger gestures. Zooming a card shows the actual blog paragraph content. Bloggers can search keywords in their memory to retrieve and read particular blog paragraphs. The search word is automatically highlighted on the paragraph card. When a paragraph card is placed on the tabletop, it triggers the NLP technique to identify other similar paragraphs to create a related topic (paragraph groups). A word cloud is visualized for each paragraph group created by the paragraph cards on the tabletop (see Figure 5.5). A word cloud contains four components about a topic: highlighted words, feature words, number of similar documents, and average sentiment values (Figure 5.5 top). The highlighted words are the words being searched to retrieve the topic and presented with yellow borders. The size of the feature words in one word cloud is proportional to the weight of words in the paragraph group. A count of similar paragraphs in each paragraph group is presented in a circle. The connection between topics is represented by the number of paragraphs co-appear between two paragraph groups. A strip with the number of associated blogs connects each cloud pair. The width of the strip is proportional to the number of blog paragraphs that exist in both paragraph groups. The summary of paragraph groups seeks to capture a high-level concept about different topics. The layout of word cloud and positioning of different topics are implemented by a force-directed graph.

The tabletop interface contains a menu bar to use the searching function. *Search word* allows users to type a word or phrase with a virtual keyboard, displaying matched paragraphs in the scrollable paragraph card list (Figure 5.5 bottom). It allows bloggers to actively query symbolic words in their memory. With the menu bars on the sides of the tabletop interface, users can search for words, view results, and update the visualization (Figure 5.5 bottom). Paragraph cards in the card list can be dragged onto the table to read the actual blog content. *Show cluster* shows paragraph cards in each paragraph group. *Show all doc* loads all paragraph cards in the card list in chronological order. This button is added in case the

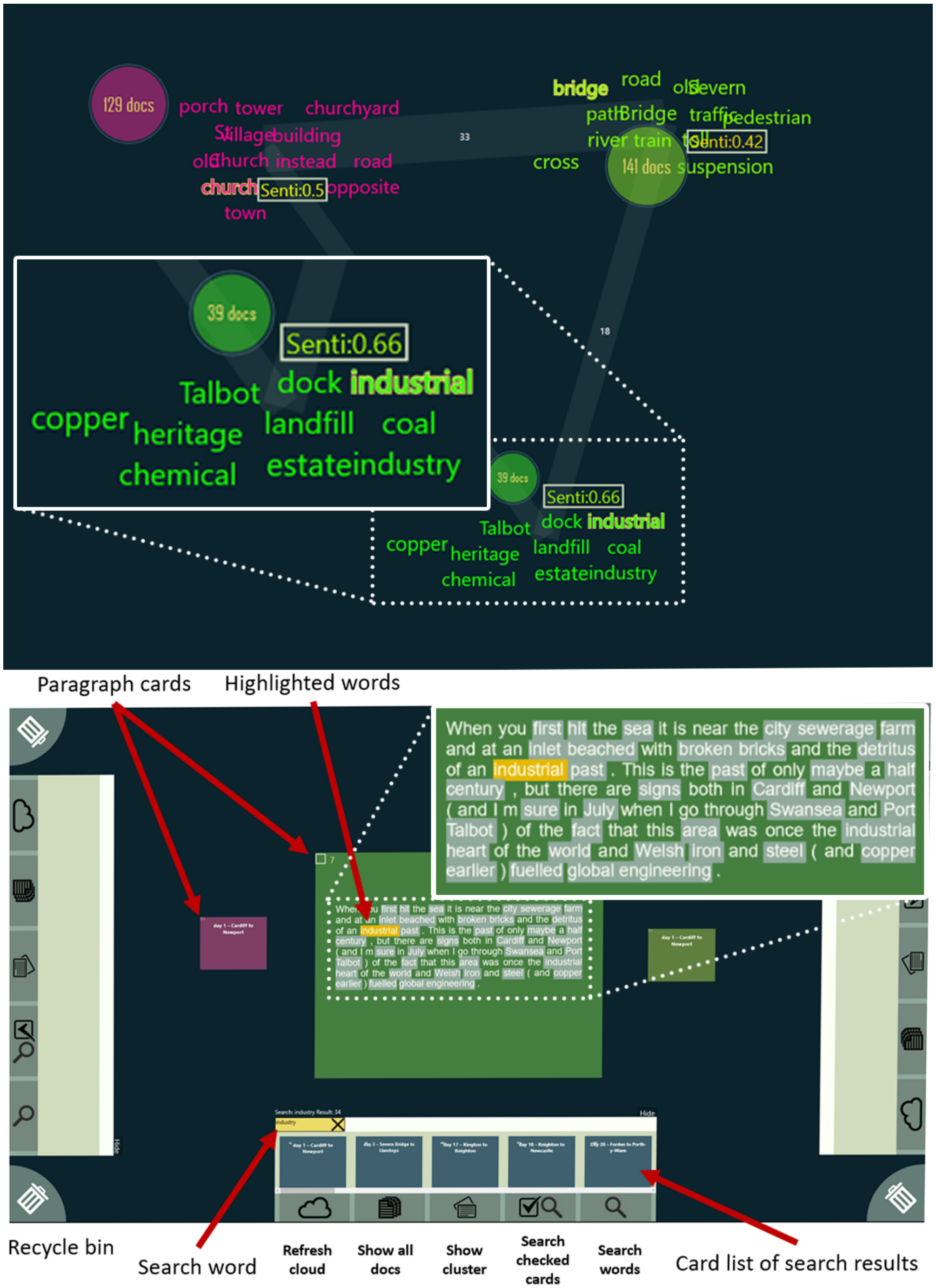

Figure 5.5: Top: Connected word cloud visualizing the *reorganization* of blogs. The word cloud abstracts paragraph groups and connect topics to inspire new perspectives. Bottom: Touch interface runs on the tabletop display. The three paragraph cards generate three word clouds in the vertical display. The card in middle is a paragraph about an industrial relic, and its corresponding word cloud is showed in the zoomed frame in the top figure.

users do not have anything to search for or want look at blogs in the original order. *Refresh cloud* button reloads the visualization.

5.4 Re-visitation to Personal Blogs

To evaluate how bloggers interact with BlogCloud and re-visit the NLP-reorganized content, we adopt the framework of "5Rs" identified by Sellen et al. [151] – *recollecting*, *reminiscing*, *retrieving*, *reflecting*, and *remembering*. We observe blog authors' interaction with BlogCloud from each of the five re-visitation activities. Recollecting and reminiscing is when blog authors think back experiences and re-live particular life events. Retrieving personal experiences depends on details in memory to find desired experiences for re-visitation. Reflecting on experiences requires examining patterns of past experiences and derive abstract representations. Remembering is suggesting prospective memory and reminding lost events in mind. Re-visitation to large personal blogs needs to solve the high effort of organizing the content, and the low expressiveness, exploration-supporting, and enjoyment of massive text data. We explore whether the NLP-reorganization could lead to new perspectives when exploring one's own data, and support multimodal interaction experiences.

Grounded on the five re-visitation activities of life-logging systems, we seek to understand whether and how the NLP-based blog reorganization implemented by BlogCloud. BlogCloud is designed for bloggers to re-visit the computer reorganized life experiences with multimodal interaction. The system allows bloggers to search and read blogs, to re-live specific life experiences and reminisce about emotional and sentimental traits. The searching function enables retrieving symbolic memories by exploring different words among blogs. While reading the actual blogs, the visualization depicts the topics of the re-visited sections to support reflection. When multiple topics from the blogs are read together, the inferential information of topic sizes and connections between different topics afford reflection from a new perspective. When exploring a topic, bloggers could possibly encounter content that fades in memory and trigger remembering of the experience. To examine the opportunities of natural language processing in supporting multimodal interaction with one's own large personal blogs, we report our experiences inviting long-distance hikers reading their hiking blogs with BlogCloud.

5.5 Examining BlogCloud with *"5 Rs"*

In planning an examination of the NLP-based reorganization and how BlogCloud supports reading one's own large personal blogs, we recognized great value in gaining perspectives both from frequent bloggers and from interface and interaction experts. We identified three blog authors who also had relevant research skills in areas including human-computer interaction, user experience, ethnography, tech design, industrial systems engineering, and management systems to re-visit their blogs with BlogCloud (Figure 5.6). Each of these blog authors have crafted a blog that describes a long-distance (over 1000 miles) hike that they undertook. Long-distance hiking is chosen as the blog theme because of its life significance and need for re-visitation: dedicated hikers prepare for months or even years for a long-distance endeavor, and they often blog, journal, or otherwise write about the hike's significance in their lives (e.g., Trail Journals[3], The Hiking Life[4] and [17, 18]). During events when hikers are gathered, re-visiting and reflecting on such hiking experiences is worthwhile even years after the accomplishment, when memories may have faded and the enormity of the writings from the hike may appear even more daunting. Considering the challenges of measuring blog re-visitation through controlled lab studies (e.g., quantifying reflection and motivating

[3] http://www.trailjournals.com/
[4] https://www.thehikinglife.com/

sharing personal experiences) [10] and given the early stage of this research, we chose to engage in highly interactive and largely qualitative observation sessions with a small number of experts who maintain large personal blogs and also have relevant research knowledge. Observing blog authors' reflective activities and summarizing their feedback help us obtain descriptive understanding of the roles of NLP and VIS in multimodal interaction with blogs. The author sessions were conducted during an evening session at a hiking-themed workshop in which the authors were invited guests. (One author could not make it to the invited session but took part later in a semi-private demo.) During each session, blog authors were intended to re-visit their extended hiking experiences, and share their hiking knowledge with others verbally so that the research team could understand their thought patterns. In each author session, we sought to observe how bloggers interact with the reorganized blogs presented by BlogCloud, with a focus on learning the following "5R" categories of re-visitation activities:

- How do bloggers **recollect** and **reminisce** about both high level ideas and specific experiences?
- How do bloggers interact with BlogCloud to **retrieve** symbolic memories from the reorganized experiences?
- How do bloggers perceive the topics derived from the re-visited blog paragraphs and **reflect** on the reorganized content?
- Whether bloggers' re-visitation to the reorganized blogs triggers **remembering** lost memories?

In the author session, each blog author spent 20-40 minutes using BlogCloud to explore his or her own hiking blogs. During the workshop, other attendees occasionally joined the conversation and engaged with the system. However, the blog author remained the primary user of the system throughout the session. A graduate student served as the exhibitor to introduce the system and explain operations. The qualitative data was collected through the conversation with blog authors while they were interacting with the system, and emails afterwards discussed feedback to the system.

Blog author 1 (A1) is a male HCI researcher and a dedicated hiker who keeps a personal hiking website with more than 100 hiking-related blog posts since 2012. In A1's online blog set there are 97 blog posts with 3999 paragraphs and 230,159 words in total about a 1000 mile hike that he undertook. Blog author 2 (A2) is a female HCI researcher, consultant, university instructor, and ethnographer who maintains a personal website that contains her hiking blog posts. During one 2500 mile hike, A2 recorded her hiking experiences and posted on her personal website. This blog set has 34 posts, which contain 467 paragraphs and 23,663 words. Blog author 3 (A3) is a male university professor and a section hiker (a hiker who breaks a long trail into sections). Starting in 2007, A3 started hiking sections of a 2000 mile trail, and wrote one post for each section he hiked. Cumulatively, he posted 213 blogs with 1904 paragraphs and 1,536,054 words.

5.6 Findings

Blog authors acknowledged that it was a unique and valuable experience using BlogCloud to explore their own blog collection. All three blog authors noted they did not carefully organize the blogs and tweak the writing, and all had an unfulfilled wish to clean up and better organize their blogs when they have time (though all authors completed their hikes several years prior to our session). They commented that the system helped them re-visit and organize thoughts about their blogs, which implies potential extended utility of the blog

Figure 5.6: A1 uses the BlogCloud to reflect on his own blogs. The visualization shows a word cloud of blog entries.

reorganization.

5.6.1 Recollecting and Reminiscing

Recollecting and reminiscing are interaction with life-logs which lead to "re-live" specific experiences and reminiscing the past experiences. During the interaction with BlogCloud, authors reminisced particular experiences that connect to their memories and recollect experience topics from an unfamiliar non-temporal dimension.

Reminiscing about Particular Experiences

Through word searching, matched experiences are grouped by BlogCloud, avoiding skimming through the most-recent posts. During the author session, blog authors reminisced about particular experience, meanwhile connecting them to the symbolic words that represent symbolic memories. When A1 searched "climb" (see Figure 5.7), he explored the first few results and picked a paragraph about a gradually narrowing cliff path. A1 reminisced about the experience on the cliff path by telling a story: *"It was a path on the cliff. The first time when I passed it, it was this wide,"* A1 opened his arms to show how wide it was. *"But the second time when I was there it was barely my feet's width. I have to pass it with my body clinging to the cliff and be careful."* The particular experience of passing a terrifying cliff path reorganized this kind of *climb* experience. A2 noted that reflecting on the word cloud surfaced a memory about her experiences: *"the connections I got to explore and the way that the semantic connections surfaced specific memories... it was a really cool experience to see words connected that acted as triggers to surface memories that I otherwise would not necessarily have been thinking about."* Reading the visualization raised the reminiscence about particular experiences, which suggests that re-visiting a general experience topic turns into reminiscing a particular one [173]. However, without the NLP reorganization, the experience might be neglected in the long blog stream, with fewer chances to encounter a particular experience and reconstruct that type of experience.

Figure 5.7: Word cloud of "climb" generated by A1.

Crossing the Time Dimension

We notice the broken-and-recombined experiential items bring forth a new perspectives to perceive blogs by recollecting multiple experiences across multiple days and merging them into a topic or story. A1 re-visited multiple paragraphs from different days after each search, trying to interpret whether the content matched his internal conceptualization of the tough nature of his experiences. A2 searched for the word "picnic", and after viewing the visualization (Figure 5.8) and several paragraph cards, she reminisced about two specific experiences on two different days: *"[Interacting with the system reminded me of] a very specific memory about ... a nearby store that had non-backpack-friendly snacks available for purchase"* and another time *"... at a picnic table in time for the luxury of a place to sit-down while eating a less exciting rehydrated meal."* BlogCloud helped A2 bring two experiences together, explaining how hiking food needs to be prepared for hikers. A3 noted he wanted to view content about different topics, commenting *"It (BlogCloud) allows me to compare different things. This tool can help me organize my thought, like if I am thinking about writing a book about section hiking"*. The keywords in the visualization were abstracted high-level descriptions of a general idea, but the actual content comes from content at different time. Our blog authors appreciated viewing experiences across time, enabling recollection of similar items that are sparsely distributed.

5.6.2 Retrieving

BlogCloud uses user-defined keywords to retrieve and reoraganize the blog content. In our observation of BlogCloud, we noticed the importance of the symbolic words in bloggers' memory. Based on blog authors' choice of words to describe memorable experiences, we identify the patterns of keywords usage when retrieving symbolic memories.

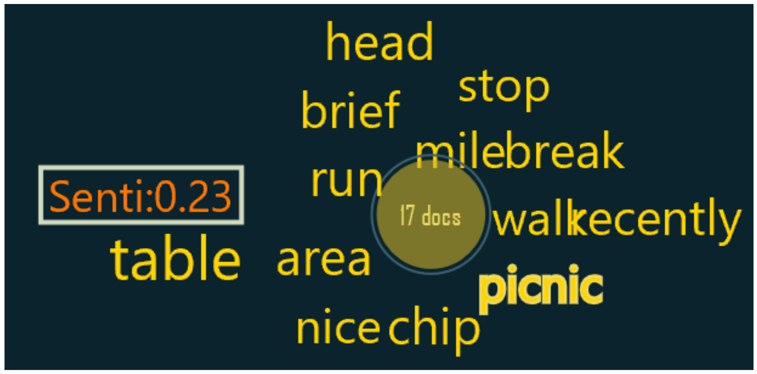

Figure 5.8: Word cloud of "picnic" generated by A2.

Active Experience Seeking

During the author session, blog authors were seeking familiar experiences with BlogCloud. Though BlogCloud allows blog viewing with the show-all button (a non-reorganized presentation), blog authors rarely selected paragraphs from their original order, using the search tool to search their own blogs, in contrast with the skimming and random reading observed in prior studies [9, 119]. All three blog authors spontaneously identified multiple interesting words to interact with BlogCloud. All three authors could explain why they wanted to search for these words to retrieve interesting memories, which direct the interaction with BlogCloud. Rather than passively or randomly re-visit the blog paragraphs, blog authors used BlogCloud in an active manner: they actively asked questions to the system to seek the reorganized content related to their memories.

Using Alternative Search Words

Blog authors used search words that contrasted common semantics. The NLP used in BlogCloud introduced bias interpreting author semantics in the context of their experiences. A1 wrote about a "bus shed" in his blogs, an uncommon term for observers. He noted *"it is my own geographical neologism...I was using it to mean something different as a parallel to a* *'water shed'. It is not so much a single landmark as a generic kind of feature, but boundaries which are easy to walk across, but hard to return by public transport."*. Similarly, A2 used "picnic" in her blog, but in contrast to "picnic" in common sense. Her use of picnic referred to "non-backpack-friendly snacks" and "rehydrated food". Identifying unique semantics of words which contrast ordinary meaning but importantly represent experiences is a challenge for natural language processing technique used by BlogCloud.

Authors attempted to identify alternatives to imprecise search words. When realizing their words were semantically different from ones found in blog paragraphs, blog authors sought alternative words to describe their experiences. After realizing results for the searched term "tear" was not related to sadness, A1 came up with another search word "cry" as an alternative. But again he noticed the word "cry" were mostly used to describe animal sounds. A3 searched the phrase "New Jersey" but noticed results only matching "new", so he searched "Jersey". These issues imply that blog authors had particular topics to explore that were not well retrieved, so they had to refine and adjust their search words or acknowledge failure for a topic. Text processing techniques should reflect alternative word meaning, and interactive visualization should guide bloggers for clarification when necessary.

5.6.3 Reflecting

BlogCloud derives topics from the re-visited paragraphs and and conducts reorganization of related contents. It presents similar contents as topics in the visualization, to provide abstract representations of blogs and support reflection. During the author session, the topics identified from the entire blog collections led to alternative ways to re-visit hiking experiences.

Making Sense of Topics

BlogCloud offers a different view of experiences to trigger reflection. BlogCloud reorganize experiences by similarity. Information about experience topics can be extracted to inspire new perspectives. In the author sessions, blog authors undertook sensemaking activities with their own blogs. A1 found sensemaking important for reflection on personal content. He commented, *"although you have written the blog, it does not mean you fully grasp the big themes that run through it ... hence the need for sense-making tools."* A2 searched several words and reflected on the overview of multiple experiences. She commented *"the connections were the interesting part, much more than just reflecting on some experience alone."*. The visualization of paragraph groups was used by A3 to make sense of symbols as a way to reflect on his own blog from a different perspective. A3 used the visualization to compare recurring experiences; he searched "difficult", "rocky", "steep", and "hot", creating four corresponding paragraph groups. After reading the connecting strips (Figure 5.9), A3 commented, *"it makes sense to me since 'steep' is more related to 'rocky' and 'difficult' than 'hot"'*. When seeing "bike" had more documents than "scooter", he commented *"[the visualization] reflects that I used bike* more than *scooter for transportation"*. When speculating that "cold" was mentioned more than "hot" in his blogs, he paused for a while and said, *"'cold' is bigger than 'hot', hmm... maybe that is because it took me more time hiking the colder north part, than the warmer south."*. Making sense of the visualized blog reorganization leads to new perspectives and deeper reflections about the experiences.

Connecting Related Topics

Blog authors associate related symbolic memories during reflection. Besides perceiving experience overviews and making sense of experience aspects, blog authors were also interested

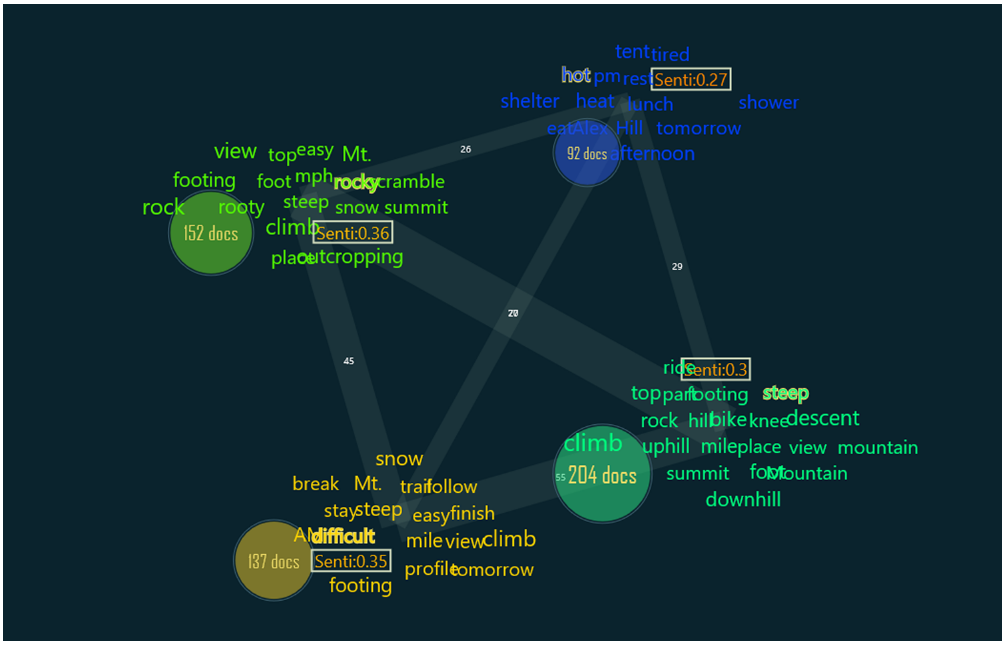

Figure 5.9: Four word clouds created by A3.

in delving into the connections between different experience topics. Seeing connections between word clouds of different topics helped A2 interpret related experiential items, noting: *"it would be good if I could see the words between two groups, like on the table, or in the visualization, so I know how the words relate to each group, and know what things fall between [the two word clouds]."* The connection from one topic to another could also be a flow of recalling consecutive experiences. When reading blog paragraphs about "bramble", A1 remembered on that day there was one "bus-shed", though the paragraph was not directly describing it, and he explained his unique definition of "bus shed". Connecting groups of reorganized experiential items sheds light on design improvements: besides showing abstracted information, the visualization should reflect how different experience topics are connected.

5.6.4 Remembering

Remembering in Sellen et al.'s definition emphasizes suggesting prospective events [151]. However, blogs store experiences along life and contain large volume of content, therefore memory might fail even with the blogs created by oneself.

Recovering Lost Memories

Experience documentation has been recognized as the most prevalent purpose for blogging [65, 121]. However, considering the large number of blog posts and time passed since creation, experiential items might be lost in memory. During multiple rounds of searching and reading the visualization, blog authors have chances to explore content they did not remember well. We notice all three blog authors found words in the visualization or paragraphs on cards that they did not immediately recognize. But blog authors did not skip these clues; they would collect more information to recover their lost memory. For example, when the visualization showed "dead" and "porpoise" as keywords in one paragraph group, one observer asked the author whether seeing "dead porpoise" made A1 sad? A1 could not remember where he wrote about a porpoise, but a search revealed that he once thought the cracked wood looked like "snout of a dead porpoise". As another example, A3 searched "Jersey", and several people's names were displayed. Through reading the paragraphs related to the names, he recalled hikers he met in New Jersey. In addition, efforts to recover failed memories were also reflected through their suggestions for system improvement. A1 realized he could not find consecutive paragraphs with BlogCloud, so he recommended to add a "before" and "after" button to help transition gently from searching to reading. Similarly, A2 suggested an additional layer to show the whole blog entry. To recover lost memories, blog exploration tools should not only present the blog sections, but give enough contextual information to help memory recovery.

5.7 Discussion

The extended author sessions demonstrate how the reorganization of blogs can support interaction with large blogs and leads to novel re-visitation experiences (as illustrated by Figure 5.1). With support from NLP and VIS in BlogCloud, blog authors interpreted experiences independent of time. Rooted in the findings, we discuss opportunities to identify and incorporate NLP and VIS in systems to enable interaction with the reorganized topics from one's own large personal blog data.

5.7.1 New Materials for Reflection

Natural language processing for re-visiting blogs can break apart the time stream, clustering blogs into *reorganized topics* with non-temporal associations that often are not clear in temporally ordered blog, thus offering new materials for multimodal interaction with blogs. In this work, *reorganized topics* are sets of similar, related blog sections from large personal blogs that, in their traditional form, highlight bloggers' temporally-ordered experiences. BlogCloud demonstrates how natural language processing (NLP) can be used to combine-and-reorganize the blogs by word-matching or NLP-based similarity grouping [8, 19]. Since notable experiences are not isolated and involve abstraction and comparison of multiple related experiences, NLP technologies can be used to identify them; e.g., A1's hiking difficulties from many tough experiences; the poor "picnic" experience of A2 from multiple poor food experiences; bikes or scooters as signifiers in A3's experiences. Instead of re-visiting a single experience, NLP can collect experiential items from different times that have never been reflected upon together, combining them as *reorganized topics* to offer novel materials for reflection. From our observation, the minimal interpretability nature of NLP raised an anticipation to examine the NLP-driven results; e.g., A1 and A2 actively interpreted the keywords from the word clouds; A3 deliberated on the numerical information in the visualization. The timeline-breaking ability of NLP produced reorganized topics. Not knowing what will emerge from NLP led to active searching and reflection. Our author sessions imply that for re-visitation, blog exploration systems should consider the ability of natural language processing to break the order of personal content and recombine related experiences, thus making reflection materials more expressive and triggering curiosity about the reorganized topics [19].

5.7.2 New Paths for re-visitation

Visualization of *reorganized topics* encourages generating new perspectives, providing new paths for blog re-visitation. The NLP- and VIS- augmented content leads to unique paths of re-visitation in recollecting, reminiscing, retrieving, reflecting, and remembering ("5 Rs") with blogs [151], expanding the paths to explore new ideas and perspectives [8, 19]. In the author session, blog authors started with words describing general feelings or common activities; e.g., "tear", "cry" for A1, "picnic" for A2, "difficult", "hot" for A3. They reflected on matched or similar experiences by re-visiting NLP-reorganized topics, and select examples to validate their symbolic memories. In contrast to skimming through the chronologically-ordered blogs, those activities match the mental process of reflection; to reflect on a general idea, people segment experiences and reminisce particular experience [173]. BlogCloud not only allows reminiscing particular experiences through searching, but also extends bloggers' cognitive ability to recollect topics from the extended blogs. The visualization suggests things to search, and reading a particular experience reconstructs general ideas about that type of experience. Visualizing reorganized topics that contradict bloggers' temporal perception of experiences leads to sensemaking of the similarity-connected experiential items and connecting different experience categories, as alternative paths for reflection. NLP shuffles the order of blogs, increasing the chance to read blogs that are not often re-visited. re-visiting unrecognized things in VIS encourages recovering lost memory. Exploring questions about the visualization provokes interactions to recover experiences that are dormant in memory. Blog exploration systems should consider visualizations to develop new re-visitation paths such as sensemaking, reminiscing feelings by re-visiting particular experiences, and encountering less re-visited experiences.

5.7.3 Interaction with Reorganized Topics

Symbolic words describing symbolic memories should center the identification of *reorganized topics*, to enable multimodal interaction with memories. Symbolic memories are impressions about experiences, represented by words and descriptions of experiences, that come to bloggers' mind and express the need for reflection [19]. The reorganization should consider the interactiveness of words in bloggers' memory: they provide clues for NLP to better retrieve blogs and trigger interactions with the experiences. Symbolic memories are not common and standalone experiential items. They are most meaningful experiences that form general feelings and remembered by bloggers. Three blog authors were focused on particular symbols. "Toughness" for A1, "less satisfying hiking food" for A2, and "bike & scooter" for A3 were all symbolic words from their journeys that the authors investigated. Blog authors were interested in retrieving reorganized topics related to symbolic memories when interacting with BlogCloud, leading to a novel re-visitation experience. Technologies supporting reflection of large textual datasets should actively allow users to express their symbolic words. Nevertheless, there are challenges in adopting symbolic words in natural language processing. Symbolic memories rooted in people's experiences are highly specific and contextual, and people want know how they connect contextually in the blog. It might make more sense to assume "backpack" and "store" were more related to A2's "picnic", more so than "table" and "chip". Falsely interpreted user symbolic words may confuse bloggers, resulting in dead-end searches. A resolution opportunity could use the user's ability to find alternate symbolic words. New system designs should consider how to visualize symbolic content to indicate the context, as well as provide hints and clues to encourage users to better describe symbolic memories for blog retrieval. Future design for reflection should consider meaningful ways to capture symbolic experiences in memory, enabling rich interaction with symbolic memories – supporting reflection and avoiding confusion regarding NLP results.

5.7.4 Towards Better Natural Language Processing and Visualization for re-visitation

The reorganization of blogs implemented by NLP and VIS to deliver novel multimodal blog re-visitation experiences [19]. There is a trend that intelligent technologies such as machine learning are getting more human-focused and open to non-expert users [31, 93]. Advancement in text processing and artificial intelligence will definitely introduce richer and more flexible ways to reorganize large personal content. We see a promising design space to introduce and explore the state-of-the-art information modeling and analysis technologies such as machine-learning and topic modeling to support better extract reorganized topics. Design opportunities raised from the identification of user's symbolic memories can be applied to other forms of personal content such as pictures and videos, as well as other personal archives like Twitter and Facebook posts. Future designs can incorporate different manners to collect symbolic words, such as iteratively and interactively asking users to suggest things they know (or don't know) about their own experiences. From high-level but vague memories about large blog data to the reorganized and against-expectation topics for reflection, NLP and VIS technologies provide new design possibilities to deliver new re-visitation experiences. With advanced data processing methods and alternative interaction techniques, there is an open space to develop rich *reorganization* methods on the large personal content to augment re-visitation.

5.8 Chapter Summary

In this study, the term reorganization describes a pathway to incorporate natural language processing and visualization in support of re-visitation of large personal blog repositories (see Figure 5.1). Author sessions served to investigate how re-organized blogs led to new ways of interacting with those blogs, towards understanding one's own past experiences. Based on the experience with BlogCloud, *reorganized topics* offer reflection materials and build new re-visitation paths, and they allow bloggers to interact with symbolic memories. Ever-growing personal content is becoming a valuable repository for people to re-visit and reflect on previous experiences, but following this is the challenge of designing interactive systems to identify values and create meanings from large personal datasets [82, 126]. Natural language processing as a material for design could be used to bridge the gap between the massive amount of personal content and humans' need to re-visit and reflect on meaningful experiences [31]. From this study, we conclude the following regarding sub-questions S3 and S5:

- S3: Sensemakers explore large amounts of personal data by searching for key memories. Connecting retrieved topics in a visualization offers new materials and pathways to support data interpretation.

- S5: Visualization of reorganized topics offers new methods for individual exploration, raises awareness of related data, and generates new perspectives which could trigger potential discussion.

Follow-up research is certainly needed. The small number of participants and brief author sessions were useful in delving deeply into usability issues, but questions remain about the generalizability of findings. Similar to other exploratory studies on emerging issues and opportunities in designs for reflection [126, 164], the present work focused on qualitatively understanding how bloggers interact with a multimodal design that presents NLP reorganized personal blogs to facilitate re-visiting past experiences. While only a small number of participants were included, the three blog authors who were selected were found to have valuable knowledge about large personal blogs as well as usability and engineering. Short but focused sessions with them helped to probe whether the *reorganization* led to creative re-visiting activities, and what user experience would be expected. Through the sessions with the dedicated bloggers, this study investigated the re-visitation interaction and issues that emerged from the reorganized blog content.

Chapter 6

Investigating Paradigms of Shared Overviews in Multiple Display Environments

In collaborative situations, notifications can deliver information about the actions of others onto one's own workspace, integrating a partner's work into the context of one's own sensemaking [30]. When collaborating on a data-intensive task, notifications only inform users about actions, without providing overviews of group activities to foster discussion. Prior research has explored how a shared overview on a secondary display could present group work to support collaboration. Sensemakers' individual control, awareness, and communication are influenced by an overview of associated group activities. However, some studies have encouraged a separation of individuals' work to enable task distribution [116, 138, 172], while others have connected related parts to trigger discussion [16, 72, 99, 118]. The design choice of separating or connecting group work still requires knowledge on how each choice affect sensemaking activities and outcomes.

To explore how a collaborative visualization serves as an awareness-supporting technique and supports co-located sensemaking, key sensemaking activities are extracted from BlogCloud, and VISGRAINS is re-designed and implemented. VISGRAINS is a dual-display system that allows users to retrieve, organize, and visualize sensemaking activities. Furthermore, it is a co-located tabletop-based system which allows two to three sensemakers to search for social media data from a database and create data representations. Search results are represented on digital cards and can be sorted into category boxes. A vertical display visualizes all search results in one of the three paradigms: parallel, connected, and merged. The parallel paradigm puts individual work side-by-side; the connected one uses machine learning technology to link related search terms; and the merged one automatically integrates all search results into one self-layout auto-connected visualization.

To evaluate how different overview paradigms of VISGRAINS affect co-located sensemaking, this study explores the scenario in which two sensemakers identify and organize information from a large hiking-themed Twitter collection. The sensemakers use searching tools, data cards, and visualization to identify important items and categorize them for sensemaking. This work follows the study on topic visualization and extends the answer to the third research question (RQ3). It explores different design options to connect and present related individual work (S3) and examines how sensemakers work individually or collaboratively with a shared visualization (S2). The findings address S5, *"how do shared overviews presenting group work affect co-located space factors?"* and S6, *"how do shared overviews lead to different styles of collaboration?"* The study on collaborative notifications suggested that teams who perform the task more individually can forage more information for sensemaking [113, 154], but their low awareness may result in repeating others' work [123] and having more conversations on coordinating actions [54]. On the other hand, having collaborators perform the same task all the time can achieve higher awareness, but it also prevents collaborators who are not interacting from exploring and contributing more information. When using notifications to deliver awareness information, people have higher awareness and are able to work independently. However, collaborators also pay less joint attention to the connected thoughts and are less inclined to discuss alternatives. The visualization presenting individual and collaborative work needs to balance the individual control of sensemaking tasks and the effort to maintain awareness and communicate findings.

This study investigates three different types of shared visualizations – parallel visualization (PAR), visualization of connected actions (CON), and merged visualization (MER). These three paradigms emphasize different factors of control, awareness, and communication. The different levels of the divided visual space alter the perceived need for social communication and awareness of others' related work. Highly inter-dependent visualization may lead to more frequent social exchange, which reduces the task division and individual control. A totally separated visualization (PAR) could support sensemakers in performing actions simultaneously, which potentially enhances the utility of the data, but this visualization may also degrade the willingness to communicate and consider others' insights. A merged visualization (MER) presents integrated changes after each sensemaking activity. Sensemakers can have an overview of how individual work affects the group work, and they can discuss with others when useful information is identified. However, the inter-dependency in changing the visualization may lead to less individual control in sensemaking. Using visual cues to attract attention by connecting visual components (CON) could balance the individual control and awareness of inter-connected actions and activities. Machine learning techniques could be used to identify connections such as related search terms or relevant tweets. Awareness of key sensemaking components could connect individual activities, while encouraging the communication of related items from the machine learning results.

6.1 Abstract

It is increasingly common and important to support collaboration in sensemaking tasks involving massive amounts of data and information [77, 153]. However, designing shared

overviews that meaningfully present group work to promote participation and communication is still challenging. Sensemaking tasks involving large amounts of data require sensemakers to forage for initial useful subsets of the data, to try out different ways to form structures, and to organize the findings and knowledge to derive hypotheses [134]. Performing sensemaking activities in a co-located space benefits from multiple-display environments (MDEs), which consist of tabletops or wall displays to support individual and collaborative work [6, 11, 100, 138, 166]. MDEs facilitate sensemaking not only by making data simultaneously accessible, but also by providing shared views to support awareness and discussion [11, 138]. Multiple sensemakers can divide the labor, contribute diverse ideas, and exchange information and knowledge with shared displays [77]. However, the question of how different ways of presenting individual work in a shared overview could affect key aspects of co-located sensemaking remains under-explored.

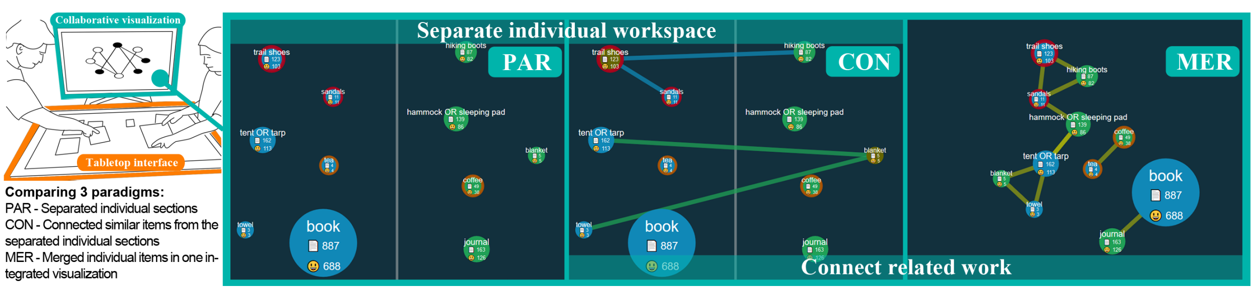

Figure 6.1: This study examines three paradigms of separating or connecting individual work during co-located sensemaking. Left: The VISGRAINS system consists of a tabletop interface for data organization and a vertical display presenting one of the three visualization paradigms. Right: three visualization paradigms overview the same data representations organized on the tabletop.

Large interactive tabletops support sensemaker pairs or trios in working at the same time and seeing each other's actions and activities [72, 149]. Prior research has explored the benefits of introducing shared overviews in MDEs to present collaborative information [49, 100, 138, 175]. When collaborating with a shared tabletop, collaborators create personal territories in their interactions with multi-user displays [150]. Personal territory is a re-served area, typically near where an individual sits or stands, where one can obtain, explore, and initially organize data representations. This area reserves individuals a private space to clarify personal thoughts. The segmentation of the space can be utilized to differentiate individual work. In contrast, the shared overview serves as a center place to monitor others' work and discuss the group activities [16, 99, 138]. Although many prior studies on MDE-supported sensemaking have considered shared screens or views to present group work (e.g., [16, 49, 100, 100, 138, 175]), it is unknown how different options to relate and present individual items could affect sensemaking collaboration. Some studies have explored separated or replicated individual work to reduce interference and support task distribution [116, 138, 172, 175], while others have connected and integrated personal work to promote externalization and discussion [16, 72, 99, 118]. However, knowledge is under-developed regarding the design tradeoff of whether individual items should be connected together or left separated in a shared overview. Completely merging individual work makes the overview depend on group coordination and undermines sensemakers' ability to interpret individual findings. Separating individual contributions in parallel reduces the mutual interference, but could degrade the awareness of others' work and the perceived need to discuss the common work.

This study examines the design trade-off between *separation* and *connection* of individual work in shared overviews during co-located sensemaking. Three paradigms of collaborative visualizations are identified to present the data organized by different sensemakers; these paradigms separate or connect individual items in different ways (Figure 6.1). The *parallel paradigm (PAR)* separates individual work in the overview without connecting related items. The *connected paradigm (CON)* separates individual sections but uses cross-workspace links to highlight related items. The *merged paradigm (MER)* integrates and connects individual work automatically in a self-layout visualization. The three paradigms of shared overviews are instantiated by an MDE system: VISGRAINS. VISGRAINS supports co-located sensemaking using a tabletop interface to organize data representations, and another vertical display to present shared overviews. Twenty-seven sensemaker pairs are recruited to collaborate with VISGRAINS while completing a Twitter analysis task. We collect data to analyze how the three paradigms affect the effectiveness of sensemaking and styles of collaboration. The three paradigms are compared on three key co-located space factors: control, awareness, and communication [153]. The findings contribute a comparative understanding about the choices of separation and connection of individual work in shared views, visualizations, and display devices. The implications for the overview designs in MDE are discussed to better support data-intensive co-located sensemaking. The following are the study's key findings:

- Non-connected individual work (PAR) in a shared overview ensures control over the workspace and leads to more interaction with the data representations.

- Splitting the visual spaces to present individual work (PAR and CON) better facilitates the monitoring of one's partner's work.

- Automatically integrating an amount of individual information makes the shared overview overwhelming and less effective due to the complexity and value added to the task.

- Separated views without connection (PAR) encourage the establishment of sensemaking roles; links connecting individual workspaces (CON) encourage joint discussion.

6.2 Three Paradigms of Separation and Connection in Overviews

The design of a shared overview in MDEs affects how sensemakers engage in personal work or participate in communication [16, 100]. When designing ways to present data managed by different sensemakers, one needs to understand their influence on collaboration: partitioning interaction space and distributing data representations allows simultaneous work, but could degrade sharing and communication; a centralized visualization suggests the structure of collaborative work, but requires sensemakers to coordinate actions to maintain consistent understanding. Data visualization and machine learning techniques offer technological approaches to automatically identify and connect similar items. Different ways to incorporate these technologies to connect group work affect individual control, awareness maintenance, and communication. Presenting the computer-connected work could encourage recognition of common work and discussion of related information, but the merged presentation of group activities requires sensemakers to pause individual tasks and interpret together.

This study considers a basic scenario in which two sensemakers collaborate with a tabletop interface to organize and make sense of a large Twitter dataset, while using a shared overview to maintain awareness and communicate findings. To explore the design choices of separation versus connection in the design of shared overviews, an MDE-based sensemaking system is implemented: *VISGRAINS* (VISualizing GRoup Activities IN Sensemaking). VISGRAINS instantiates the separation and connection of individual work using three paradigms of shared overviews: the *parallel paradigm (PAR)*, *connected paradigm (CON)*, and *merged paradigm (MER)* (Table 6.1).

Table 6.1: The comparison of three overview paradigms. PAR separates individual sections but does not connect related work. CON separates individual sections and connects related items from different sensemakers. MER does not separate individual sections but connects related items from different sensemakers.

	Separated sections	Connected related items
PAR	Yes	No
CON	Yes	Yes
MER	No	Yes

6.2.1 Parallel Paradigm (PAR)

The parallel paradigm (PAR) presents individual work separately without connecting it (Figure 6.2). In co-located collaboration with tabletops, collaborators establish personal territories near their physical positions to manage individual work [150]. People have the sense of protecting individual work [16, 53] and avoiding intruding on others' workspace [28]. PAR emphasizes preserving individual work in the shared overview by separating personal sections. Changes in one's personal workspace are directly mapped to a section in the shared overview, and different sections collectively present the work of different collaborators. Mapping personal territories to different overview sections reduces the interference of individual control. When two sensemakers work at different sides of the table, it also provides an alternative space to stay aware of others' work, instead of reading it upside-down [89].

6.2.2 Connected Paradigm (CON)

The connected paradigm (CON) incorporates separated individual sections, but highlights related items between individual work (Figure 6.3). Similar to PAR, CON maps the personal workspace into the visualization, but it recognizes related item pairs from personal territories and uses cross-workspace links to connect each pair. Prior studies have suggested that

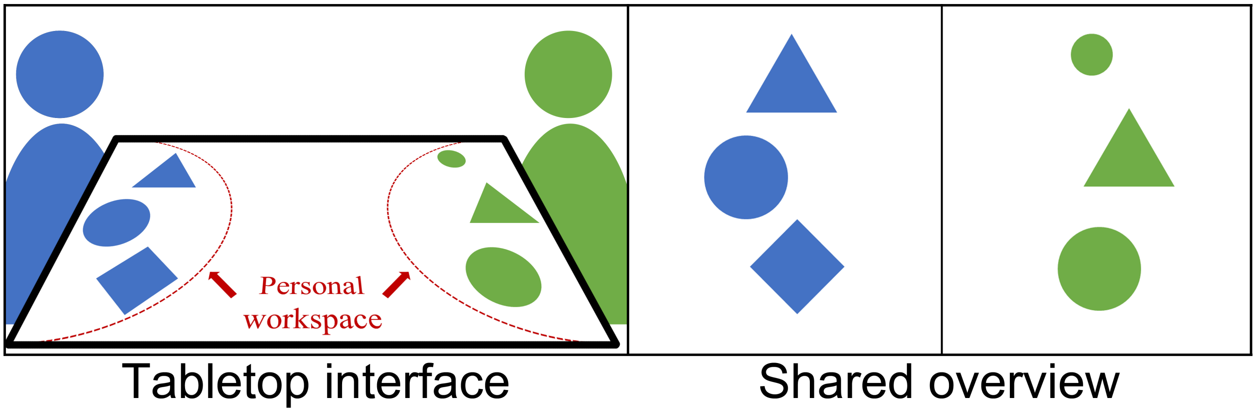

Figure 6.2: The concept of the parallel paradigm (PAR)

connecting common work encourages sensemakers to express personal thoughts and supports coordination and maintaining awareness [99]. CON links similar parts and indicates common items in the shared overview. Since CON still consists of separated sections, sensemakers preserve their individual work and can monitor others' workspace from the partner overview section. Recognizing and associating related data into useful subsets centers sensemaking activities [134]. The links connecting related items draw attention to the common work and could trigger discussion about synthesizing individual findings.

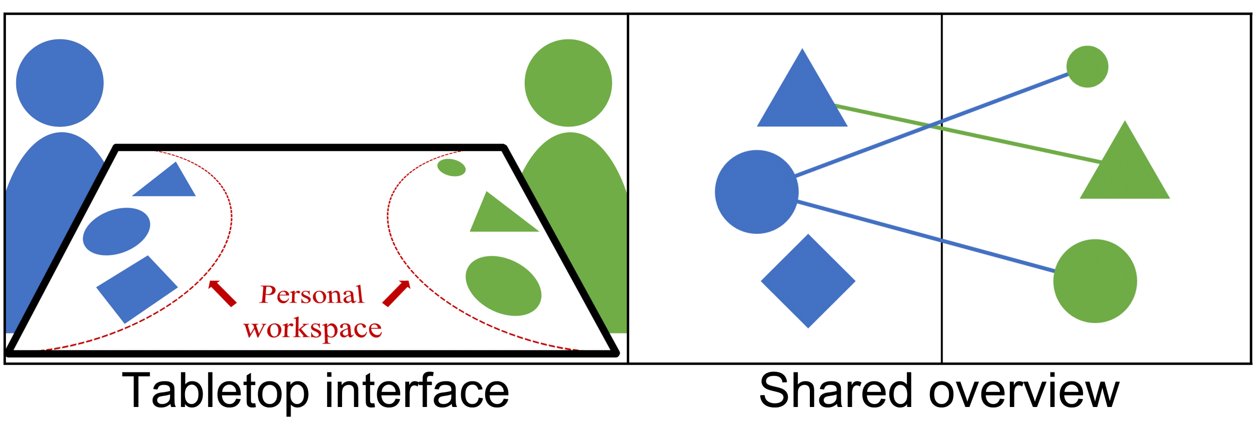

Figure 6.3: The concept of the connected paradigm (CON)

6.2.3 Merged Paradigm (MER)

The merged paradigm (MER) merges all group work together into one integrated visualization (Figure 6.4). Like CON, MER also connects related individual items, but it places similar ones closer in the visual space. It reflects the overview design used in prior studies: associating individual contributions together, reorganizing collective information by the computer, and presenting group work in one shared view [2, 16]. MER aims to merge group work together to depict overall work status and knowledge structure [16, 175]. It does not maintain separated sections in the overview, and thus supports less awareness of others' individual work. As individual actions result in changes in the shared overview, sensemakers need to coordinate actions when interacting with artifacts in personal space to maintain a consistent understanding. MER reorganizes individual items and presents connections all together, which could potentially support communicating the overall task.

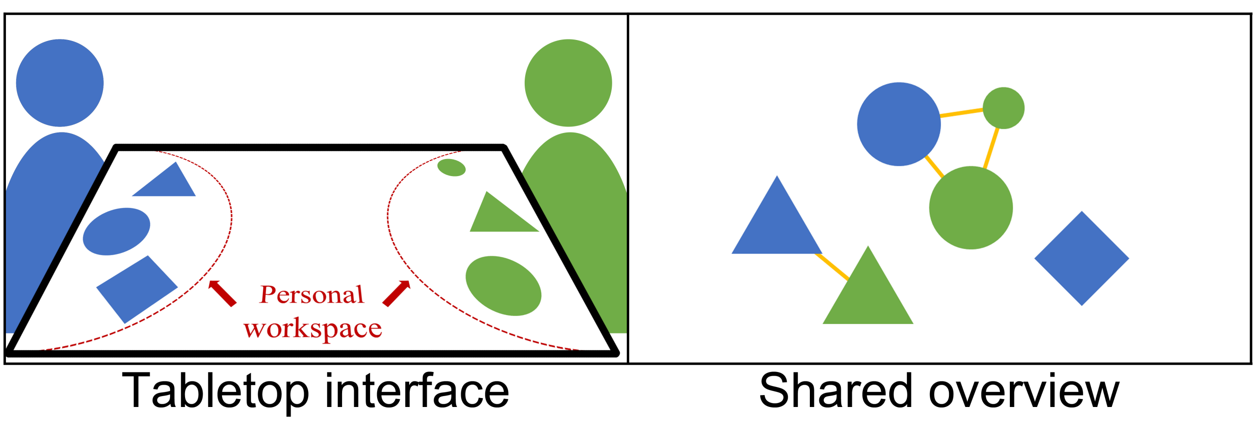

Figure 6.4: The concept of the merged paradigm (MER)

6.3 System Design and Implementation

Collaborative visualization helps people explore and make sense of data together, but tends to focus on merging individual contributions. It is imperative to understand how a shared visualization could balance the individual work and collaboration. Prior research implies that overview settings affect sensemakers' individual control, awareness, and communication. Some studies have encouraged separated individual work to enable task distribution [116, 138, 172], while others have suggested connecting related parts to trigger discussion [16, 72, 99, 118]. However, the design choices of separating or connecting group work still require knowledge on how each choice affects sensemaking activities and outcomes. Grounded in prior research, this study implements and examines VISGRAINS, a co-located sensemaking system providing different visualization paradigms of group activities. The study seeks to provide a deeper understanding of how three overview design options affect co-located sensemaking.

VISGRAINS is a system that allows two sensemakers to search through a Twitter dataset and create data representations. VISGRAINS incorporates a large tabletop interface for establishing individual work territories, and another peripheral vertical display to show a visualization of group work. Tabletop displays feature large interactive space and allow multiple users to establish a personal workspace and work at the same time [140, 149]. The VISGRAINS tabletop is a multi-touch interface for viewing, manipulating, and exchanging Twitter data representations. The visualization presents an overview of the data items created by the sensemakers. This study considers sensemaking of data on Twitter due to its popularity as a social media platform and importance in many data analysis tasks [127]. VISGRAINS is tailored to present Twitter data for this study, but it has the potential to be configured to support other document types as well.

6.3.1 VISGRAINS Tabletop Interface

The VISGRAINS tabletop interface runs on a 55' Microsoft multi-touch display. The design borrows the settings from prior similar systems [72, 118, 182]: two collaborators work at different table sides and interact with touch-enabled cards (Figure 6.5). Digital cards are an interactive metaphor that has been widely used by prior tabletop systems (e.g., [49, 123, 182]). The tabletop interface consists of three parts: two menu bars on two sides to search and create search cards, an open interactive space to organize the cards, and virtual boxes in the middle to categorize the cards (Figure. 6.5). Sensemakers can search for keywords or keyphrases with a pop-up virtual keyboard (Figure 6.5, ②, opened by tapping ①) and retrieve Twitter data from the database. After searching for a word or phrase, a search tab is added (Figure 6.5, ③) and displays the matched tweets in a scroll-able list (Figure 6.5, ④). Double-tapping a tweet opens it on the Twitter website. Clicking the add-card button on a search tab adds a card of the corresponding search onto the table (Figure 6.5 bottom center). Each search card shows the keyword and number of associated tweets and users (Figure 6.5, ⑦), and can be dragged, rotated, and zoomed in on with touch interaction. Two or more overlapping cards form a *card group* (Figure 6.5, ⑧). Three sort boxes in the middle of the table represent three categories for card organization (Figure 6.5, ⑤). Drag-and-dropping a card onto a box can sort it to that box, and the card border changes to the box color (Figure 6.5, ⑨). Drag-and-dropping a card to the recycling bin removes the card from the table (Figure 6.5, ⑥).

6.3.2 Implementation of Three Visualization Paradigms

The vertical display has a visualization that presents an overview of card status in the workspace (Figure 6.1 left). The visualization uses circle glyphs to represent each search

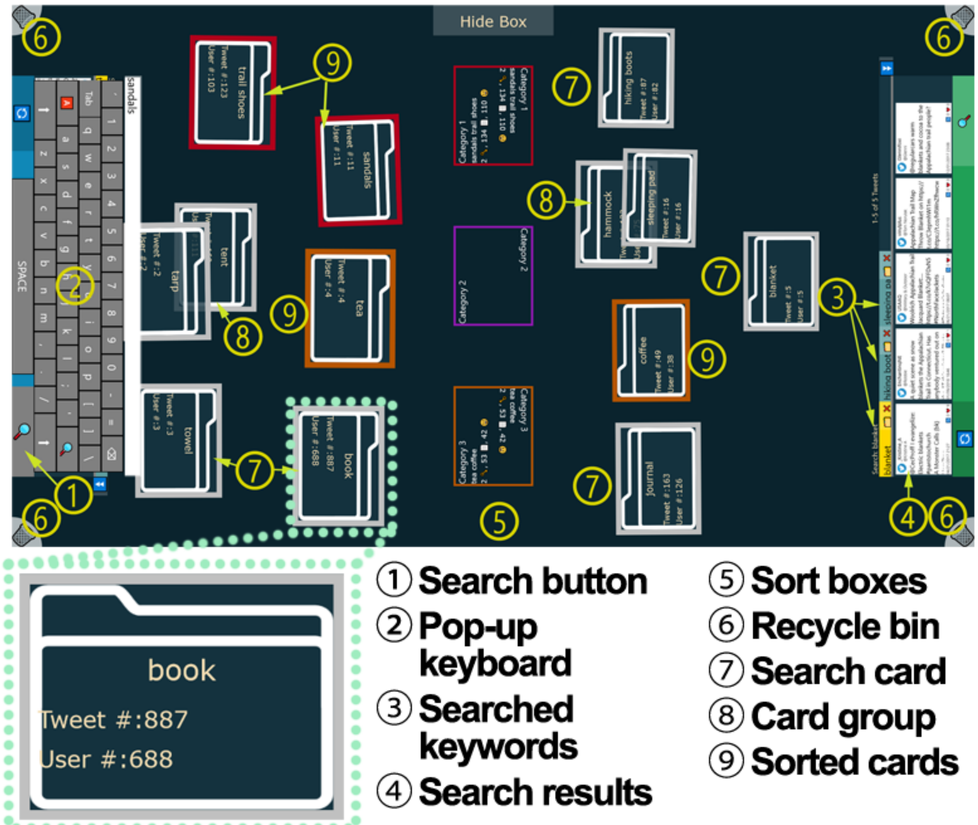

Figure 6.5: The tabletop interface of VISGRAINS. Each digital card shows the number of tweets and users mentioning the keyword. Cards can be moved and zoomed in on with touch interaction.

result. Each card generates a circle with the keyword, the tweet number, and the user number (Figure 6.6 left). The circle size is proportional to the number of tweets in the search result. Cards created by the user on the left generate blue circle glyphs, while those by the user on the right generate green circle glyphs. The circle outline changes to the box color after its card has been sorted (Figure 6.6 middle). For a card group, the circle glyphs are merged into one circle, with tweet number and user number updated to the total number of mentions of at least one of the keywords (Figure 6.6 right). To compare different ways to present group work, VISGRAINS displays circle glyphs in three different paradigms.

PAR seeks to leave individual work more separated without indicating similar or related

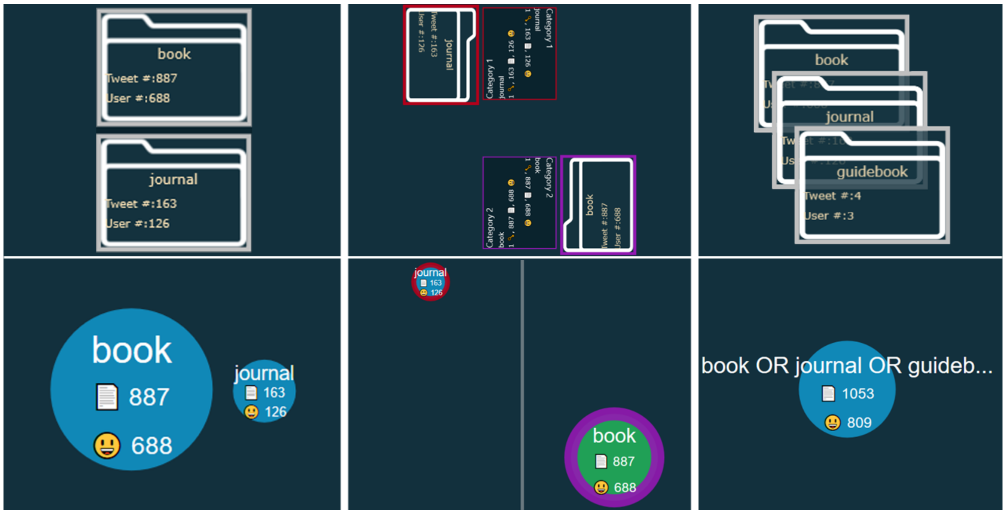

Figure 6.6: The top row shows different card placement, while the bottom row depicts the corresponding circle glyphs in the visualization. Left: two search cards. Middle: two sorted cards created by different sensemakers. Right: a card group created by overlapping the cards.

items. It directly maps the positions of cards or card groups on the tabletop to the positions of the circle glyphs in the visualization (Figure 6.1 left). A center line splits the visualization into two spaces. Prior studies have found that users tend to place individual artifacts in a table area that is physically close to them, and that they tend to interact intensively with items in personal territories [150]. The separated views of the shared visualization and the color encoding of glyphs reflect the sense of personal territories and ownership of the items. Like PAR, **CON** also directly maps the card positions to the glyph positions, but it uses lines to connect circle glyphs with the same or similar keywords (Figure 6.1 left). The similar keywords are determined by the Google word2vec machine learning model [50], which builds on the data corpus and can give a similarity score (0-1) to a pair of words or phrases. Higher scores indicate similar semantics. VISGRAINS determines that two circles/words are similar if the score is above 0.33 (threshold determined by empirical testing). When a card is moved or tapped, the system identifies similar keywords from the workspace and connects their glyphs to the circle of the last interacted card. The last interacted circles turn yellow. One circle from the left space and another circle from the right generate links one at a time. Links from the circle on the left are blue and those from the right are green. Finally, **MER** emphasizes deeper connection of individual work by merging all glyphs into one integrated view; it does not maintain separated spaces in the visualization. MER directly merges all the circle glyphs into a self-layout, node, and link graph generated using the force-directed technique [64] (Figure 6.1 left). The links are also identified by the Google word2vec method, but all similar keywords in the glyphs are connected at the same time. Adding, moving, or deleting any card from the table will trigger the re-configuration of the force-directed layout. The regeneration of the layout takes one second.

6.3.3 Software Architecture

VISGRAINS consists of a client-server structure which runs on a web server and the local MDE interface (Figure 6.7). The server side stores the Twitter data in a Solr database [1]. Twitter data can be retrieved with Solr queries. The web server also runs a service built on the Google Word2Vec machine learning model [50]. The service can take any pair of words or phrases and return the similarity between them. The tabletop and visualization provide an interactive interface for co-located sensemakers to retrieve the data from the server. Once the user has searched for the keywords and created the digital cards, the system queries the database and generates information about the search results. The tweet and user numbers and the term similarity information are associated to generate the visualization.

[1] https://lucene.apache.org/solr/

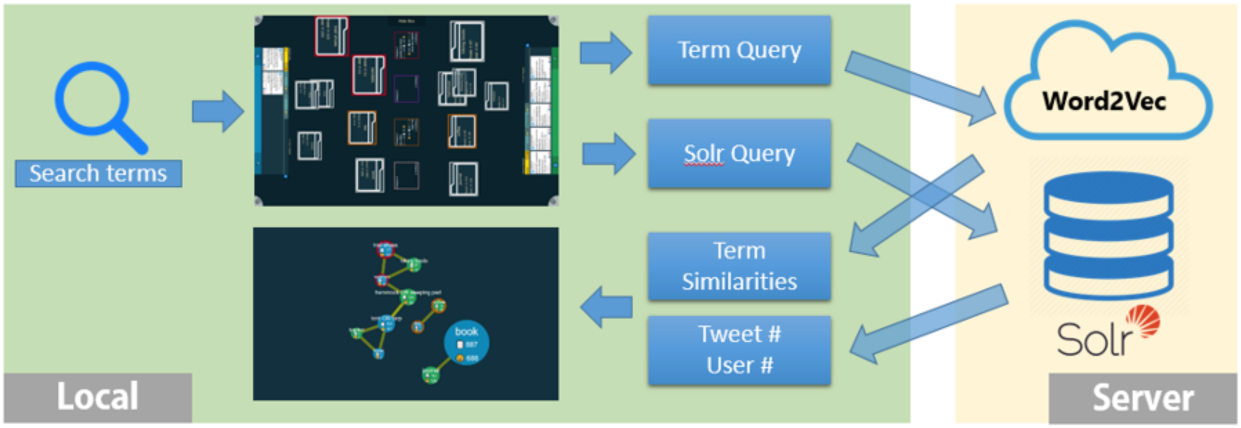

Figure 6.7: The architecture of the VISGRAINS system. The data is stored on a web server which can be retrieved interactively on the tabletop and visualization interfaces.

6.3.4 Co-located Sensemaking with VISGRAINS

To collaborate with VISGRAINS, sensemakers can work separately on the two sides of the tabletop and use the virtual keyboard to search for keywords. Prior studies have suggested that searching for words in a large dataset and making sense of the search results are common information seeking and sensemaking activities [113, 129, 153]. Tabletop systems offer an open and interactive space to support retrieval and organization of the search result representations at the same time [72, 118]. VISGRAINS enables simultaneous searching and organization of search results with the metaphor of digital cards on the tabletop interface. After searching for a word or phrase, matched results will appear in the search result list (Figure 6.5, ③). Sensemakers can read the matched results to obtain an initial understanding of how the Twitter users mention the term. Search tabs are added above the search results to show different keywords. If sensemakers feel that the results of a search term are relevant to the task, they can use the "add card" button on each search tab to create digital cards. A search card will then be added to the tabletop (Figure 6.5, ⑦). Sensemakers can create and organize multiple cards on the tabletop interface.

To support awareness of all the search cards on the tabletop, the shared overview on the vertical display presents the research keys in circle glyphs (Figure 6.6). As foraging for and filtering useful subsets of data are key sensemaking activities [134], the tabletop interface offers a space to cluster related search terms and form semantic groups. When cards are clustered, their circles will be merged into one larger circle showing the number of documents in the combined result. The circle sizes are proportional to the number of tweets in each search result. Sensemakers can quickly know which terms or term groups are mentioned more in the dataset by using the visualization (Figure 6.1), to obtain an overview of how multiple keywords are used in the data.

To facilitate the generation of sensemaking hypotheses, the sorting box is used to sort the search cards into high-level categories. Creating categories helps collaborators find common ground about important information types in the dataset and manage the sensemaking representations. After sorting, the visualization changes the border color of the circles to indicate categories (Figure 6.6 middle). The category box also shows basic information about the keywords in the category, including how many cards have been sorted to this category, which terms are included, and how many tweets and users in total have mentioned these words.

6.4 Co-located Space Factors

VISGRAINS supports collaborative sensemaking by allowing sensemakers to search in the Twitter set, organize search results, and reflect on the search results with the visualization. To support information foraging and organization [134], VISGRAINS uses the node-link graph to represent significant information and knowledge structures. The three visualization paradigms implemented on VISGRAINS emphasize the separation or connection of

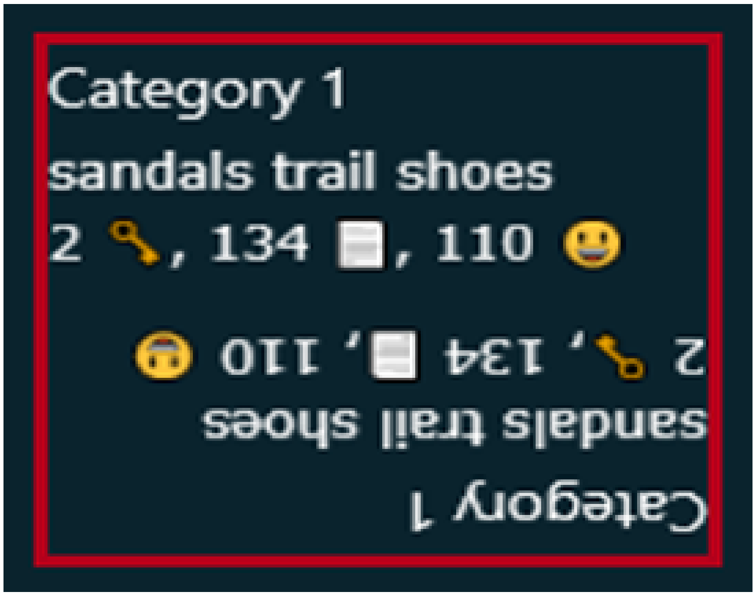

Figure 6.8: The category box showing keywords, number of keywords, and tweet and user numbers.

individual work (Table 6.1). Previous studies have found that a shared overview can be used to support activity awareness [20], which provide materials for discussion [16], and that multi-displays allow individual control over the shared view [138]. To explore how the design choices implemented by different visualization paradigms affect co-located sensemaking, this study compares the three paradigms with the three key co-located space factors identified in [153]: *control*, *awareness*, and *communication*.

6.4.1 Control

Control over the workspace determines individuals' power to interact with the information and affect the collaboration [55, 99, 154]. When collaborating with a tabletop interface, sensemakers can divide the task and labor and work in parallel [124, 182], or collaborate in a closely coupled way to focus on the same problem at the same time [72, 161]. When interacting with digital cards on VISGRAINS, different visualization paradigms separate or link individual searches in the workspace. The dependency between the different users' work shown by the connections may introduce interference in individual work and reduce the control over the workspace. Differences in control lead to different utilities of the shared artifacts and abilities to contribute to the sensemaking task.

6.4.2 Awareness

Awareness in the context of collaborative activities refers to users' understanding of each other's activities performed in the work environment [20, 53]. Higher levels of awareness reflect an increase in a sensemaker's ability to consider and use others' findings in the context of his or her own activities [30]. Shared overviews affect the awareness of others' work and the smoothness of the collaboration [16, 100, 175]. Separating individual work and map cards in the visualization offers a peripheral space to track others' searches from the other side of the table. Connecting similar searches by machine learning technique indicates common work to facilitate the grouping of related subsets. However, the awareness and understanding of individual and group work also depend on the way similar items are associated, presented, and interpreted.

6.4.3 Communication

Communication centers the social coordination and knowledge exchange in face-to-face sensemaking [99, 153]. Working separately and independently helps finish personal tasks, but lack of communication may result in duplicated work [123] and less effective teamwork [176]. Authors are increasingly in agreement that close collaboration through discussion and information exchange improves the quality of sensemaking outcomes [72, 172, 176]. The digital cards and visualization in VISGRAINS offer references and materials to support the communication of the search results. Different ways to present group work in a shared overview offer different information to discuss. Non-connected individual work depends on interpretation and discussion to synthesize group work. Automatically related items can be associated to form conceptual groups. Different paradigms of separating or connecting individual work could affect the approaches sensemakers take to reach a common ground and agreements.

6.5 User Study

To investigate the effectiveness and effect of different overview designs of VISGRAINS, a three-way comparative study is conducted with the PAR, CON, and MER paradigms. The user study considers a collaborative Twitter analysis scenario with the VISGRAINS system. Study data is collected on the effectiveness of sensemaking, styles of collaboration, and the co-located space factors of control, awareness, and communication.

6.5.1 Task Design

This study considers the scenario in which two collaborators use large interactive displays to make sense of a Twitter collection. Twitter data is chosen because it is increasingly used to forage for and make sense of public information to support decisions. The user study considers the sensemaking tasks that require searching for keywords, organizing the information, and making sense of the facts. For example, two peer sensemakers address a list of questions by exploring different items, organizing the information, and exchanging knowledge about findings. The participants are asked to collaborate with their partner and use VISGRAINS to search for 50 hiking items among a hiking tweet dataset, and to answer a list of questions about the dataset. The Twitter data used in the study is a collection of 65,617 tweets that mention “Appalachian Trail” (or other variations such as #AppalachianTrail, #AT) crawled from the Twitter website.

Search Terms

During the task, each sensemaker dyad is given 50 different hiking items on worksheets, including items such as “trail shoes”, “book”, and “energy drink mix”. The items are selected by three steps. We first conduct an open-ended brainstorming and generate a list of 106 hiking-related items from websites of hiking preparation, including general categories of hiking essentials, camping gear, food, navigational devices, entertainment, etc. Then we search keywords among the Twitter dataset, to make sure the keywords appeared at least once. Hiking items not appeared in the dataset or contains multiple meanings (e.g., water appears in “drinking water” and “Delaware Water Gap”) are removed. After this step, the candidate items are sorted into four big categories by the research investigators. We created apparel, food/meal preparation, hiking/camping gear, and technologies as the potential categories to ensure the search terms can be sorted and categorized. We pick items with highest numbers of search results from each category, and divide them into the two category lists. Item list can be found in Appendix A.2.

Sensemaking Tasks

One participant is given a list of 25 items and the other participant has the rest 25 items generated by the research investigators (see Appendix A.2). On the worksheet, each hiking item contains a name, a picture, and a short description. The 50 items are categorized and each category is divided evenly between the two lists. Before the task starts, a researcher introduces the VISGRAINS system to the participants, demoing functions including keyword searching, tweet viewing, creating and manipulating search cards, and sorting the cards. The visualization is introduced and its mapping to the card is explained. Each team has a 5-minute trial task to search for and sort eight words (lake, mountain, hill, valley, etc.) and answer three questions similar to the actual task questions. The participants are instructed to search for their own 25 items, work on their own side of the table, and complete the task together in 45 minutes. A researcher stays in the corner of the experiment room during the task to provide step-in help with the system, but does not intervene in the sensemaking process.

The experiment task consists of 11 questions provided on sheets of paper (see Appendix A.3). The two participants have identical question sheets and are informed that all questions are based on all 50 hiking items. The questions simulate a foraging process, in which the participants must sort the cards into general categories, and a sensemaking process, in which they must determine key facts about the data (See Table 6.2 for the questions) [134]. During the task, the participants are encouraged to use the visualization to identify related items. To calculate the number of tweets mentioning a group of items, participants are instructed to form card groups by overlapping multiple cards and to read the number from the combined circle glyph in the visualization. For the groups with CON and MER paradigms, participants are informed that related items are connected by the lines.

6.5.2 Measurements and Data Collection

Data is collected on three aspects: sensemaking effectiveness, collaboration styles, and the three key co-located space factors. Overall effectiveness reflects the general performance of different overview paradigms. Collaboration styles refer to the ways in which the system is used. The analysis of co-located space factors helps understand the advantages and dis-

Table 6.2: Questions to be answered by the participants. See Appendix A for the actual questions

Q1	Identify the top three items that have the largest number of tweets
Q2	Categorize 50 items into three categories, with each category containing 5-15 items. Write a short description about each category.
Q3-Q8	Identify four items that are related to a specific item (six different items for six questions). How many tweets mention these items?
Q9-Q10	Identify the top five electronic devices/overnight items. How many tweets mention these items?
Q11	Are there more tweets about cold or hot weather hiking?

advantages of each paradigm. The data is collected from system logs, video recordings, a post-study questionnaire, and answers on the worksheet. VISGRAINS records every card movement with a time-stamp and screen coordinates on the tabletop. A camera records the participants' actions, focus of attention, and conversation during the task. A post-study questionnaire is taken by every participant separately; it includes Likert-style questions and open-ended comments about the system.

Effectiveness of sensemaking

Effectiveness of sensemaking is measured through the answer quality, task time, and subjective difficulty. The answer quality is measured using the missed items from the majority answer. Q3 to Q10 ask the participants to find multiple hiking items to form card groups and determine the tweet number (Table 6.2). The "golden answer" to Q3-Q10, respectively, is defined as the most common items identified by all the participants to answer that question. Then, for each participant group, the researchers count how many items in total are missed from the golden answers of Q3 to Q10. Failure to identify common items in the answers indicates that the sensemaking missed information that could make more sense. The task time is tracked by VISGRAINS, from the launching to the closing of the system. Task difficulty is rated on a 7-point Likert-style scale in the post-study questionnaire.

Styles of collaboration

Styles of collaboration are developed based on prior work and re-configured for this study's specific setting [16, 72]. The collaboration styles in which sensemakers use the visualization and tabletop interface to answer the questions are observed and identified to describe how attention is focused, similar to the video encoding methods taken by [16, 72]. Four researchers (who also encode the videos) watch four videos independently and make notes. The style categories are generated through affinity diagramming of the notes. Three hundred screen shots from six other videos (two from each condition) are sorted to validate the categories. A total of 11 collaboration styles with six different styles of attention focus are identified (Figure 6.9). The styles are grouped by whether the participants communicate, interact with the cards, or maintain awareness of the collaborative work. Face-to-face communication (FTF) is when participants talk face-to-face. In joint focus on visualization (FV) and joint focus on tabletop (FT), the participants use cards on the table or a shared overview to discuss or think about answers. Joint focus on one's workspace (FOW) and joint focus on different displays (FDD) reflect the time when the task is led by one participant and the other participant looks at his or her partner's cards or visualization, respectively, to give comments or just to observe his or her partner's work. Focus on individual work (FIW) is a style in which the two participants interact with cards at the same time, with or without occasionally exchanging information. To distinguish communication versus no communication, sub-styles use trim -C (communication) and -N (no communication) to mark conversation status for FV, FT, FOW, FDD, and FIW (e.g., FV-C is a sub-style when participants look at the visualization and talk; FV-N is a sub-style when participants look at the visualization but do not talk). Different collaboration styles reflect different collaboration components. In FDD, FOW, and FIW, participants interact with the system, indicating a higher level of control. FDD is when one participant works on the individual task and the partner obtains awareness of the changes from the shared overview. FV, and FDD describe participants discussing the integrated work from the shared overview. To encode the video, each recording is segmented based on speech sessions (conversations about the same topic marked by the researchers) and interaction sessions (periods of time when two consecutive interactions are less than five seconds apart, as identified from the system record). Videos are separated by the beginning and end of speech and interaction sessions. One segment is tagged as one of the collaboration styles. Each video is tagged by two coders, and the third coder tags sections on which there is disagreement. The majority tag is used as the final style of each video segment. The video encoding is analyzed with ANVIL software [2]. The normalized time proportions are used to compare different paradigms with each of the collaboration styles.

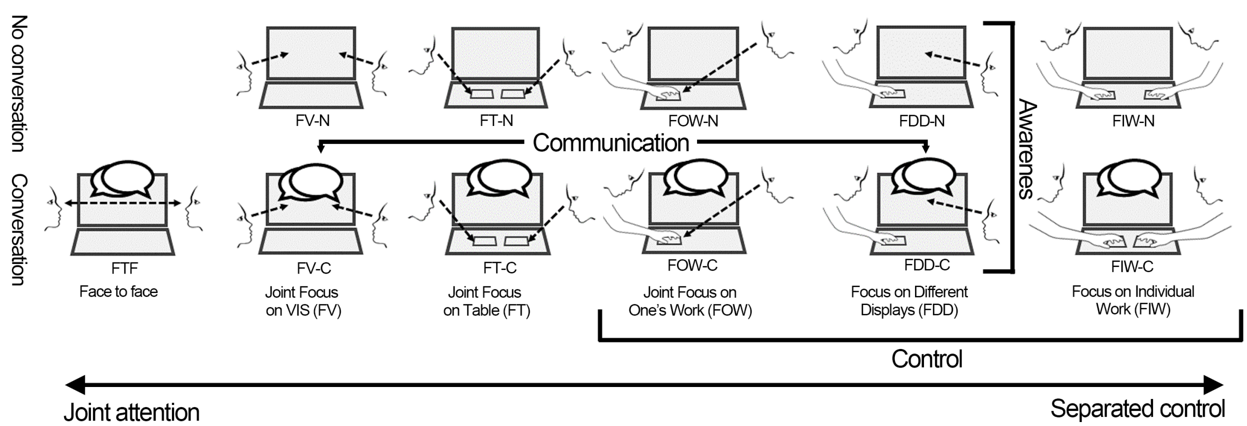

Figure 6.9: Collaboration styles when interacting with VISGRAINS. The attention and collaboration styles are identified by observing videos and summarizing with affinity diagram. Styles toward the left reflect more joint attention, while styles toward the right reflect more interface control.

[2]http:www.anvil-software.org

Collaboration Components

Collaboration components are measured using a questionnaire, system logs, and video data. Different collaboration styles reflect different collaboration components. In FDD, FOW, and FIW, participants interact with the system, indicating a higher level of control (Figure 6.9). Control is also measured by the amount and frequency of card movements, as well as by two questions about work altered by the partner and whether it is easy to concentrate on the individual task. FDD is when one participant works on individual task and the partner obtain awareness of the changes from the shared overview. Awareness is also compared by asking participants whether they use the tabletop or the visualization to track their partner's work, and another three questions about the effectiveness of the visualization in finding items. FV, and FDD describe participants discussing the integrated work from the shared overview. Besides the video encoding, communication is also measured using a question about whether the participants refer to the visualization or the tabletop when discussing answers to the questions.

6.6 Results

A total of 54 college students (age 18-23, with 30 females) participated in the study. They were recruited from an email list and a pool of student volunteers. The participants' majors included computer science (19), psychology (10), neuroscience (5), HNFE (5), and biology (3), among others. They were randomly assigned to one of the three conditions, with nine pairs using each of the visualization paradigms. The average task time was 37.52 minutes ($SD = 7.09$). Statistical analysis was conducted on the experiment data. The significance analysis is based on a one-way ANOVA and pairwise t-test, with an alpha of 0.05.

6.6.1 Sensemaking Effectiveness

We first analyze the overall sensemaking effectiveness of the three paradigms by comparing missed common answers, total task time, and subjective rating of the task difficulty. The quality of sensemaking outcomes is measured by how many common items for Q3-Q10 were not included in the corresponding answers. According to the results, PAR, CON, and MER groups missed 4.78 ($SD = 1.30$), 4.33 ($SD = 1.73$), and 6.67 ($SD = 1.80$) common items respectively ($F_{(2,24)} = 5.22, p = 0.013$, Figure 6.10). A pairwise t-test further reveals that MER groups missed significantly more answers than PAR and CON groups ($p_{(PAR,MER)} = 0.021$ and $p_{(CON,MER)} = 0.006$). MER groups took 41.52 minutes to complete the task ($SD = 6.24$), which was more than the PAR and CON groups ($mean_{PAR} = 36.16, SD = 8.15, mean_{CON} = 34.87, SD = 5.49$). When asked *"how difficult was it to complete this task (1-very easy and 7-very hard)?"*, the MER groups gave an average rating of 4.00 ($SD = 1.58$), which is lower than the PAR and CON groups ($mean_{PAR} = 5.28, SD = 1.13, mean_{CON} = 4.27, SD = 1.18, F_{(2,51)} = 4.32, p = 0.019$, Figure 6.13 (1)). Pairwise comparison shows that MER groups rated the task significantly harder than CON groups ($p_{(CON,MER)} = 0.005$). The results regarding sensemaking effectiveness show that the MER groups had the worst effectiveness, while PAR and CON groups had relatively similar performance.

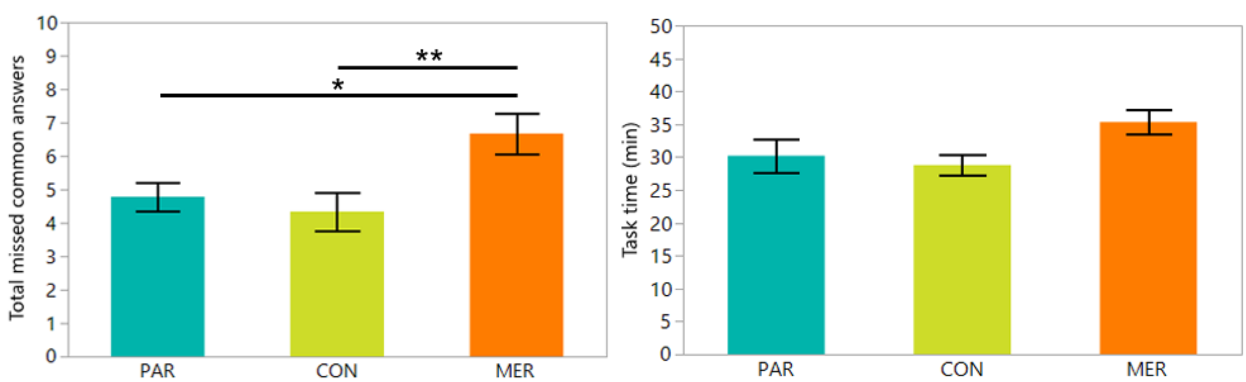

Figure 6.10: Left: the number of missed common items for Q3-Q10. Right: the task time

6.6.2 Collaboration Styles

During the task, participants began with searching all the gear and creating cards, then organized the cards to answer the task questions. Since searching the words was mostly conducted individually without referring to the visualization, the collaboration style analysis only includes the phase after the sensemakers started answering the questions. The analysis of collaboration styles revealed similar collaboration patterns as in previous studies [16, 72, 124]: working in the individual workspaces took the majority of the task time (Figure 6.11). As FIW entails two sensemakers working individually on their own side, this is one of the loosely coupled styles [161]. It was noticed that PAR groups spent more time on FIW ($mean_{PAR} = 43.22\%, SD = 9.67, mean_{CON} = 35.29\%, SD = 6.15, mean_{MER} = 35.43\%, SD = 7.55$). Furthermore, CON groups and MER groups spent more time looking at the shared overview together in FV style ($mean_{PAR} = 6.01\%, SD = 3.39, mean_{CON} = 17.93\%, SD = 6.24, mean_{MER} = 12.91\%, SD = 6.34$), and in both cases this result was significantly higher than that of PAR groups ($F_{2,24} = 10.69, p < 0.001, p_{(PAR,CON)} < 0.001, p_{(PAR,MER)} = 0.014$). Besides working separately in the individual workspaces, PAR groups also spent the most time on FOW ($mean_{PAR} = 20.91\%, SD = 6.88, mean_{CON} = 13.46\%, SD = 3.40, mean_{MER} = 17.71\%, SD = 2.21$), with PAR scoring significantly higher than CON ($F_{2,24} = 5.91, p = 0.008, p_{(PAR,CON)} = 0.002$). MER groups spent more time looking at the tabletop (FT), though no statistical difference was found. From these results, it can be observed that those in PAR groups tended to spend more time working in their personal workspaces, or having one participant helping the other. CON participants spent more time looking at the visualization and seeking the answers together. When collaborating with their partner, MER participants tended to look at the cards on the table rather than the visualization, indicating the limited use of the latter. CON and MER groups spent less time working individually (FIW), suggesting the need to coordinate actions with the partner.

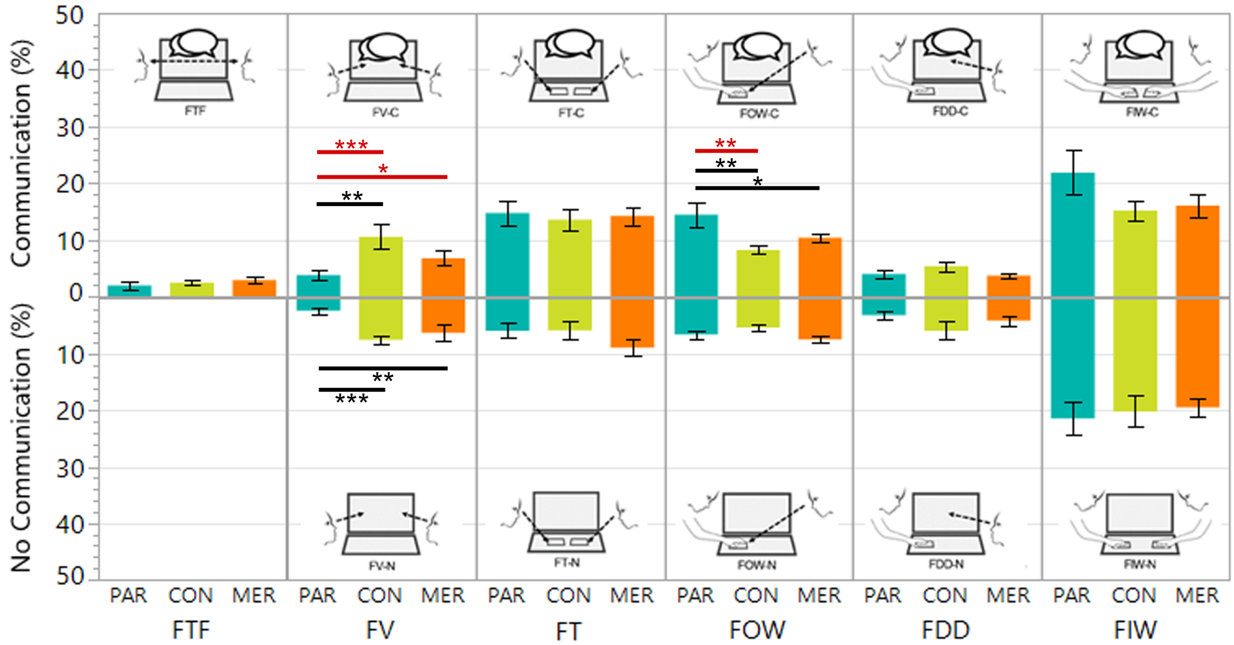

Figure 6.11: Time distribution among six styles of collaboration. Top bars are time with communication. Bottom bars are time without communication. Red horizontal bars show statistical differences between different collaboration styles. Black horizontal bars mark statistical differences between communication sub-styles. Statistical differences are identified by pairwise t-test (p*<0.05, p**<0.01, p***<0.001)

6.6.3 Control, Awareness, and Communication

Control, awareness, and communication are three key co-located space factors in co-located sensemaking. This study seeks to understand whether and how different paradigms to connect or separate group activities affect three co-located space factors. Our analysis of the three paradigms depends associates the video encoding of collaboration styles (Figure 6.11), system logs, and post-study question (Figure 6.13).

Control

In the styles of FOW, FDD, and FIW, sensemakers interact with the digital cards and control the workspace. When comparing the sum of FOW, FDD, and FIW, PAR groups

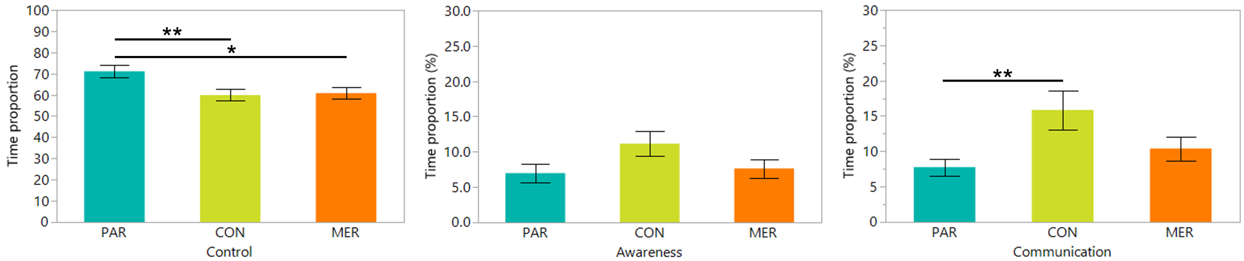

Figure 6.12: The proportion of time spent on styles related to control, awareness, and communication.

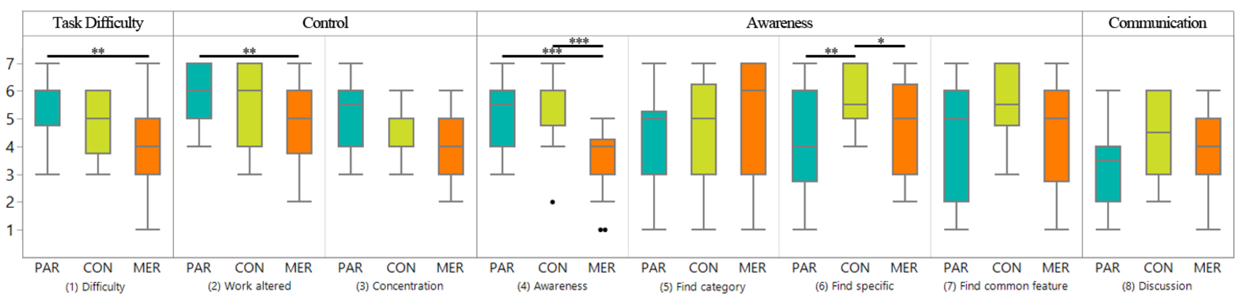

Figure 6.13: Questionnaire results from the three conditions. All questions are Likert-style with a scale of seven. The box plots show the 25%, 50%, and 75% quartiles. The horizontal lines and asterisks indicate statistical differences from the pairwise t-test (p*<0.05, p**<0.01, p***<0.001).

were found to spend more time controlling the interface than CON and MER groups (Figure 6.12 left). PAR groups spent 71.12% (SD = 8.29) time on styles related to control, significantly higher than CON's 59.90% (SD = 8.28) and MER's 60.78% (SD = 8.28, $F_{(2,24)} = 5.11, p = 0.014, p_{(PAR,CON)} = 0.008, p_{(PAR,MER)} = 0.014$). From the system logs, groups with the PAR paradigm also had the highest touch frequency and gave the lowest rating of the level of interference. PAR groups moved the cards more frequently ($mean_{PAR} = 43.48ct/min, SD = 13.12, F_{(2,24)} = 4.77, p = 0.018$, Figure 6.14 left) – significantly more frequently than CON groups ($mean_{CON} = 32.27ct/min, SD = 5.38, p_{(PAR,CON)} = 0.011$) and MER groups ($mean_{MER} = 31.48ct/min, SD = 7.34, p_{(PAR,MER)} = 0.017$). PAR groups moved the cards 1572.67 times on average (SD = 615.92), while CON and MER groups did so 1111.56 times and 1296.67 times (SD = 178.42 and 295.42, Figure 6.14 right). respectively. These results reflect that the groups with the PAR paradigm moved their cards more freely than those in the other two conditions, which indicates higher control over the workspace and shared artifacts.

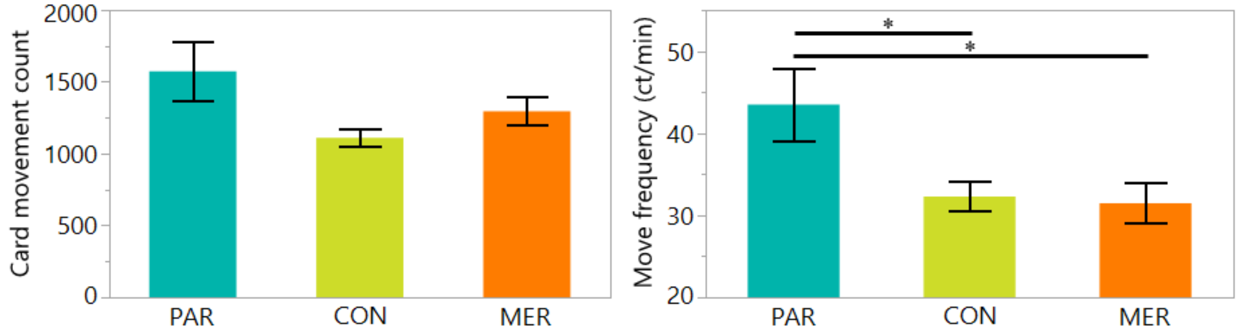

Figure 6.14: Left: card movement count. Right: card movement frequency. Error bars show standard errors. Horizontal lines indicate statistical significance. Same below.

Based on the questionnaire results, PAR participants also felt that their work was less altered by their partner and that it was easier to concentrate on individual work. When asked *"how often did the partner alter the cards you were using (1-always, 4-neutral and 7-never)?"*, the PAR respondents gave an average rating of 6.00 ($SD = 1.08, F_{(2,51)} = 4.18, p = 0.021$), which is significantly higher than the MER groups' rating ($mean = 4.72, SD = 1.49, p_{(PAR,MER)} = 0.006$, Figure 6.13 (2)). PAR participants also found it the easiest to concentrate on their individual work ($mean_{PAR} = 5.05, SD = 1.21$); they rated this higher than the CON and MER groups ($mean_{CON} = 4.72, SD = 0.83, mean_{MER} = 4.28, SD = 1.18$, Figure 6.13 (3)). The results of the two questions suggest that the non-connected paradigm reduces interference between individual work.

Awareness

In the style of FDD, sensemakers consider group activities from the shared visualization. When comparing FDD, PAR groups were found to spend less time monitoring others' work

(Figure 6.12 middle). However, from participants' comments, the shorter time spent monitoring others' work did not mean that PAR groups didn't use the shared overview to maintain awareness. In fact, PAR and CON groups found the visualization more helpful than the tabletop to monitor others' work. When asked whether they found partners' items in the visualization or on the tabletop (1-tabletop only, 4-half/half, 7-visualization only), groups with PAR and CON gave an average rating of 5.17 ($SD = 1.29$) and 5.39 ($SD = 1.29$), significantly higher than MER groups ($mean_{MER} = 3.61, SD = 1.24, F_{(2,51)} = 10.37, p < 0.001, p_{(CON,MER)} < 0.001, p_{(PAR,MER)} < 0.001$, Figure 6.13 (4)). The reason PAR groups spent less time looking at the visualization when the partner is working could be that the parallel paradigm makes it easier to capture others' work, so that it requires less time reading the shared overview. For example, one PAR participant commented the following about the visualization: *"the visualization on the vertical display helped me see what my partner was doing with her cards and help us figure out how to categorize my cards. I also found it useful in searching for a particular card."* Another participant from a different PAR group noted *"the vertical display was useful in collaborating with my partner, except for the fact that it was delayed in updating. However, it was particularly useful in determining what cards my partner had and was the quickest way to see how many tweets were counted in each card pile."* Similar comments were given regarding the CON paradigm. For example, one participant in the CON condition stated, *"the visualization is where most of the collaboration comes in. It helped tremendously to see what the other person was doing"*. However, the links caused confusion when several terms were related: *"(the visualization) allows you to see the related items very easily, but if there are a lot of items on the board then it's sometimes very difficult to see related ones because the lines overlap."* In contrast to PAR and CON, MER group found the connected group items overwhelming and could hinder awareness: *"with large amounts of data, the connecting lines were more distracting than helpful ... (though) it was helpful to be able to see what my partner had."* and *"I think the visualization helped* *very much with tweet counting and finding the largest/most tweeted terms ... however, the relations indicated by the yellow lines were almost useless as they seemed to overlap too much for a user to interpret."* From these results, it was found that participants in the PAR and CON conditions used the visualization to track their partners' work, suggesting that the separation of individual workspaces helped maintain awareness. On the other hand, due to the additional information from interpreting lines in CON, using this paradigm to track others' work cost more effort and lead to more time spent on FDD.

In the question sheet, Q2 asked participants to identify categories; Q3-8 instructed them to identify items related to a specific item; and Q9-11 required them to find items with common features. The post-study questionnaire asked them how useful the visualization was in answering each type of question. The CON paradigm seemed to better support Q3-8 and Q9-11, but did not show a compelling advantage in identifying overall categories (Q2, Figure 6.13 (5)). The CON groups rated the helpfulness of the visualization in finding items related to a specific item as 5.89 ($SD = 1.08, F_{(2,51)} = 5.46, p = 0.007$), which is significantly higher than the ratings of the PAR groups ($mean_{PAR} = 4.17, SD = 1.89, p_{(PAR,CON)} = 0.002$) and MER groups ($mean_{PAR} = 4.72, SD = 1.71, p_{(CON,MER)} = 0.033$, Figure 6.13 (6)). Based on the pairwise comparison, CON also appeared to be superior to PAR and MER in supporting the search for items that shared some common features (Figure 6.13 (7)). The results indicate that besides supporting the monitoring of partners' work, the CON paradigm also helped participants to be aware of related items from the shared workspace.

Communication

Communication and information exchange are forms of close collaboration and center collaborative sensemaking activities [77, 99]. It was noticed that participants in the CON paradigm condition tended to communicate by looking at the visualization and discussing answers together, while PAR groups exchanged cards and determined the answer by following one participant's lead. Though there was no difference in total time of communication, the video analysis revealed that CON groups had more FV-C and FDD-C – the two styles in which at least one participant looks at the visualization and communicates (Figure 6.9). CON groups spent significantly more time looking at the visualization and discussing (FV-C + FDD-C), indicating that they used the visualization as a focus view for discussion ($mean_{PAR} = 7.76\%, SD = 3.63, mean_{CON} = 15.85\%, SD = 8.25, mean_{MER} = 10.34\%, SD = 5.09, F_{(2,24)} = 4.30, p = 0.025, p_{(PAR,CON)} = 0.008$, Figure 6.12 right). However, PAR groups spent more time on FOW-C, with one participant interacting with the cards and the other participant communicating with her or him. The FOW-C for PAR, CON, and MER was 14.43%, 8.21%, and 10.35% ($SD = 6.32, 2.30, and 2.10$), respectively, with PAR scoring significantly higher than CON and MER ($F_{(2,24)} = 5.43, p = 0.011, p_{(PAR,CON)} = 0.003, p_{(PAR,MER)} = 0.044$). When asked whether they looked at the visualization or the tabletop when discussing (1-tabletop only, 4-half/half, 7-visualization only), CON groups indicated looking at the visualization significantly more than the PAR groups did (Figure 6.15 top). CON groups gave an average rating of 4.5 (SD=1.50), while the PAR and MER groups rated this 3.44 (SD=1.38) and 3.83 (SD=1.38) respectively (Figure 6.13 (8)). Connecting personal workspaces encouraged participants to look at the visualization and discuss answers together (Figure 6.16 right).

PAR groups had more cards passed to the partner's space than the CON groups (Figure 6.15 left), and PAR participants performed more movements on the cards created by their partner (Figure 6.15 right). The communication in PAR groups also involved exchanging the cards. CON groups passed 20.89 cards on average ($SD = 2.76$) while the PAR groups passed 26.56 cards ($SD = 6.64$). PAR participants performed more actions on cards created by their partner ($mean_{PAR} = 410.89, SD = 263.02, mean_{CON} = 211.67, SD = 79.00, mean_{MER} =$

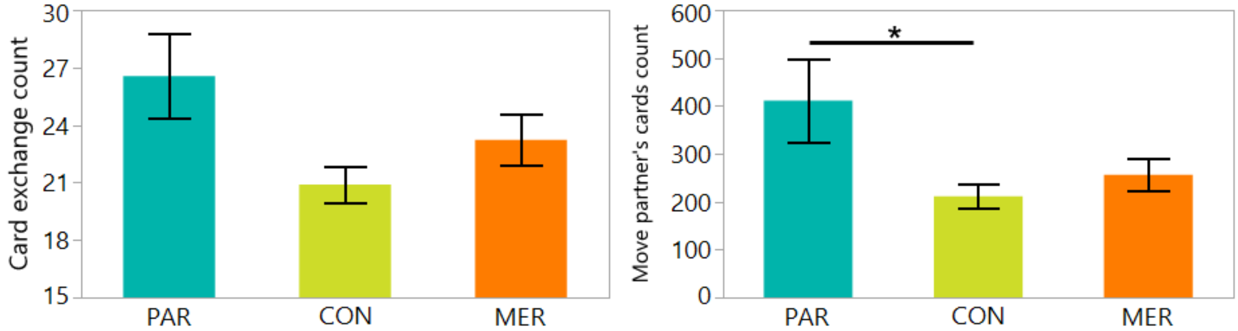

Figure 6.15: Left: number of cards exchanged during the task. Right: card movements performed on the cards created by one participant and passed to the partner.

$256.22, SD = 98.73, p = 0.048$, Figure 6.15 right) – significantly more than in the CON condition ($p_{(PAR,CON)} = 0.019$). Figure 6.17 shows the accumulated move traces of the cards created by one participant but moved to the other participant's workspace. Instead of discussing the answer with the visualization, the PAR groups preferred to pass potentially useful cards to each other and then make the decision (Figure 6.16 left). PAR groups were more likely to have one participant act as the forager while the other led the decision, which suggests that separated workspaces may encourage the assignment of sensemaking roles [172].

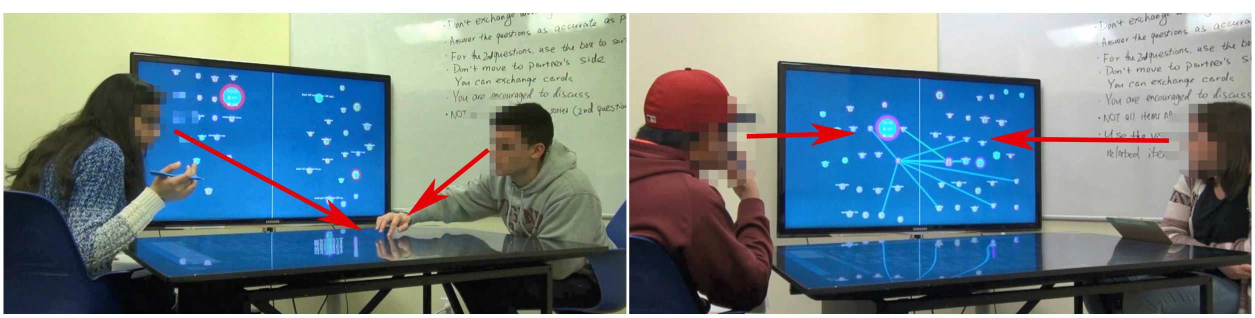

Figure 6.16: Group PAR and CON used different styles of collaboration when answering questions. PAR groups (left) tend to gather useful cards to one's workspace and figure out the number from the visualization. CON groups (right) look at the visualization together and discuss.

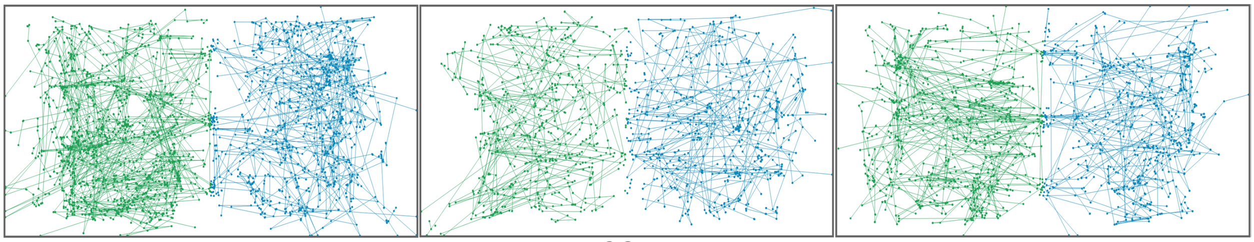

Figure 6.17: Accumulated traces of cards created by the partner. Green lines are traces of cards created by the participant on the right but moved to the left side of the table. Blue lines are traces of cards created by the participant on the left but moved to the right side of the table. PAR groups performed more movements on cards created by the partner than CON and MER groups.

6.7 Discussion

Overviews of sensemaking activities in multi-display environments (MDEs) are effective techniques to support awareness [72, 118] and communication [16, 175]. Prior studies examining overview designs have identified benefits of both separated and connected individual work. This study further investigates the two design choices by comparing different paradigms of collaborative visualization. The three paradigms emphasize the separation of individual work and connection of collaborative work, thus relating to RQ3: *"how do shared overviews connecting related individual work affect individual control, awareness, and communication?"* Based on the experiment results, the following discusses the key findings and implications for MED overview design.

Finding 1: In co-located sensemaking, non-connected individual work (PAR) presented in a shared overview ensures control over the workspace and leads to more interaction with the data representations than having individual work connected (CON and MER).

The PAR paradigm uses separated views without connecting individual work, which leads to higher interaction frequency and movement count with the digital cards. Prior research found that sensemakers who collaborate with separated computers visit more information than those who use one computer [154]. An extra shared screen allows sensemakers to display personal content without interfering with others' projection [138]. This study's results show that more individual interaction with the cards is ensured by the less inter-dependent presentation of group activities. Displaying group work without relating the items of different sensemakers retains the individual control over the tabletop, which reduces interference and leads to more interaction with the digital cards. The higher card movement count and frequency with the PAR paradigm suggest that reducing connections between sensemakers in a shared overview could avoid mutual influence and protect engagement in the personal workspace. When introducing shared overviews in co-located MDEs, designers could consider displaying individual work in parallel to ensure the free interaction with the workspace.

Finding 2: In a shared overview, splitting the visual sections to present individual work (PAR and CON) helps monitor partners' work better than merging items from different sensemakers into one integrated view (MER).

Prior studies on co-located collaboration have suggested that groupware needs to support workspace and activity awareness [20, 54]. On-screen widgets [72, 118] and separated overview displays [16, 175] have been introduced to enhance sensemakers' awareness of others' actions and activities. This study's results indicate that distinguishing others' work from one's own by splitting view spaces makes shared overviews more beneficial in tracking others' work. In this study, the PAR and CON paradigms of VISGRAINS projected the cards on the tabletop to the visualization and displayed individual glyphs separately. The layout of visual representations was not automatically adjusted to integrate group work. Participants with PAR and CON considered the visualization more helpful in finding items from their partner's side. CON also helped them stay aware of their partner's related items and items with common features. The results of this study implied that for MDE overview design, separated individual sections that map personal workspaces could allow the overviews to better support awareness of partners' activities.

Finding 3: Automatically integrating a large amount of individual information could make the shared overview overwhelming and less effective; synthesizing individual work needs to account for complexity and value added to the task.

Prior research has examined the linking of common work to encourage the expression of individual thoughts and the coordination of collaborative activities [99]. Duplicating a shared workspace may not offer enough value to sensemaking tasks [175]. VISGRAINS provides two different ways to link individual work: connecting related items from the personal workspaces when performing actions (CON) and merging all items from the workspaces and generating a layout automatically (MER). In this experiment, MER led to a worse task performance than CON and PAR. MER groups found the fewest key items for the questions, spent the longest time on the task, and gave it the highest difficulty rating. Though both CON and MER link individual work, the higher level of interference and weak awareness with MER reduce its effectiveness. We anticipated participants would use the MER paradigm to identify overall categories and answer question Q2. However, only a few participants noted that they used MER to figure out categories. From the post-study questionnaire, many participants felt the spreading of the circles and connections between words made the visualization hard to use. For example, one MER participant noted *"all of the lines/circles were so close together that I couldn't really see the connections well. We looked at it the first time to try to figure out connections but quickly decided that it was too congested to actually use so we started just looking at the table top. It was helpful to see my partners cards mixed in with mine though."* Another MER participant noted *"the visual display helped a lot in answering the questions as the size indicated how many tweets each card or group of cards had. However the machine learning lines that were drawn between them were hard to read and understand."*

Presenting all information at once complicates the visualization and reduces its benefits of awareness-supporting. Considering that sensemaking activities usually involve large amounts of data representations, overview designers need to be cautious about automatically merging individual work. Designers need to consider the interpretability of the combined individual artifacts and how the connections add value to the sensemaking tasks.

Finding 4: Separated views and non-connected individual items in a shared overview encourage the establishment of sensemaking roles (PAR); overviews highlighting connections between items in individual workspaces encourage joint discussion (CON).

Communication center face-to-face collaboration and led to closer collaboration [77, 99]. Furthermore, closely coupled collaboration is considered to improve sensemaking outcomes [72, 176]. This study's results reveal that sensemakers with different overview paradigms communicate and exchange information in different manners. A prior study suggested that sensemakers establish roles as foragers and sensemakers when collaborating with shared displays [172]. In the present study, participants in the PAR condition passed more cards to their partner's workspace (as the forager) and let the latter lead the task (as the sensemaker). This phenomenon was less intensive in CON groups. The connections in CON bridged the personal workspaces and provided extra information that needed to be interpreted together. Instead of establishing roles and communicating by exchanging cards, the CON groups discussed the answers by looking at the shared overview together. This is in line with prior studies that found that shared overviews serve as a focus of attention and support discussion [16, 99]. Reflecting on these results, it is argued here that when designing a shared overview to support co-located sensemaking, individual work could be more separated if sensemakers have different roles or expertise in the task (e.g., drivers and facilitators). For peer sensemakers who contribute equally, a shared overview connecting related items from individual workspaces could better support discussion [161].

6.8 Chapter Summary

This chapter explores how the techniques in VISGRAINS support the collaborative sensemaking activities identified in Chapter 5. This study examined three paradigms for how shared overviews can affect co-located sensemaking. The PAR paradigm presents individual work separately without connection. The CON paradigm incorporates separated individual sections, but connects related items from individual workspaces. The MER paradigm merges group work together into one integrated visualization. The three paradigms were compared using a co-located Twitter analysis task. The results showed that separating individual work in a peripheral visualization ensures individual control over the workspace. Splitting the visual sections is beneficial in monitoring and staying aware of others' work. Automatically integrated individual work may reduce the use of a shared overview to maintain awareness and discuss sensemaking outcomes. In contrast, separated views encourage the establishment of sensemaking roles, while overviews with connections between items in individual workspaces support discussion with a shared visualization. Based on this study, the following points address sub-question S2, *"how do sensemakers work individually and collaboratively with a shared tabletop?"*, S3, *"what are the ways to connect and present related individual work?"*, S5, *"how do shared overviews presenting group work affect co-located space factors?"*, and S6, *"how do shared overviews lead to different styles of collaboration?"*

- S2: Sensemakers working with a shared overview that does not connect individual work leads to more simultaneous control.
- S2: Connecting related items from personal workspaces encourages joint attention and discussion using the shared overview.
- S3: Connecting individual workspaces outperforms merging items into one view; the former supports awareness and discussion, while the latter requires effort to interpret

connections and coordinate actions.

- S5: A non-connected overview leads to the highest individual control; separating workspaces encourages awareness; and connecting individual work better supports communication.
- S6: Separated views and non-connected individual work lead to the establishment of sensemaking roles; connecting individual workspaces encourages joint discussion with the visualization.

This research examined three paradigms for how shared overviews can affect co-located sensemaking in a multi-display environment. The PAR paradigm presents individual work separately without highlighting connections. The CON paradigm shows separate individual sections, but shows connections between related items in individual workspaces. The MER paradigm merges group work together into one integrated visualization. The three paradigms are captured in a MDE-based sensemaking system, VISGRAINS, which supports information searching, creation of search representations, and organization of retrieved information. The three paradigms were compared using a co-located Twitter analysis task. The results showed that separating individual work in a peripheral visualization ensures individual control over the workspace. Splitting the visual sections is beneficial in monitoring and staying aware of others' work. Automatically integrated individual work may reduce the use of a shared overview to maintain awareness and discuss sensemaking outcomes. In contrast, separated views encourage the establishment of sensemaking roles, while overviews with connections between items in individual workspaces support discussion with a shared visualization.

Merging individual work did not support awareness of the overall situation. The complexity introduced by the MER paradigm makes it hard to interpret the relationship between the combined individual items. Future design needs to consider and explore different design options which facilitate the interpretation of the overall sensemaking situation. This research explored a task which asks sensemakers to forage for information, figure out relationships, and organize the data representations to generate knowledge structures – in a path of bottom-up sensemaking. It is unknown how visualization of different paradigms could facilitate the top-down path of problem-solving, as sensemakers interpret the overall situation first, select and filter necessary information, and solve problems regarding details. It is valuable to compare how different visualization paradigms support different problem solving approaches; e.g., by asking whether your partner altered your work. In this study, sensemakers are required to agree upon the answers to the questions. The post-study survey asked questions regarding the experience of collaboration. However, we did not set up tasks and questions to explicitly measure agreement of individual work. Future work will also explore tasks in which sensemakers may contribute differently, while common understanding can be visualized to promote reaching the common ground.

Chapter 7

Conclusions and Future Work

This dissertation explored how awareness-supporting techniques in co-located sensemaking spaces connect individual work and affect collaboration. Notifications and collaborative visualizations were explored as two common techniques to connect related items from individual work. They affect individualness and collaborativeness of co-located sensemaking through individual control, awareness, and communication. The study in Chapter 3 examined simultaneous interaction and sequential interaction during an ideation task to explore how people worked individually or collaboratively with a multi-user multi-touch tabletop. The study in Chapter 4 introduced notifications in the personal workspace to support action, social, and activity awareness. It was found that individual control, social communication, and team performance were affected by notifications. The study in Chapter 5 examined connecting topics from personal work, and the results showed that searching and connecting related topics centered re-visitation and knowledge sharing activities with a large social media collection. Chapter 6 investigated how to support searching and connecting individual work in a shared visualization and studied how three paradigms of shared overviews affected collaboration. The present chapter summarizes the results of the four studies and extends the findings to the tradeoffs between control, awareness, and communication in awareness-supporting design.

7.1 Connecting Individual Work in Co-located Sensemaking Space

Connecting related items from individual work is a promising technique to raise awareness and encourage discussion. The visualized relationship between items from individual workspaces suggests partners' items that one needs to be aware of, with the potential to interrupt individual control and trigger discussion about common work. The four studies presented in this dissertation explored collaboration styles, notification, and shared overviews in co-located sensemaking, to understand how awareness-supporting techniques affect control, awareness, and communication. This section summarizes the findings regarding each research question, as described in Figure 7.1

Chapter 3 focused on RQ1 and examined simultaneous and sequential interaction on a multi-user tabletop. This study found that the personal *control* over the workspace is preferred to be always simultaneously available, while the *awareness* maintenance and *communication* lead to sequential interaction (S1). Despite providing technology and encouragement in support of simultaneous interaction, sequential interaction is the dominant collaboration technique with the multi-user touch display (S2). The rich and simultaneously manipulable digital materials facilitate idea generation, but the organization and synthesis of the ideas require a less interruptive and distracting approach to collaborate over the shared materials (S2).

Since maintaining awareness is an important group activity and leads to the collaborativeness of sensemaking, Chapter 4 examined collaborative notifications in a card-sorting task (RQ2). This study found that notifications affect social, action, and activity awareness through individual control, new awareness acquiring paths, and more efficient communication (S1). When presenting notifications, one needs to realize the tradeoff between the intrusion in the individual's control and the increased awareness of others' alternative thoughts (S3). Notification-supported communication can increase the efficiency of the collaborative task exchanges, but may reduce the expression of alternative ideas (S4). Notifications improve collaborators' ability to work independently, especially for collaborative tasks that are suitable for divide-and-conquer, thus improving simultaneous work (S4).

Notifications do not provide enough visual cues to support discussion. In fact, increased action and activity awareness reduces conversation. The in-workspace notifications also interrupt individual control and decrease willingness to express alternative opinions. Two studies (Chapters 5 and 6) were conducted to explore RQ3 and examine how a collaborative visualization on a peripheral display could offer shared overviews to reduce interruptions in personal work and trigger communication. Chapter 5 presented the researchers' experience designing and deploying BlogCloud. It was concluded that connecting retrieved topics in a visualization offers new materials and pathways to support data interpretation (S3), and that visualization of reorganized topics offers new methods of individual exploration, raises awareness of related data, and generates new perspectives to trigger potential discussion (S5). Chapter 6 presented a study on VISGRAINS – a collaborative sensemaking system for searching and organizing search results. VISGRAINS incorporates a shared overview to support group activities. This study found that working with a shared overview that does not connect individual work leads to more interaction of the sensemakers with the data representations (S2). Connecting related items from the personal workspace encourages joint attention and discussion using the shared overview (S2). Connecting individual workspaces is a better way to indicate related items between individual work than merging all items together (S3). A non-connected overview yields the highest individual control, separate workspaces encourage awareness, and connecting individual work better supports communication (S5). Furthermore, separate views and non-connected individual work lead to the establishment of sensemaking roles, while connecting individual workspaces encourages joint discussion (S6).

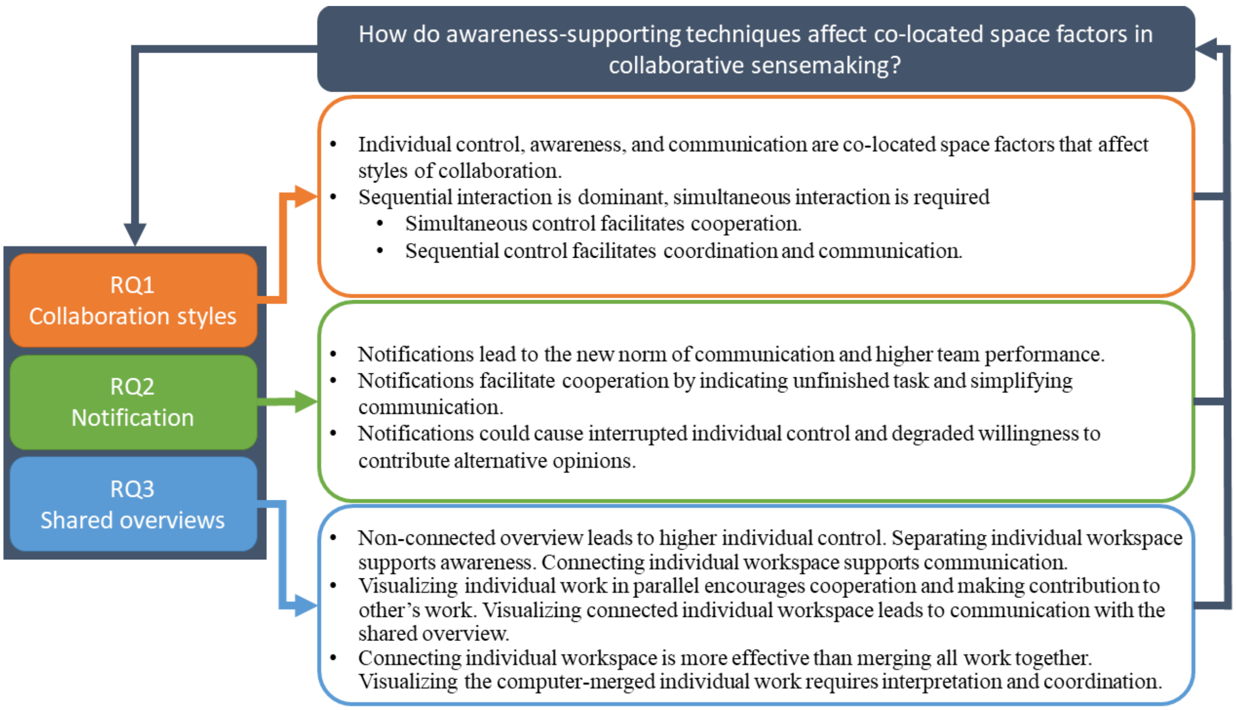

Figure 7.1: A summary of the research questions.

7.2 Summary of Research Sub-questions

The four research studies explored the three research questions by answering the six sub-questions, as illustrated in Figure 1.3. This section addresses the sub-questions with the findings from the four studies.

S1 was, *"what co-located space factors determine the styles of collaboration?"* The study on simultaneous and sequential interaction indicated that the need to maintain awareness and communicate makes collaborativeness superior to individual control in co-located sensemaking. The second study found that notifications affect social, action, and activity awareness through individual control, new awareness acquiring paths, and more efficient communication and better team performance. From the two studies, it is concluded that control, awareness, and communication determine the individualness and collaborativeness of sensemaking collaboration.

S2 was, *"how do sensemakers work individually and collaboratively with a shared tabletop?"* The study in Chapter 3 found that despite providing technology and encouragement in support of simultaneous interaction, sequential interaction was the dominant collaboration technique. The rich and simultaneously manipulable digital materials facilitate idea generation, but the organization and synthesis of the ideas require a less interrupting and distracting approach for sensemakers to collaborate over the shared materials. The study in Chapter 6 explored shared overviews and found that working with a shared overview that does not connect individual work leads to more simultaneous work. Connecting related items from personal workspaces encourages joint attention and discussion using the shared overview. Based on these findings, it is concluded that in co-located sensemaking with a shared tabletop, the need to maintain awareness and communicate makes sensemakers spend more time working collaboratively. Less connected individual work in a shared overview increases individual control, but decreases the joint discussion using the collaborative visualization.

S3 was, *"what are the ways to connect and present related individual work?"* This dissertation examined two ways to do this: notifications and collaborative visualization. When presenting notifications to connect related individual work, one needs to realize the tradeoff between interrupting the individual's on-going task and the need to discuss alternatives and new possibilities brought by others' actions (Chapter 4. Sensemakers explore large personal data by searching for key memories. Connecting retrieved topics in a visualization offers new materials and pathways to support data interpretation (Chapter 5). Connecting individual workspaces outperforms merging items into one view; the former supports awareness and discussion, while the latter requires effort to interpret and is thus less effective (Chapter 6). Addressing this research question highlights the tradeoffs required by awareness-supporting techniques. When connecting individual work, it is necessary to be aware of how it affects different co-located space factors.

S4 was, *"how do notifications supporting awareness affect co-located space factors?"* This sub-question generally concerns how notifications affect co-located sensemaking. This study showed that working in parallel with notification-supported communication can increase the efficiency of the collaborative task exchanges, but notifications may reduce the expression of alternative ideas due to awareness of others' decisions. Notifications improve collaborators' ability to work independently, especially for collaborative tasks that are suitable for divide-and-conquer, thus improving team efficiency through simultaneous and synchronized work.

S5 was, *"how do shared overviews presenting group work affect co-located space factors?"* This question was explored through two studies. An examination of BlogCloud found that visualization of reorganized topics offers new methods of individual exploration, raises awareness of related data, and generates new perspectives which could trigger potential discussion. An investigation of VISGRAINS revealed that a non-connected overview leads to the highest individual control; separating workspaces encourages awareness; and connecting individual work better supports communication.

Finally, S6 was, *"how do shared overviews lead to different styles of collaboration?"* The study in Chapter 6 found that separate views and non-connected individual work lead to the establishment of sensemaking roles, while connecting individual workspaces encourages joint discussion using the visualization. The encoding of collaboration styles showed that though working individually is still the primary way to collaborate, connecting individual work reduces simultaneous individual work. When there is no connection between individual work, sensemakers tend to take on roles in the collaboration. One sensemaker interacts with the cards and the other makes comments, leading to more contribution to the partner's work. When the shared overview connects individual work, the collaborative visualization offers a visual space for sensemakers to look at and discuss together.

7.3 Control, Awareness, and Communication

From the experience of designing, implementing, and experimenting with the four collaborative sensemaking systems, a deeper understanding was gained of awareness-supporting techniques in affecting control, awareness, and communication, as three key co-located space factors. Figure 7.2 summarizes how awareness-supporting techniques affect different aspects of control, awareness and communication.

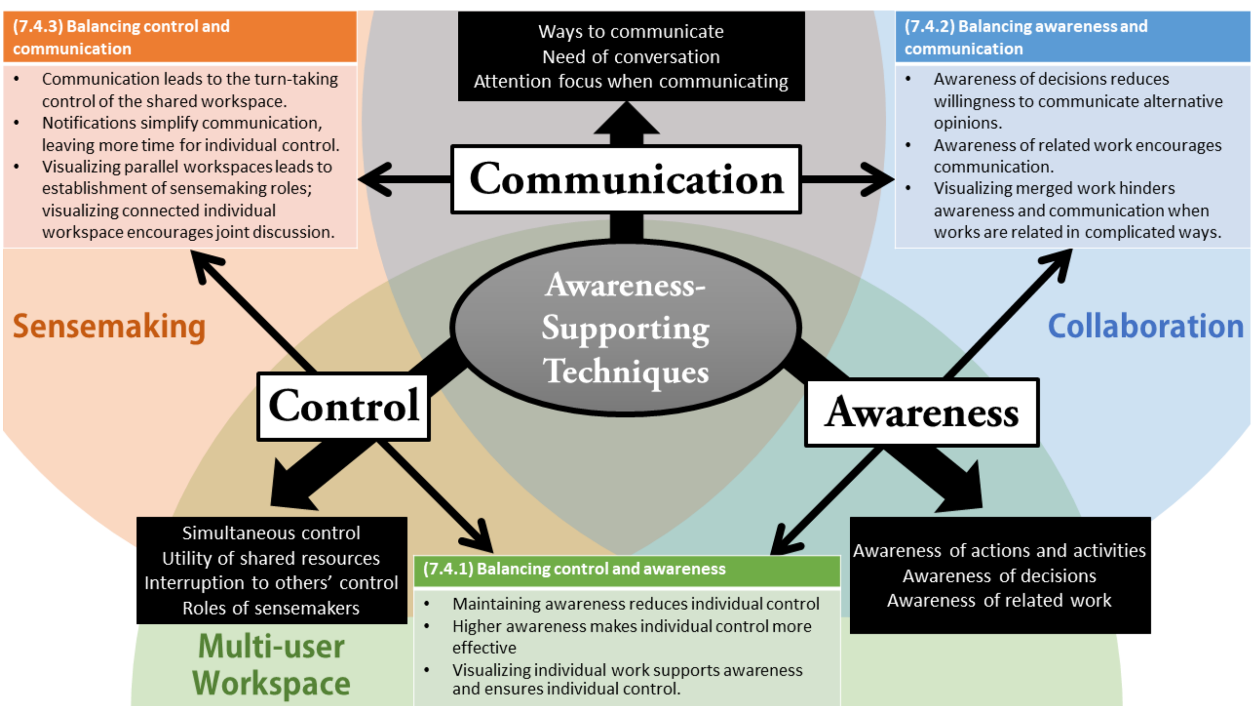

Figure 7.2: How awareness-supporting techniques affect and balance control, awareness, and communication in co-located sensemaking.

7.3.1 Control

Individual control over the shared multi-user workspace determines individual ability to participate in the sensemaking task. Gutwin argued that individuals demand powerful and flexible means of interacting with the shared interface in co-located collaboration [55]. Yuill and Rogers defined control of action as the extent to which the user can control actions and decisions [181]. Multi-user multi-touch devices such as tabletop displays add flexibility to support users in gaining more individual control over their actions [181]. Morris argued that division of labor is important to sensemaking tasks, especially when dealing with large amounts of information [113].

This dissertation explored how awareness-supporting techniques affect individual control during co-located sensemaking. When collaborating with a tabletop display for an ideation task (Chapter 3), due to the need for social communication and coordinating access to collaborative territory, sensemakers spend more time taking turns to interact instead of working simultaneously. When incorporating notifications to inform actions (Chapter 4), sensemakers perform more actions on the unfinished task. However, these notifications are also a source of interruption. Sensemakers pay attention to the card indicated in the notification and are less likely to express alternative opinions. A peripheral visualization reduces interruptions in the individual workspace, and presents and connects items created by different sensemakers. By examining the three paradigms of the shared overview, it was found that connecting related items from individual workspaces reduces actions performed on digital objects. Presenting individual work in parallel increases the control over data representations. With parallel paradigms, sensemakers can work at the same time and form sensemaking roles to improve cooperation. When useful items are gathered in one sensemaker's workspace, the task depends on that sensemaker's control, and other sensemakers can contribute to the decision makers' work.

Control over the individual workspace affects the level of cooperation with the multi-user multi-touch interface. When accessing shared resources, sensemakers need to coordinate actions regarding the data representations, which reduces the simultaneous control of the workspace. Notifications indicate the completed work, serving as a technique to indicate which cards to look at and affect the utility of shared resources. However, reacting to notifications makes sensemakers to shift attention and cause interruption to individual control. The collaborative visualization that separates individual work ensures individual control over the personal workspace. Sensemakers with individual work in parallel tend to establish different roles and control the individual workspaces in different ways – one sensemaker forages for useful information and the other sensemaker organizes and makes sense of the data. The findings from the studies demonstrate that awareness-supporting techniques affect individual control in co-located sensemaking from the following aspects:

- Simultaneous control
- Utility of shared resources
- Interruption to other's control
- Roles of sensemakers

7.3.2 Awareness

Supporting awareness is a critical issue in collaborative sensemaking systems [153]. Dourish defined awareness as "understanding of the activities of others, which provides a context for your own activity" [30]. Gutwin and Greenberg noted that workspace awareness – the up-to-the-moment understanding of another person's interaction with a shared workspace – needs to be supported by co-located systems [53, 54]. Notifying collaborators of each other's interactions could support their action, social, and activity awareness [20].

The awareness-supporting techniques studied in this dissertation provide awareness information and directly affect awareness. Interacting in turns is a natural way to maintain awareness of others' actions. Notifications affect activity awareness by indicating others' actions. Sensemakers working with notifications have better awareness of the completed tasks and could avoid duplicating others' work. When presenting group activities with a shared visualization, separating individual workspaces makes it easier to monitor others' work. When connecting related items together, a shared overview helps sensemakers be aware of others' related work, providing extra awareness information to support the creation of information subsets to answer sensemaking questions.

Awareness in co-located sensemaking affects different styles of collaboration. When cooperating, sensemakers need awareness of the task roles and plans, to work at the same time. Notifications supporting awareness of others' work coordinate the actions and activities and improve the efficiency of the team work. High awareness of simplifies the conversation needed to coordinate the collaborative work, and helps reduce redundant work. However, the awareness of others' decisions reduces expression of alternative thoughts. A collaborative visualization on a peripheral display allows sensemakers to maintain action and activity awareness from a shared space, to enable them to contribute to the collaborative work through a shared overview. When presenting similar items in a shared overview, the awareness of related work encourages communication. Concluded from the studies, following key aspects of sensemaking awareness are affected by awareness-supporting techniques:

- Awareness of actions and activities
- Awareness of decisions
- Awareness of related work

7.3.3 Communication

Encouraging communication is an important way to promote close collaboration and make sensemaking more effective [46]. Close collaboration relies on effective communication between sensemakers and generally leads to better sensemaking outcomes [72, 161, 175]. A large interactive display offers an open space to support face-to-face discussion [55, 77]. Prior studies have noted that face-to-face conversation is still the major way to communicate findings and coordinate actions [72, 100]. However, besides conversation, sensemakers could also use awareness-supporting widgets indicating others' work to exchange information [92, 123]. The awareness-supporting techniques not only present other's work, but could also trigger conversation [72, 118].

This research showed that communication affects how the shared interface is used and the ways to exchange information. The need to talk about the sensemaking task leads to sequential interaction with the shared artifacts. Notifications in co-located space serve as an alternative channel besides verbal communication. Sensemakers give touch reactions instead of verbal feedback, simplifying the conversation and leading to more interaction with the digital cards. Data mining and visualization could reorganize the data to bring up new perspectives. When collaborating with a shared overview, though different visualizations do not affect the amount of communication needed to complete the task, groups with individual work connected by the system prefer to look at the visualization and discuss the answer. This indicates that presenting related items from personal work encourages joint thinking and facilitates communication.

Encouraging communication is essential to awareness-supporting techniques [99]. Awareness obtained from notifications facilitates the coordination of the sensemaking task and simplifies the conversation. Sensemakers give touch response, instead of verbal confirmation, as an alternative way of communication. However, the high awareness of others' decisions also reduces sensemakers' willingness to communicate an alternative idea. A shared overview on a peripheral display offers an extra visual space to observe others' work. Different paradigms to present group activities in a shared overview lead to different ways to communicate as well. When individual work is presented in parallel, sensemakers take on roles, with one sensemaker contributing related items and the other making the decision. Presenting information about related items from individual workspaces makes the collaborative visualization a focus to discuss group work. Awareness-supporting techniques lead to different attention focuses when communicating by separating or connecting individual work. Based on these findings, the following aspects about communication are affected by awareness-supporting techniques:

- Verbal confirmation
- Ways to communicate
- Attention focus when communicating

7.4 Awareness-Supporting Techniques and Co-located Space Factors

The four studies explored notifications and collaborative visualizations as two major awareness-supporting techniques to connect individual work and support sensemaking collaboration. This section summarizes these findings and answers the question, *"how do awareness-supporting techniques affect co-located space factors in collaborative sensemaking?"* This extends the findings from S1 to S6, focusing on the design tradeoffs brought by awareness-supporting techniques between control, awareness, and communication. Figure 7.2 summarizes how notifications and collaborative visualizations balance the three co-located space factors – control, awareness, and communication, as described in Figure 7.2.

7.4.1 Balancing Individual Control and Awareness

Maintaining awareness during co-located sensemaking costs time and makes sensemakers pause individual work [55]. The study on simultaneous and sequential interactions with tabletops showed that participants preferred to have an always-open individual space and full control over the personal cards. Being able to work simultaneously allows sensemakers to forage for more information, potentially expanding the scope of ideation [154]. Presenting the cards in the collaborative space storing the sensemaking group work, sensemakers communicate about the collaborative task and take turns making contributions. The need to coordinate actions to make changes leads to sequential interaction. Individual simultaneous interaction is seceded to maintaining awareness of the changes made to the shared work, reflecting the tradeoff between individual control and awareness.

Awareness-supporting technique such as notifications can affect the tradeoff between control and awareness by reducing the effort to monitor partners' work. Notifications indicate partners' work in one's own workspace, allowing sensemakers to be more focused on the unfinished task and avoid duplicating others' work. However, the awareness-supporting widgets in the personal workspace also introduce interruptions and distractions in personal work, which restricts personal control.

Using a collaborative visualization to present group work offers peripheral awareness without directly interrupting individual control, but designers need to understand how to present group work to balance the tradeoff between individual control and showing awareness information. Based on this study, presenting individual work in parallel offers the best support for both control and awareness. A sensemaker can monitor his or her partner's work using the visualization, even if actions are being performed in the partner's personal workspace. By presenting work in parallel, sensemakers can directly read the visualization to quickly capture what the partner is doing. Monitoring each other's work with fewer interruptions allows sensemakers to perform more actions on the data representations.

From these findings, it is concluded that individual control and maintaining awareness are both important to co-located sensemaking but need to be balanced. Maintaining awareness could surpass individual control when working on shared resources. Awareness-supporting techniques offer approaches to reduce the effort of maintaining awareness and make individual control more effective. To reduce the interruption introduced by awareness-supporting techniques, a shared visualization presenting group work in parallel could help sensemakers monitor each other's work in the co-located space. Non-connected individual work reduces the interference between sensemakers and increases the control over the data representations in the personal workspace. The balances between control and awareness can be summarized:

- Maintaining awareness reduces individual control.
- Higher awareness makes individual control more effective.
- Visualizing individual work supports awareness and ensures individual control.

7.4.2 Balancing Awareness and Communication

In co-located sensemaking, awareness and communication center the group activities to distribute tasks and integrate findings. Multi-user devices such as interactive tabletops offer open space for face-to-face communication and observing others' actions. The design of awareness-supporting techniques has to consider the tradeoff between supporting awareness and triggering conversation. High awareness of one's partner's work does not mean that two sensemakers communicate intensively to exchange information. In the study on co-located notifications, sensemakers relied on notifications to exchange information, instead of observing others' actions and giving feedback. High awareness in fact simplifies the information exchange and leads to fewer conversations. The notification design in this study only indicated what the partner was doing, without suggesting ways to integrate alternative opinions. With high awareness and less communication, sensemakers did not contribute alternative thoughts or change others decisions.

The study on BlogCloud highlighted the importance of *reorganization*. Even though they crafted it themselves, bloggers did not recognize the similar content along the time stream. NLP and visualization cluster the related items and raise awareness of different topics. Reminiscing on particular experiences leads to the discussion of related topics. When designing shared overviews, one also needs to understand how to balance awareness and communication. In the study on VISGRAINS, the parallel paradigm and connected paradigm offered better support to observe partners' work. However, connecting related work further supported awareness of related items between individual work. Collaborative visualizations designed for awareness support (like the PAR paradigm of VISGRAINS) may not attract intensive joint attention. Sensemakers read others' work quickly and are more focused on individual work. Data processing techniques and machine learning could associate group work in an automated manner and offer additional information to facilitate communication. Sensemakers can rely on the computer-identified information to interpret group activities and direct sensemaking, but connecting individual work to support communication also needs to balance awareness. Automatically integrating all individual work may make the visualization overwhelming, which would hinder awareness and communication.

Reflecting on the results of the presented studies, it is concluded that awareness-supporting techniques in co-located sensemaking systems need to balance awareness and communication. A simple action indicator may quickly deliver awareness information, but could also reduce the perceived need for communication, and especially the expression of alternative opinions. Using data processing techniques such as NLP and machine learning could help sensemakers to mine related topics and communicate findings. Collaborative visualization could show how individual work is related to raise awareness of ways to collaborate, but the awareness and complexity of connections need to be balanced. The balances between awareness and communication can be summarized:

- Awareness of decisions reduces willingness to communicate alternative opinions.
- Awareness of related work encourages communication.
- Visualizing merged work hinders awareness and communication when works are related in complicated ways.

7.4.3 Balancing Individual Control and Communication

Similar to awareness, the need to communicate with others in a face-to-face environment also interferes with individual control. However, in contrast to awareness, initiating communication with others interrupts partners' individual work. In the study on simultaneous and sequential interaction, sensemakers contributed to group work in the group territory. Sensemakers performed actions in the center of the table and communicated about ideas at the same time. Some semantic actions like zooming in on the card to emphasize importance occupied the collaborative space, blocking others from controlling the group work. The need to communicate about findings led to sequential interaction with the tabletop.

Notifications in the co-located sensemaking system bring others' actions and activities into one's own workspace, forming an alternative channel to communicate with one's partner. Lee et al. discussed the three spaces in the co-located collaboration [91]. In addition to the social channel, the notification system enhanced the "digital space" with the ability to synchronize group activities. In this study, sensemakers performed immediate actions on the cards indicated in the notification, as the primary way to react to their partner's decision. This new social norm reduced the verbal communication happening in the co-located space. In fact, prior studies have suggested that communication to coordinate group work is a high-cost way to exchange sensemaking knowledge [54, 92]. A reduced need to communicate about others' actions increases the control over personal work. Exchanging information through notifications allow sensemakers to better cooperate by divide-and-conquer, which improves the overall team performance.

Collaborative visualizations with data processing techniques such as NLP and machine learning augment individual control by offering new ways to retrieve and re-visit the data. The study on BlogCloud found that bloggers searched their memory to re-visit their large amounts of personal content, and interpreted and communicated about connections between different experiences. Sensemaking systems could leverage the ability of visualization and data processing techniques to increase individual control and provide materials for discussion. In the study on VISGRAINS, the PAR paradigm directly presented individual work without connections. Sensemakers took on the roles of decision maker and information forager. The CON paradigm automatically connected individual workspaces and offered a shared overview to discuss group activities, despite the reduced individual control over the data representations. This indicates that awareness-supporting techniques can not only be the channel of communication, but can also associate individual actions to provide a shared space to facilitate discussion.

The findings from the four studies suggest that synchronizing awareness information by face-to-face communication leads to the turn-taking control of the workspace. There are opportunities to use awareness-supporting techniques such as notifications and data visualizations to enhance individual control and support communication. It is especially promising to support collaborative sensemaking during data-intensive tasks. When dealing with large amounts of data, individual control over the workspace involves more foraging and organizing actions with the data representations. Designers should consider notifying users of others' work to reduce the effort needed to communicate less important decisions and thus increase the efficiency of individual control. Designers could also leverage visualization and machine learning to further process the data and augment individual control, which could offer new collaborative information for joint discussion and promote closer collaboration. The balances between control and communication can be summarized:

- Communication leads to the turn-taking control of the shared workspace.
- Notifications simplify communication, leaving more time for individual control.
- Visualizing parallel workspaces leads to establishment of sensemaking roles; Visualizing connected individual workspace encourages joint discussion.

7.5 Future Directions

As an important life and work activity, sensemaking needs to be facilitated by future computer-supported collaborative technologies and interaction designs. This research explored notifications and collaborative visualization as two awareness-supporting techniques to affect individual control in co-located sensemaking. However, this work is limited in several ways. First, this study examined tabletop interfaces that offer simultaneous touch interaction and a face-to-face environment. However, common collaborative tools for sensemaking also include multiple tablets, laptops, and tabletop computers, and a combination of devices with different form factors. Awareness-supporting techniques might introduce new group behaviors and activities when collaborating with different devices and systems. Second, the task scenario examined in this research looked at pairs or trios of co-located sensemakers working on a 20-60 minute sensemaking task. In the increasingly complex work scenarios, however, collaborating with larger groups calls for new sensemaking tools. Even small teams could use interactive display technologies to reflect on long term collaboration. The design knowledge identified in this dissertation will be re-examined with a comparison between short-term scenarios like workshops or conference settings where sensemakers come together for a few hours or days and long-term scenarios like committed organizations where sensemakers collaborate on a daily basis using our techniques. It is reasonable to consider factors like group size, different member relationships, length of collaboration, and categories of sensemaking tasks in future studies. Third, with the advancement of communication technologies, the definition of "co-locatedness" has also changed. Some sensemakers may be physically co-located while others virtually join the collaboration through video conferencing tools. How technologies that connect individual work affect sensemaking activities needs to be examined with virtual co-location scenarios. Forth, this research only covered sensemaking tasks completed by small groups dealing with hundreds of data representations. The sensemaking task can be scaled in two directions: a large group, such as a social media community, dealing with a situation and making sense of the data and information; and a group of collaborators dealing with a large dataset which requires data processing techniques to connect individual contributions. The former requires sensemaking tools to associate the activities of a large stakeholder group; the latter needs to increase individual ability to retrieve and connect big data. When developing future awareness-supporting techniques, one should consider how to incorporate machine learning and data visualization in design to support larger-scale collaboration.

Moving forward, I will keep seeking design knowledge on sensemaking systems, along with more human-centered applications, to solve the complexity of collaboration in data-intensive tasks. Rooted in my prior research, my future work will aim to expand visualization-, NLP-, and machine-learning-supported collaboration.

During co-located events such as conferences, workshops, and exhibitions, people come together and share life and work experiences. Participants' digital life records such as blogs and social media posts collectively form a large repository of stories and memorable moments. However, recognizing and presenting related experiences from this repository is challenging, which makes life data underutilized to connect people. Visualizing the same or related experiences inspires conversation and supports social exchange. I plan to promote the idea of event mining: how to collect, connect, and present event participants' collective experiences through the design of NLP and data visualization. I am interested in examining systems for event data exploration, for people to understand each other and identify common interests.

Global events, such as festivals, elections, natural disasters, and public incidents, attract public attention. Social media users generate large amounts of content about such events, from which stakeholders can browse, analyze, and study public opinions and identify trends in events. However, in general, there is a small degree of understanding of how people configure different interests when making sense of event data together. I am interested in building and evaluating systems on large interactive displays to help co-located analysts explore event trends. I plan to design and study NLP and data visualization methods for monitoring, understanding, and tracking events.

Data has augmented collaborative design, and public opinions are playing more important roles in supporting planning and design. Tasks such as public event planning, infrastructure design, and product and service design benefit from incorporating people's opinions. I am interested in studying how to incorporate NLP and visualization to mine useful information from large social media datasets and to support collaborative interaction on large interactive displays. As a continuation of the current work, I plan to examine design solutions to present and connect people's ideas to data processing approaches and to explore how people use the shared display and data presentations to evaluate decisions.

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Appendices

Appendix A

Study Materials

A.1 Example of Cards used in the Notification Study

2/9/2016

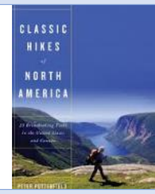
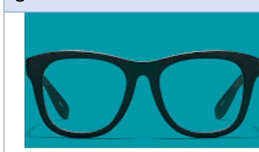
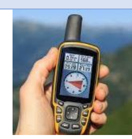

New York City, NY, 1 days,
$1200

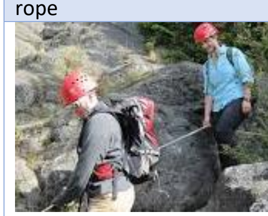
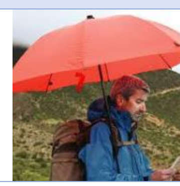

Boston, MA, 1 days, $1400

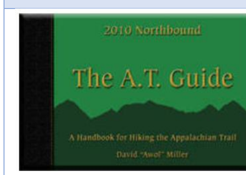
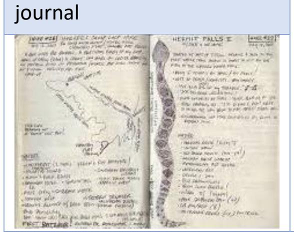

Denver, CO, 1 days, $1500

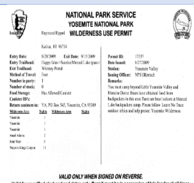
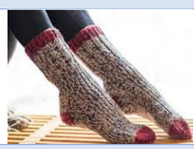

Orlando, Fl, 2 days, $1600

A.2 Hiking Gears Provided to the Participants

bear canister 	Plastic bin with a cover. It stores food in a canister to prevent bears from taking it.	book 	To be brought along either for pleasure or for helpful information that can be used as reference when hiking specific trails.
camera 	Device that would allow a hiker to take photos.	compass 	Instrument with a magnetized pointer that shows the direction of magnetic north and bearings from it. Can be used alongside a map for direction in the case where a GPS is unavailable.
energy drink mix 	Powdered drink mix that can be added to water. Can help with hydration and provide electrolytes and energy to the hiker.	glasses 	Corrective lenses for hikers to help avoid issues with vision.
GoPro 	Compact action camera capable of capturing photos and video in extreme conditions.	GPS 	Global Positioning System. Used to determine a user's exact location, velocity, and time 24 hours a day, in all weather conditions.
hat 	Can protect the wearer from sun, wind, and various weather conditions.	iPhone 	Allows the hiker to stay connected to the outside world – make calls in the case of an emergency and stay connected with people.
knife 	Sharp cutting blade that can be used for cutting or as a weapon when outdoors.	parka 	Insulated, waterproof coat with a hood that will protect from various hazardous weather conditions (wind, rain, cold, etc.)
peanut butter 	Paste of ground roasted peanuts, usually eaten spread on bread.	protein bar 	Provide protein/calories in a compact, easy to digest, and shelf stable package.

repellent 	Substance applied to skin, clothing, or other surfaces that discourages insects from landing or climbing on that surface. Known as insect repellent or bug spray.	rope 	Length of strong cord made by twisting natural fibers. Used for climbing, hanging up food to prevent animals from taking it.
rucksack 	Bag with shoulder straps that allow it to be carried on someone's back, typically made of a strong, waterproof material and widely used by hikers; a backpack.	sandals 	Opened toed shoes. Can be used for hiking in the summer. Can be used for wet and uneven ground.
spork 	Spoon-shaped eating utensil with short tines at the tip. Can be used as both a spoon and a fork.	stove 	Portable stove designed to be portable and lightweight. Used in camping, backpacking, or other use in remote locations where an easily transportable means of cooking or heating is needed.
tarp 	Lightweight and waterproof. Can be used as cover for sleeping with a hammock or sleeping bad.	tea 	Drink made by infusing dried, crushed leaves of the tea plant in boiling water.
trail shoes 	Footwear for short day hikes that don't involve a heavy pack or technical terrain. Slightly heavier and more supportive than sneakers. Ideal for easy-moderate terrain.	umbrella 	Collapsible item that will provide protection against rain.
warm coat 	Heavy upper body garment that a hiker can wear with cold weather conditions.		

bandana 	Handkerchief worn around the head or neck, can be used to wipe off a hiker's sweat.	bear bag 	Bag that will shape and conform to the food placed in the bag to prevent bears from taking the food.
blanket 	Piece of woolen or similar material used as a bed covering or other covering for warmth.	coffee 	Drink made from roasted and ground beans that a hiker can make while hiking.
cook pot 	Rounded metal container used for cooking.	flashlight 	Battery operated portable light that can help a hiker see at night or in poorly lit areas.
freeze dried meal 	Convenient, calorie dense, lightweight food pouches that are ready to eat by adding boiling water.	guidebook 	Guide that will help a hiker while on the trail by providing tips on hiking or helpful information (weather patterns, routes, etc.) about a specific trail itself.
hammock 	Bed made of canvas or of rope mesh and suspended by cords at the ends.	hiking boots 	Footwear for longer hikes, carrying heavier loads, and more challenging terrain. Study/high cut boots that come up over the ankle bone.
iPad 	Tablet with a touchscreen interface that can be used for entertainment purposes.	jacket 	Light upper body garment that a hiker can wear on moderately cold weather conditions.
journal 	Log for hiker to record news/events or thoughts while hiking.	long sleeves 	Long sleeved shirts that can be worn on windy or warm hiking days.

map 	Can be used to tell you where you are and how far you have to go. Can help find campsites, water, and an emergency exit route in case of an accident.	pants 	Trousers that can be worn when hiking in cold, windy, or rough terrain
permit  NATIONAL PARK SERVICE YOSEMITE NATIONAL PARK WILDERNESS USE PERMIT … VALID ONLY WHEN SIGNED ON REVERSE.	Some outdoor activities and areas require fees and you must obtain permits for backcountry camping, hunting, and fishing.	radio 	A portable device that would allow the hiker to listen to podcasts, music, or various station for entertainment purposes.
sandwich 	Can be easily made while hiking. Consisting of bread and meat.	shirt 	Short sleeved shirts that can be worn on warm hiking days.
skillet 	Frying pan used for cooking.	sleeping pad 	Ground pad used in conjunction with a sleeping bad to provide padding and thermal insulation.
socks 	Garment for the feet for warmth and padding for long distance walking.	sunscreen 	Cream/lotion rubbed onto the skin to protect it from the sun.
tent 	Portable shelter made of cloth, supported by one or more poles and stretched tight by cords or loops attached to pegs driven into the ground.		

A.3 Worksheet of Study on VISGRAINS

Please answer the questions based on all 50 items given to your team. Use the system and your own judgment to decide the answers. Work together to answer the questions as accurate as possible.

1. What are the top three items that have the largest number of tweets?

Item names: __________ __________ __________

2. Categorize the 50 items and identify the top three categories that have the largest number of tweets. Create 3 categories with the 3 category boxes on the tabletop. A category should contain at least 5 but at most 15 similar or related items.

- Categorize items based on similar or related functions.
- Note not all items need to be sorted (at least 5 items cannot be sorted since each box holds up to 15 items).
- Use the visualization, descriptions on worksheet, the tweet content, and your own knowledge to decide similarity.

Please answer the following questions:

Name the top three categories and write down the number of tweets in each category.

Category 1: __________ Number of tweets: __________

Category 2: __________ Number of tweets: __________

Category 3: __________ Number of tweets: __________

3. Identify 4 items that are most related to hiking boots. Choose related items by their functions. How many tweets mention these items? (including hiking boots)

Number of tweets: ___________

4. Identify 4 items that are most related to parka. Choose related items by their functions. How many tweets mention these items? (including parka)

Number of tweets: ___________

5. Identify 4 items that are most related to tarp. Choose related items by their functions. How many tweets mention these items? (including tarp)

Number of tweets: ___________

6. Identify 4 items that are most related to flashlight. Choose related items by their functions. How many tweets mention these items? (including flashlight)

Number of tweets: ___________

7. Identify 4 items that are most related to guidebook. Choose related items by functions. How many tweets mention these items? (including guidebook)

Number of tweets: ___________

8. Identify 4 items that are most related to energy drink mix. Choose related items by functions. How many tweets mention these items? (including energy drink mix)

Number of tweets: ___________

9. Identify the top 5 electronic devices that have the largest number of tweets, how many tweets in total mention these 5 items?

Number of tweets: ___________

10. Identify the top 5 overnight hiking gears that have the largest number of tweets, how many tweets in total mention these 5 items?

Number of tweets: __________

11. Are there more tweets about gears for cold-weather hiking or for hot-weather hiking?

Cold-weather gears are mentioned more

Hot-weather gears are mentioned more

Appendix B

IRB Approval Forms

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: November 26, 2014

TO: Scott McCrickard, Troy D Abel, Shuo Niu, Steve Harrison

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires April 25, 2018)

PROTOCOL TITLE: Investigating Design Activities in a Collaborative Interaction Space

IRB NUMBER: **14-1134**

Effective November 25, 2014, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**November 25, 2014**
Protocol Expiration Date:	**November 24, 2015**
Continuing Review Due Date*:	**November 10, 2015**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

VirginiaTech

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE:	February 11, 2016
TO:	Scott McCrickard, Shuo Niu, Sophia Maianh Nguyen, Kavin Aravind, Sushant Bhattarai, Usman Anwar, Steve Harrison
FROM:	Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)
PROTOCOL TITLE:	Investigating Notifications on a Large Multi-touch Display
IRB NUMBER:	**16-064**

Effective February 11, 2016, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**February 11, 2016**
Protocol Expiration Date:	**February 10, 2017**
Continuing Review Due Date*:	**January 27, 2017**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

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If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: October 19, 2018

TO: Scott McCrickard, Shuo Niu, Julia Nguyen

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Investigating Visualization Paradigms to Support Collocated Sense-making

IRB NUMBER: **18-818**

Dear Investigator(s):

RE: Protocol Submission for WIRB Review

The Virginia Tech Institutional Review Board (IRB) office screened this study and determined that it is ready for WIRB review.

Please download the "Instructions for the PI to Transfer the VT IRB Protocol to WIRB":

https://www.research.vt.edu/irb/documents/wirb_submission_instructions.pdf

Please go to https://connexus.wcgclinical.com to complete the protocol submission process to the WIRB.

ATTENTION:

* Scott McCrickard MUST BE LISTED AS THE PI ON THE WIRB SUBMISSION.

* All references to the VT IRB (including phone number and email address) MUST be removed from all study documents and replaced with Western IRB - (800) 562-4789, help@wirb.com.

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.