Investigating Data Exploration Techniques Involving Map Based Geotagged Data in a Collaborative Sensemaking Environment

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The recent advancement in Global Positioning Systems (GPS) using satellite and geotagging has opened many opportunities for data-driven decision-making in fields such as emergency response, military intelligence, oil exploration and urban planning. The enormity and explosion of geospatial data necessitates the development of improved tools to support analysis and decision-making around this complex data – a process often known as sensemaking. A typical geotagged map can have hundreds of data points that are multi-dimensional, with each point having meaningful information associated with its location, as well as project specific information e.g., photographs, graphs, charts, bulletin data among many other information parameters. Sensemaking activities involving such complex data often involve a team of trained professionals who aim to make sense of this data to answer specific sets of questions, and make key decisions. Researchers are currently exploring the use of surface computing technology, such as, interactive digital tabletops and touch-based tablets to form methodologies to enhance collaborative sensemaking. This thesis examined the impact of two multi-surface interaction techniques that allowed individual group members to explore detailed geotagged data on separate peripheral tablets while sharing a large geographical overview on a digital tabletop. The two interaction techniques differed in the type of user input needed to control the location on the tabletop overview of a bounded "region of interest" (ROI) corresponding to the geotagged data displayed on the personal tablets. One technique (TOUCH) required the ROI to be positioned on the tabletop using direct touch interaction. The other technique (TILT) required the ROI to be positioned via 3-dimensional (up-down, left-right) tilt-gesture made with the personal tablet. Findings from the study revealed that the effectiveness of the respective interaction techniques depended on the stage of sensemaking process, and on which collaboration strategy groups employed during collaborative sensemaking.

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List of Acronyms

GPS –Global Positioning Systems

ROI – Region of Interest

ML – Magic Lens

SS – Participants seated at Short side

LS – Participants seated at Long side

O+D – Overview-plus-Detail

ST – Strong Territoriality

WT – Weak Territoriality

NC – Navigation space Coupled

ND – Navigation space Decoupled

IC – Information space Coupled

ID – Information space Decoupled

INC – Information and Navigation space Coupled

IDNC – Information Decoupled and Navigation Coupled

2D – Two-dimensional

3D – Three-dimensional

DOF – Degree of freedom

Chapter 1

Introduction

"*Data is only as useful as the users' ability to navigate and interact with it*" –Dzmitry Aliakseyeu

Imagine a co-located group of analysts engaged in a data-driven decision-making task around a map of the Arctic Region. The group is trying to decide what the most efficient shipping navigation route is through the Arctic Ocean. The available geographical data consists of Arctic sea-ice conditions in the form of graphs, charts, photographs and bulletins that are geotagged to certain geographical locations. Geotagged data refers to any piece of information that has a direct spatial correlation to a geographic point. For example, a graph representing historic ice coverage data for a region can be geographically tagged (geotagged) to its associated location on the map. Similarly, an aerial photograph can be geotagged to a map based on the exact location where it was captured. Decisions made regarding a geographic region may require considering a large amount of geotagged data and involve various analysis and cognitive stages. This overall process of overviewing, comprehending, and interpreting the data to make an informed decision is called "sensemaking" (Pirolli & Card, 2005) or simply "how people make sense out of their experience in the world" (Klein et al., 2006, p. 70).

The above sensemaking process often starts with an exploration of complex and vast amount of available data. Researchers have previously explored various data exploration tools to enhance visualization and exploration, such as utilizing the peephole and lens metaphors (Bier et al., 1993; Fitzmaurice, 1993; Stone et al., 1994; Brown & Hong, 2006; Spindler et al., 2009; Spindler & Dachselt, 2010; Spindler et al., 2010). Most of these techniques provide magnified or zoomed views (Bier et al., 1993; Stone et al., 1994; Brown & Hong, 2006; Spindler et al., 2009);

or a multi-layer views of an existing interface (Spindler & Dachselt, 2010). However, only few of these tools were designed for geographic data exploration (Rodrigues et al., 2014) and none were used specifically to explore geotagged data.

In complex domains like oil and gas exploration, emergency response, and military intelligence, where data-driven decisions are critical, group decision-making is valued (Isenberg et al., 2010; Wu & Zhang, 2009; Bortolaso et al., 2013 2013; Seyed et al., 2013). Previous research has shown the value of providing group members with an individual perspective in conjunction with a shared perspective enhances the overall sensemaking process (Brennan et al., 2006; Morris et al., 2010; McGrath et al., 2012; Wallace et al., 2013). However, little research has focused on designing a collaborative sensemaking environment to enhance data exploration when the group works together. Hence, this thesis focuses on developing a collaborative environment that supports sensemaking involving geotagged data. In particular, a collaborative environment that supports individual exploration for building a personal perspective of data in the context of a shared overview of data.

Further, collaborative data exploration often involves both individual and collective exploration, which requires alternating between working independently and working together as a group. McGrath et al. (2012) observed that groups working on a data exploration task often "branch" out to work individually and then "merge" back to work in a group. Hence, to support data exploration around a collaborative sensemaking environment, a system needs to provide both a personal and a shared space for visualization of the data, and at the same time it should enable flexible "branch-and-merge" exploration. However, there are various conflicting requirements that arise when designing a system for collaborative environments. Gutwin and Greenberg (1998) state, "[While] an individual demands powerful and flexible means for interacting with the workspace and its artifacts, [a] group requires information about each other to maintain awareness" (p. 207).

This thesis focuses on addressing the above design challenge by utilizing a tabletop-centric multi-surface environment. It explores using a digital tabletop for providing a shared perspective of the data in conjunction with individual handheld tablets that provide a personal perspective. Previous research on tabletop-centric collaborative sensemaking has found that use of a shared digital tabletop improves group collaboration during sensemaking, and using a personal device (such as a tablet) helps individuals explore data effectively by having more group discussions (Wallace et al., 2013). Moreover, using a digital tabletop to display a shared digital map mimics the use of a physical map around which groups can gather to make critical decisions. Additionally, when using a digital tabletop in conjunction with a tablet, users can work in parallel, and switch between a personal view (tablet) and a shared view (tabletop) when required.

Researchers have previously used the concept of "parallel interface" or replicated views (zoomed, magnified or layered views) for visualizing complex data where secondary views provide an add-on layer to the primary view of information (Bier et al., 1993; Stone et al., 1994; Brown & Hong, 2006; Spindler et al., 2009). In contrast, this research aims to study geotagged data exploration where the data being explored is not necessarily of geographic nature, and can also include graphs, charts, photos, etc. associated with the geographical location. Hence, the secondary interface (or tablet) provides a detail view of the primary overview interface (or tabletop) instead of providing a masked or an add-on interface.

This research draws on existing "Overview-plus-Detail" (O+D) visualization work (Plaisant et al., 1995; Buring et al., 2006; Ion et al., 2013) that provides two separate interfaces – the overview and the detail interface, and allows the user to build the connection between the two interfaces. Hence, this research applies O+D visualization in the context of viewing selected geotagged data (the detail view) and viewed in parallel with the larger geographical context (the overview). Figure 1.1 shows a tabletop view displaying icons representing available geotagged data icons at specific locations on a geographical map (1.1(a)). The available tablets can be used by each group member to view the details of specific geotagged data (1.1(b)) associated with a particular "Region of Interest" (ROI) selected on the tabletop map.

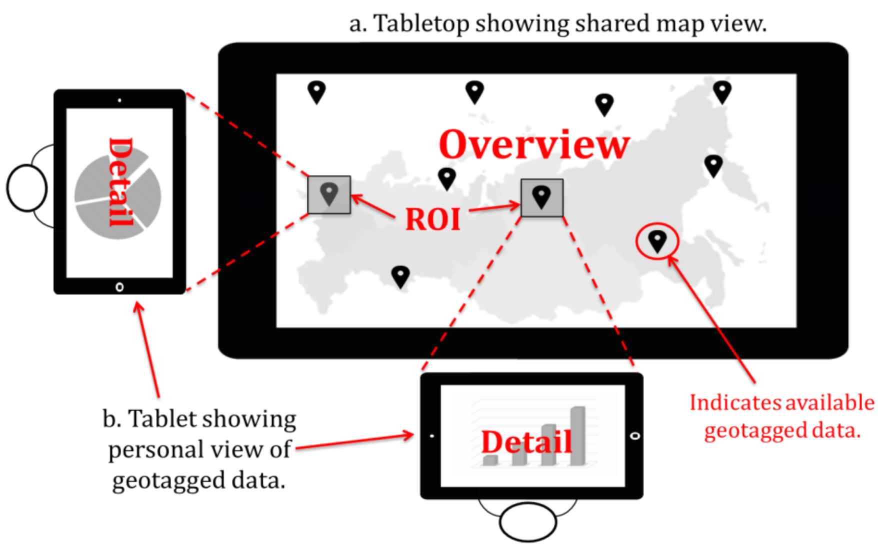


Figure 1.1: (a) Tabletop provides "overview" of map with geotagged icons; (b) Tablet provides "detail" of geotagged data.

Within such a collaborative sensemaking environment, many potential human-computer interaction issues exist. However, a key issue is the connection between the overview map on the tabletop and the viewed geotagged data on the tablets. To provide fluid collaborative data exploration, and more broadly, an effective sensemaking environment, the system must provide a useful mechanism to select what data to view on the tablets. This thesis investigates different mechanisms to control the ROI associated with each tablet view. Two ROI control interaction mechanisms were designed, based on existing techniques, and studied in a laboratory-based user study. The study tested two techniques called TOUCH and TILT. In the TOUCH technique, the ROI was controlled using direct touch manipulation gestures on the tabletop; whereas in the TILT technique the ROI was controlled through tilting gesture made with the tablet, leveraging built-in device sensors available on modern tablets.

The following sections further detail the motivation behind this research, the research objectives, and the overall organization of this thesis.

1.1 Motivation

There are two main factors that motivated the work within this thesis. First, the existing multi-surface data exploration techniques have a minimal focus on a mixed-focus collaborative exploration that requires back-and-forth branch and merge interactions. Second, existing techniques have not been studied in the context of geotagged data. With recent proliferation of geotagged data, there is an increasing need for sensemaking involving this type of data. To make the most efficient use of existing data, it is important to design a system that can support insightful exploration of geotagged data for improved collaborative sensemaking.

1.1.1 Lack of supporting environments for map-based collaborative sensemaking involving geotagged data

Present day analysts involved in analyzing geospatial data primarily depend on traditional web-based exploration. This form of exploration requires keeping track of geospatial information across a number of web pages at the same time, with minimal support for spatial correlation. This lack of spatial connection between the data, places a high cognitive demand on the user throughout the exploration process, and leads to a poor user experience. This thesis aims to design a collaborative environment that supports data exploration of geotagged data and enhance the sensemaking process by providing O+D data exploration.

1.1.2 Within a multi-surface environment there is a need for interaction mechanisms for controlling personal (tablet) views during data exploration

Analysis of the background literature on data exploration techniques, revealed a lack of research involving testing the effectiveness of techniques that support both collaborative and independent interactions. A tool that supports individual exploration may not be as effective when the task needs to be done collaboratively. Similarly, a good collaborative tool may not support the individual sensemaking process. Therefore, there is a need for a tool that can both enhance data exploration to support sensemaking, and be used in a collaborative setting.

1.2 Research Objectives

The overarching goal of this research is:

To understand the impact of overview-plus-detail (O+D) multi-surface interaction techniques on independent and collective data exploration of geotagged data during collaborative sensemaking.

To address this goal, three smaller research objectives have been identified:

1. **Identify promising cross-device interaction and data exploration techniques for multi-surface environments from existing literature**

   A literature review was conducted to understand how existing data exploration techniques support data visualization in different multi-dimensional domains. The review also details existing sensemaking models and how technology has been used to enhance collaboration and sensemaking. Chapter 2 discuss this literature review.

2. **Apply promising data exploration techniques to a multi-surface environment, that allow independent personal viewing of geotagged data during collaborative sensemaking**

   Based on the requirement to support collaborative sensemaking and knowledge gained from existing exploration techniques, the O+D visualization design was evolved to support collaborative sensemaking of geotagged data. Chapter 3 details the entire design process and adaptation of the proposed data exploration techniques.

3. **Evaluate the impact of the proposed techniques on collaborative sensemaking**

   The two proposed techniques were implemented in an experimental multi-surface application and evaluated through a laboratory-based study. The design of the study was presented in Chapter 4, and the findings and discussion (Chapters 5 and 6) describe the study outcome. The impact of proposed techniques was evaluated in the context of various quantitative and qualitative dependent variables.

1.3 Thesis Organization

This thesis is organized into the following chapters:

Chapter 1: Introduction contains the motivation and main research objective of this thesis.

Chapter 2: Background contains a detailed background literature review related to sensemaking and various single- and multi-surface data exploration techniques.

Chapter 3: Design describes the design approach and the process entailed in designing the interaction techniques starting from the basic concept to a working prototype. Moreover, it details some of the add-on features to support collaboration and awareness.

Chapter 4: Study Methodology describes the process used to test the main objectives.

Chapter 5: Findings details the empirical findings, including the results from the quantitative and qualitative data analyses.

Chapter 6: Discussion discusses the findings from a broader context, and how they can be used to better design a collaborative sensemaking tool to enhance data exploration and sensemaking.

Chapter 7: Conclusion and Future Work summarizes the main findings of this thesis and describes future direction for this by recommending some future steps that warrant future study to build upon these findings.

Chapter 2

Literature Review

This chapter details background literature on previous related work, and elaborates on how this work provides a novel contribution to the domains of human-computer interaction, and surface computing. Analyzing the gaps in support for sensemaking reveals the need for a *collaborative exploration environment to enhance data-driven sensemaking of the geotagged data*. This chapter is thus divided into two sections. The first section reviews the literature related to independent and collaborative sensemaking, highlighting various interaction phases of the sensemaking process. The second section of this chapter overviews the single- and multi-display visualization techniques that were adapted in this research to enhance the exploration phase of a collaborative sensemaking process.

2.1 Sensemaking

Sensemaking as defined by Russell et al. (1993) is the process of searching for a representation and organizing information present within that representation to answer questions specific to a task. Hence, the process of sensemaking may involve various cognitive activities. A large body of research exists on understanding the process of sensemaking. A predominant view in the literature is that the sensemaking process consists of several iterative activities, such as, viewing the data to gather information, refining the data to uncover insightful information, detecting useful patterns, and finally coming up with a result (e.g., (Van den Haak et al., 2004; Pirolli & Card, 2005; Yi et al., 2008; Wallace et al., 2013)). One of the first sensemaking models describes sensemaking as a four steps process, including, (1) information gathering (2) schema formation, (3) insight development, and (4) creation of knowledge (Pirolli & Card, 2005).

Building on this model, Yi et al. (2008) proposed an insight-based evaluation model that also consisted of four activities that groups perform during sensemaking, (1) overview, (2) adjust, (3) detect pattern and (4) match mental model. Likewise, Wallace et al. (2013) studied sensemaking in a collaborative setting directly applying Yi et al.'s model. They observed similar sensemaking activities.

During sensemaking, successful decision-making heavily depends on the number of insights that an individual discovers. Even when data is abundant, making sense of it to uncover useful insights can be difficult because insights are often complex, deep, qualitative and unexpected (North, 2006; Yi et al., 2008). Thus, various conclusions can be drawn from insights at once, which demand a profound analysis. Moreover, one key insight can uncover other key insights, and hence insightful findings can enhance the overall sensemaking process (North, 2006). Therefore, designing an efficient data exploration technology would help discover more insightful data, and as a result, will contribute to create an effective collaborative sensemaking environment.

2.1.1 Collaborative Sensemaking

In a collaborative sensemaking environment, the sensemaking process is conducted by various group members rather than an individual, and therefore it adds additional complexity to the process. When individuals collaborate during sensemaking, various social factors, such as, conflicts, compromises, communication, team cognition, group think and group dynamics need to be considered (Janis, 1982).

The collaborative sensemaking literature indicates that different groups take on different collaborative styles during the sensemaking process. For instance, some groups prefer working together as a group on a task, while other groups feel more comfortable working independently and occasionally coming together to discuss their findings (Tang et al., 2006). In contrast, some groups move back-and-forth between working independently and working in a group. Hence, a well-designed data exploration technique should support all of these collaboration styles.

During a collaborative sensemaking process, the individual group members may find themselves working at different stages of the sensemaking process (Isenberg et al., 2010; Isenberg et al., 2012). For example, while one team member is engaged in overviewing the data, another member could be detecting useful patterns in the data. Hence, a well-designed system should be designed to support multiple collaborative actions, and to prevent one member's action from interfering with another member's action when they are working on different activities.

Different collaborative activities often require different level of group cooperation. Tang et al. (2006) and Isenberg et al. (2012) studied group interaction during a collaborative data analysis task, and found that groups tend to adapt a "loosely coupled" or a "tightly coupled" interaction while performing a collaborative task. They explained that *"when participants cannot do much work before having to interact, the work is tightly coupled; conversely, when participants can work independently for long period of time, work is loosely coupled"* (Tang et al., 2006, p.2). They also found that tightly coupled interaction reduced interference between the group members, whereas, during loosely coupled interaction, group members had to rely on social protocol such as "talk aloud" to resolve conflicts (Tang et al., 2006). Isenberg et al. (2012) proposed a group interaction model based on the loosely and tightly collaborative interactions, adopted by the group during sensemaking to perform various activities, such as, investigate hypotheses, test ideas, and build narrative. They found that participants were engaged in eight different activities, either by working independent (loosely-coupled collaboration) or together (closely-coupled collaboration). These activities are illustrated in Figure 2.1. Similar group interactions where observed in the study reported in this thesis.

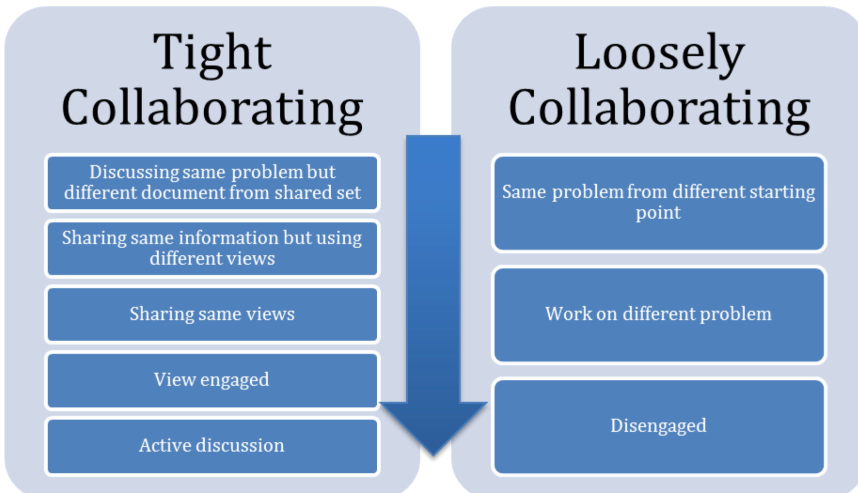


Figure 2.1: Adapted from Isenberg et al. (2012) group interaction model showing eight activities performed during loosely and closely collaborative interactions.

In most cases, a loosely coupled interaction is followed by a tightly (or closely) coupled interaction to reach "common ground" with other collaborators. The concept of reaching common ground refers to collaborators share mutual knowledge, beliefs and assumptions (Clark & Brennan, 1991). Hence, in order to reach a mutually accepted decision it is required for a group to share both the content and the process of their individual findings (Brennan et al., 2006; Tang et al., 2006).

Further, unlike individual sensemaking, collaborative sensemaking involves social factors like "workspace awareness" (defined as "up-to-the-moment understanding of another person's interaction with the shared workspace." (Gutwin & Greenberg, 2002p.10)) and "situation awareness" (defined as "the up-to-the minute cognizance required to operate or maintain a system" (Gutwin & Greenberg, 2002p.9)) that play an important role in the sensemaking process. When working in a group, decision-making depends on group consensus, or a process for determining a single decision, rather than on a single individual. Moreover, sometimes data explored by different group members can be combined for an insightful finding. Hence, collaborators should be aware, throughout the process, of their surroundings, and what other group members are exploring. The next section describes how technology has been used in the past to assist the sensemaking process.

2.1.2 Supporting Sensemaking

Researchers have looked at different aspects of sensemaking, both when individuals are independently engaged in sensemaking, and when a group is engaged in the sensemaking process. Collaborative sensemaking of complex data is challenging, and demands for effective data exploration techniques that will simplify the overall exploration process. Digital tabletops and large screen displays have widely been used to support visualization in complex data-driven environments, such as oil and gas exploration, emergency response and military control (Wu & Zhang, 2009; Bortolaso et al., 2013; Seyed et al., 2013). The shared displays support collaboration by providing a common workspace to discuss ideas and opinions. In addition, they help create a better mental model for group members by providing a spatial context to the data (Tani et al., 1994).

Previous research on co-located collaborative sensemaking indicates that having a shared workspace in the form of a digital tabletop or large vertical display, enhances sensemaking task performance, and awareness between group members (Morris et al., 2010; Wallace et al., 2013). Additionally, having a tabletop-centric workspace in conjunction with personal tablets supports important sensemaking activities, such as *formation of tableaux* (Wallace et al., 2013). A tablet interface, by providing a peripheral personal view, allows better use of the tabletop interface screen for conducting collaborative activities, such as group discussions (McGrath et al., 2012). Bradel et al. (2013) studied co-located sensemaking on a large vertical display and found that groups using the shared display were more successful in their analysis compared to the groups that were performing the task using individual desktop computers.

Although use of a shared workspace enhances collaborative sensemaking, there is still a need for a flexible environment that offers back-and-forth switching between personal and shared spaces without any interference between partners. Gutwin and Greenberg (1998) introduced the concept of a “mixed-focus environment”, where collaborators switch back-and-forth between working independently and working in a group. According to their findings, the three main requirements that should be considered while designing for the mixed-focused environment were: workspace navigation, artifact manipulation and view representation. Workspace navigation refers to the navigational control when working in a group (i.e. navigation controlled by individuals themselves versus controlled by the group as a whole). Artifact manipulation refers to how much power an individual has to manipulate artifacts and the feedback provided by the system to each group member about user actions. View representation refers to the control of the visualization aspect of a shared view. A particular visualization might lead to better representation of data for an individual than for the group. Since this research also aims to support mixed-focus environments, the above three features were considered while designing the collaborative workspace used in the study.

An example of a mixed-focused environment is *branch-explore-merge* (McGrath et al., 2012) that offered switching between shared space (coupled) to private space (decoupled). In this environment, users have the flexibility to share their workspace (branch), or work independently (explore) and then discuss their final findings (merge). While studying branch-explore-merge, it was found that most participants preferred working independently, and they tend to branch only in the early stages of collaborative task.

Brennan et al. (2006) proposed a mixed-focused collaborative model (see Figure 2.2). According to this model, a group engaged in solving a collaborative task starts by building an individual perspective and then meet up to find common ground. As the group members reach common ground, they build the knowledge base by adding more information from different sources. From this model it can be implied that efficient sensemaking is dependent on how effectively a group (as a whole) can build on the existing knowledge base. An application of this model was seen in *CommonSpace* (Willett et al., 2011), which was designed to enhance sensemaking by allowing users to build on each other's findings in an evidence gathering task. This tool allowed linking and tagging of information that helped in organizing findings as well as enhancing analysis. The next section of this chapter explores various data exploration techniques that have been proposed in the past.

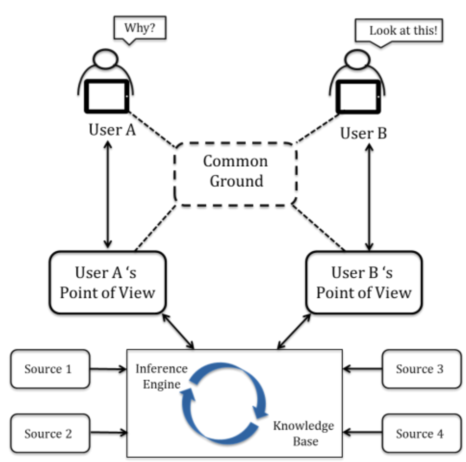


Figure 2.2: Adapted from Brennan et al. (2006) sensemaking model

2.2 Data Exploration Techniques

Designing a geotagged data exploration environment to support data-driven sensemaking requires understanding the concept of spatial management, and the different methods of visual exploration in both single- and multi-display environments. The concept of spatial management has been around for a long time, and it has been confirmed by researchers that adding a spatial context (or spatial association with the data) enhances the analysis process by increasing information retention (Tani et al., 1994), and by giving direction to the workflow that helps create a spatial layout of information (Perlin & Fox, 1993). The spatial management of data can be applied to different domains based on the types of data being analyzed. For example, a group working on a geographical data might analyze the spatial data based on the geographical location on a map (Rodrigues et al., 2014). On the other hand, a doctor examining medical images related to a tumor, or examining an X-ray image, might analyze spatial data by slicing into the 3D space inside the scanned images or the X-ray image (Spindler & Dachselt, 2010; Song et al., 2011). Therefore, visualizing spatial data may involve using single or multiple displays, where the additional screens can be used for contextual visualization. The following sections will elaborate on various data exploration techniques for viewing spatial aware information in a single- and a multi-surface environment.

2.2.1 Data Exploration Techniques with Single-Display Environment

The spatial management of digital information was initially introduced on a single-display environment (mainly desktop screens), and one of the first prototypes consisted of navigating data on a projected display, using a chair with a pressure sensitive joystick (Donelson, 1978). Donelson's work inspired various future researchers to explore different techniques to visualize complex spatial information. For example, *portals* or Pad provided a magnified peripheral view on a shared desktop screen (Perlin & Fox, 1993), and *magic lens (ML)* consisted of a movable viewing lens (Bier et al., 1993; Stone et al., 1994). Both portals and ML were primarily *see-through filters* that provide a magnified version of an original interface (or a wireframe of an original interface) and were embedded with a desktop screen.

The concept of a ML that provided a secondary view was further tested in 3D physical space by utilizing it on a handheld palmtop. Fitzmaurice (1993) applied ML to a spatially aware mobile palmtop handheld computer, and connected the real world interaction space with an exploratory 3D information space. This device was tested on a paper-based map, where the map was a stationary object, and the handheld palmtop computer could be moved around the stationary map to get information about a certain region in space, such as, weather information, travel itinerary and points of interest. Figure 2.3(c) illustrates "ML with visual content" where the handheld tablet can be moved in physical space around the visual content in the background.

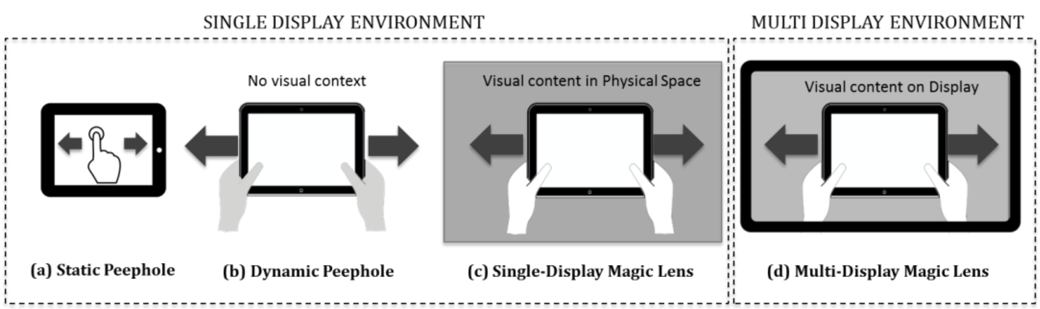


Figure 2.3: Different peephole interface in a single- and multi-display environment.

After the introduction of spatially-aware handheld ML, the design was further evolved, and different techniques were developed to improve navigation and visualization of spatial contextual information. For instance, when a sensor-based handheld device was in a static position, and the information space within the device was moved by dragging touch points on the screen, the technique was called *Static Peephole* (see Figure 2.3(a)) (Hurst et al., 2010). On the other hand, if the handheld device was moved with respect to the static background in order to change the displayed content on the screen, the technique was called *Dynamic Peephole* (see Figure 2.3(b)) (Hurst et al., 2010).

Previously, various researchers have compared and studied the application of dynamic and static peephole. For instance, Yee's (2003) design extended dynamic peephole to two-handed interaction by using a pen input to interact, while visualizing data at the same time. Moreover, Hurst et al. (2010) and Mehra et al. (2006) compared a dynamic peephole with static peephole in a three-dimensional (3D) and two-dimensional (2D) virtual environment, and found that the dynamic peephole was more effective for an orientation based task. Some of the other tools, such as *Halo* and *Boom Chameleon* adapted dynamic peephole in a more effective way. *Halo* (Baudisch & Rosenholtz, 2003) provided spatial awareness of out-of-screen objects on a handheld device screen, by displaying partial rings on the screen, where center of the rings signaled the location of out-of-screen object. Further, *Boom Chameleon* (Tsang et al., 2003) was a flat panel mounted on a mechanical boom and provided an additional options of capturing viewpoint, gestures and voice information.

Recently researchers expanded the realm of see-through interface by applying it to wearable technology. For example, Kerber et al. (2014) compared the static and dynamic peephole metaphors using a smart watch for a map navigation task, and found that participants preferred dynamic peephole over static peephole, although dynamic peephole was less efficient for performance.

2.2.2 Data Exploration Techniques in a Multi-Surface Environment

The tools discussed in the previous section focused on visualization using a single-display only, but aforementioned, having contextual information with awareness feedback can greatly enhance the visualization process (Morrison et al., 2009). Moreover, using a secondary display in the form of a digital tabletop or large screen display (for providing contextual visual content) with handheld ML (see Figure 2.3(d)), should enhance problem-solving, and promote discussions between collaborators in a multi-user setting (Morrison et al., 2009). Thus, this section elaborates on the previous work done on using exploration techniques in a multi-display environment, both with a single- and a multi-user interaction.

2.2.2.1 Multi-Surface Environment with Single-User Interaction

A series of studies conducted by various researchers, advanced the concept of spatially aware ML by using it to slice the 3D physical space, either above (a digital tabletop) or in-front of a display screen (a large vertical wall). Based on the context of the data, 3D slicing can be used to explore volumetric space (Spindler et al., 2009; Spindler et al., 2010), zoomable space (Brown & Hong, 2006) or layer space (Rodrigues et al., 2014). *Paperlens* (Spindler et al., 2009) and *tangible views* (Spindler et al., 2010) examined various interaction methods for moving a spatially aware light and flexible lens, over the 3D surface of a tabletop, to explore different types of information space, such as, volumetric, layered, zoomable or temporal information. Brown and Hong (2006) utilized zoomable ML metaphor to compare handheld ML with a tradition embedded ML (within a screen), and found that handheld ML provided natural interaction and contextual awareness, whereas, embedded ML provided precise manipulation.

On the other hand, Song et al. (2011) applied 3D slicing on vertical wall display using an iPod's 3D tilt sensing capability to slice through the volumetric space in medical images. The

TILT method proposed in this thesis, utilizes a similar rotation (or tilting) gesture in 3D space using three degree of freedom (DOF) to manipulate 2D (x- and y-axes) movement of ROI. The design of the TILT technique will be further elaborated on in Chapter 3.

Radle et al. (2013) compared multi-touch and egocentric body movement navigation for zoomable ML on a vertical screen with a handheld tablet, and found, egocentric navigation method resulted in better spatial memory, more physical workload but less mental demand. Furthermore, Cheng and Zhu (2014) compared touch-based and orientation-based navigation, and found the touch-based method to be efficient. Similar to Radle et al. (2013) and Cheng et al. (2014), this thesis compares a touch- and orientation-based techniques, however, it focuses on a tabletop-centric environment, which is better for collaboration over its vertical counterpart (Rogers & Lindley, 2004).

2.2.2.2 Multi-Surface Environment with Multi-User Interaction

Little research has explored the use of data exploration techniques in a collaborative setting. When designed for a collaborative setting, the technique needs to support face-to-face collaboration and provide awareness about other collaborators' actions (Gutwin & Greenberg, 1998). Voida et al. (2009) used a focus-plus-context visualization in *i-Loupe* and *iPodLoupe* to resolve resolution discrepancies between multiple displays, and support face-to-face collaboration in a tabletop-centric collaborative environment. Plaue and Stasko (2009) found that by having a shared workspace side-by-side, collaborators were able to identify more insightful information in a sensemaking task. In the study design, this thesis incorporated the sharing aspect by using a dropbox feature (refer to section 3.3.1), and there are various user interface feedback elements to help support workspace awareness as well (refer to section 3.3.2). These design features will be elaborated in Chapter 3.

Further, Seyed et al. (2013) studied collaboration and visualization of geographical data for viewing multi-layered data related to oil and gas exploration in a tabletop-plus-tablet environment. Even though this thesis uses a similar domain context, unlike Seyed et al.'s work, this thesis examines data exploration of geotagged data in a sensemaking environment.

2.2.3 Data Exploration Techniques using Overview-plus-Detail (O+D) Interface

In the domain of zoomable user interfaces (ZUI's) researchers have looked at different methods to represent secondary information. One common approach is the overview-plus-detail (O+D) visualization, where one interface called the *detail* interface elaborates on a specific section of a broader information space. On the other hand, the other interface called the *overview* interface shows the broader context of the information space (Hornbaek et al., 2002). Researchers have compared the use of the detail interface, with and without an overview interface, and have found mixed results, as discussed below.

Hornbaek et al. (2002) found that eighty percent of their participants preferred having an overview for navigation and browsing in a map-based task. On the other hand, Buring et al. (2006) found no significant difference in preference of overview in a search task involving a zoomable scatterplot application. This thesis applied O+D in a geospatial context, hence it is expected that use of overview will have a similar positive effect, as observed by Hornbaek et al. (2002). Another study by Hornbaek and Frokjaer (2001) revealed that O+D interface was a preferred way of reading an electronic document compared to the fisheye and linear interface. Even though it was much faster to read using the fisheye interface, it was found that participants gained more understanding of the document using the O+D interface. Further, Ion et al. (2013) enhanced the O+D interface in the context of usability issues that arise when a detail view contains dynamic geospatial data that can be lost outside the selected view. Their technique (called *Canyon*) displayed a small view of an off-view object attached to the detail view and also provided context around the target location. This technique was found to improve the accuracy when exploring complex data on a map.

Similar to the TOUCH technique proposed in this thesis, where ROI box is dragged to the desired location on the tabletop, *DragMag* (Ware & Lewis, 1995) and *PolyZoom* (Javed et al., 2012) technique involved a direct dragging metaphor of the focus region on overview space to change the detail view. *PolyZoom* was a multiscale and multifocus zoom window that enabled users to narrow down the search space by building hierarchy of focus on the area of interest. This technique performed better than the pan and zoom technique on both multiscale and multifocus task, when tested on zooming into a google map view.

From the previous literature, it can be summarized that data exploration is an integral part of data-driven collaborative sensemaking process. For an insightful search, and to reach common ground among group members, a mixed-focused group should be able to carry out both independent and a collaborative data exploration. Moreover, supporting sensemaking involving a complex dataset demands a mixed-focus collaborative data exploration environment. In the past, some researchers have studied collaborative sensemaking and multi-user data exploration separately, but few have investigated data exploration in a collaborative sensemaking environment. And to my knowledge, this is one of the first studies designed to explore geotagged data in a collaborative sensemaking multi-surface environment using an O+D interface.

2.3 Chapter Summary

This chapter reviewed background literature and helped in accomplishing the first research objective of identifying promising data exploration methods from existing literature on cross-device interaction in a multi-surface environment and reviewing existing sensemaking models. It was categorized into two parts, (i) the literature related to the sensemaking process, (ii) and the various single- and multi-user data exploration methods that can enhance visualization processes, and as a result improve the data exploration. The review on sensemaking literature revealed that when an individual or a group is engaged in sensemaking they perform various iterative activates based on the stage of sensemaking process. Further, the review on previously explored data exploration methods uncovered that there is a need for collaborative data exploration environment to support insightful findings stage of a data-driven sensemaking process. While many of the existing techniques were designed to enhance single-user data visualizations, and few were designed to improve multi-user geographic data visualization, but none of these were specifically tested using multi-user sensemaking of geotagged data. The next chapter elaborates on the design aspect of this thesis.

Chapter 3

Design

The main objective of this chapter is to explore the design of a tabletop-centric multi-surface multi-user data exploration environment. The previous chapter elaborated on various data exploration methods, and the sensemaking process. Following on the requirements gathered from the literature, this chapter expands on the specific requirements and considerations for designing an Overview-plus-Detail (O+D) collaborative sensemaking environment. The ultimate design used in this study was an O+D interface and this chapter describes the iterative design process to get to the O+D visualization, and it will explain this interface much further. Hence, the design consists of three main aspects. First, the design of the multi-surface interaction control mechanism between overview and detail view, which is the primary focus of the study. Second, the design of tablet interface that represents the detail view, and has been designed to support O+D visualization. Lastly, the design of the tabletop interface that represents the geospatial overview data and has been designed to support collaborative workspace awareness. Providing a reasonably effective application interface for both the tablet and tabletop was necessary to support the collaborative sensemaking task used in the study, and will be discussed also.

3.1 Design Requirements

To design an O+D environment the following two design requirements were considered. First, designing a control mechanism for changing the "detail" view on the tablet with respect to the broader "overview" context. Second, when in static mode, providing an interface that helps the user understand the details they are viewing, and connect them with the context of the broader overview. Although the study was primarily focused on testing the control mechanism, a reasonable attempt was made to satisfy the second requirement to provide a useful experimental application for the study.

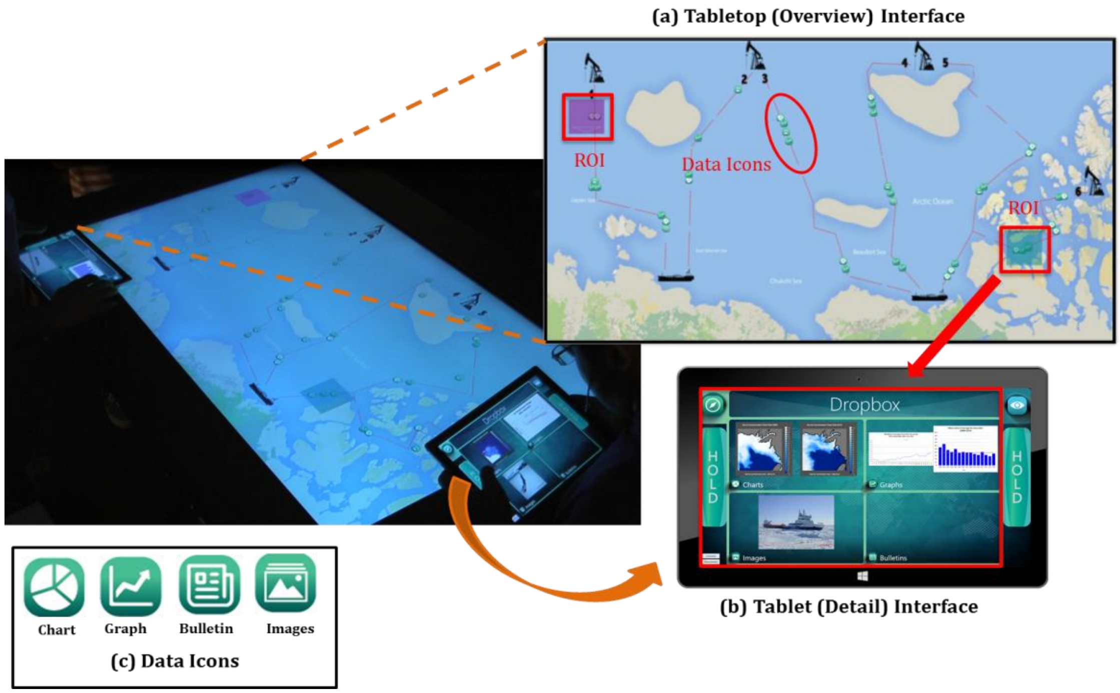


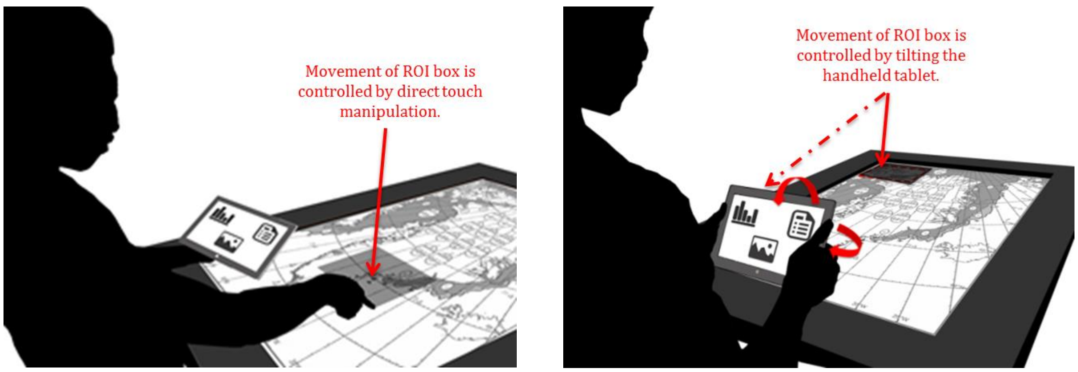
Figure 3.1: (a) Tabletop interface (or "overview") in the experimental application, showing data icons and ROI box, (b) Tablet Interface showing the "detail" view associated with geotagged data icons on the table

Gutwin & Greenberg (1998) proposed three requirements (workspace navigation, artifact manipulation, and view representation) that should to be considered when designing for a mixed-focused environment (see section 2.1.2). Hence, the interface design section of this chapter will explore the implementation of these requirements to support independent and group interactions. Figure 3.1(a) illustrates the tabletop interface that includes small data icons representing geotagged charts, graphs, images, and bulletin data, and the two Region of Interest (ROI) boxes connected to the different tablets. Once a user positions their ROI box over a data icon, the associated geotagged data is displayed on the tablet interface. If there are multiple icons within the ROI box then all the data associated with these icons are displayed on the tablet interface (see Figure 3.2 (b)). The following section elaborates on the process of designing the control mechanisms for moving the ROI that connects the overview and detail views.

3.2 Multi-Surface Interaction Control Mechanisms: TOUCH and TILT

The TOUCH and TILT control mechanisms of data exploration differed from each other, as they provided a unique way of controlling the movement of the ROI box on the tabletop overview. Building on the concept of magic lens filters (described in section 2.2.1), both the TOUCH and TILT techniques are based on the concept of a see-through interface, where the secondary interface (tablet) acts as a peephole into a primary interface (tabletop) to provide detailed information about the primary interface. However, these techniques differ from the previously proposed techniques, as our secondary interface provides a semantically related data view rather than a zoomed-in version of the information provided on the primary data view. Hence, the secondary interface acts as a "detail" screen, whereas the primary interface helps provide an "overview" to the primary interface. Moreover, the design of these techniques has been adapted to support collaboration and sensemaking around the geotagged data.

The TOUCH technique utilizes touch sensitivity of the multi-touch digital tabletop to directly manipulate or control the movement of the ROI box. As illustrated in Figure 3.2(a), users can control the position of the ROI box by directly touching it and dragging the box to a new region of interest on the tabletop. In contrast, the TILT technique utilizes built-in device sensors on tablets and hence involves the tilting motion of the tablet in a 3-dimensional space above the tabletop to control the movement of ROI (see Figure 3.2(b)). The TOUCH technique is similar to interacting with everyday touch sensitive devices like a smartphone or tablet; hence its interaction design required minimal pilot testing. On the other hand, the design of the TILT technique which leverages on-board device sensors (accelerometer, gyroscope) to detect device tilting user interaction, requires several iterations of pilot testing and refinement. The next section describes the technical implementation of these techniques, and the iterative process that was followed in their design process.



(a) TOUCH **(b) TILT**

Figure 3.2: (a) Using a direct TOUCH gesture on the table to control the ROI movement, (b) Using a TILT gesture on the tablet to control the ROI movement on the table.

3.2.1 Movement of ROI in TOUCH

The movement of ROI using the TOUCH technique utilized a direct manipulation touch gesture on the tabletop to change the detail view on the tablet. As illustrated in Figure 3.3, users can touch the ROI box displayed on the tabletop and drag the box to a new target location. As the ROI box is dragged across the tabletop map, the data associated with the icons located within the box's extents are displayed on the tablet screen.

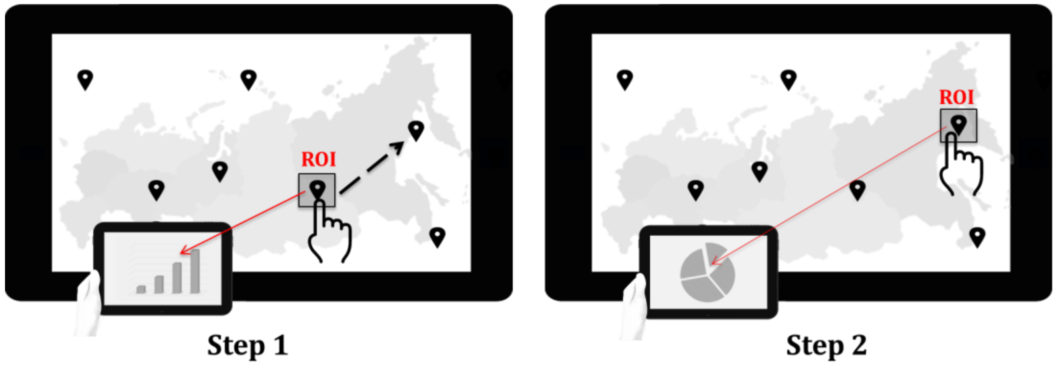
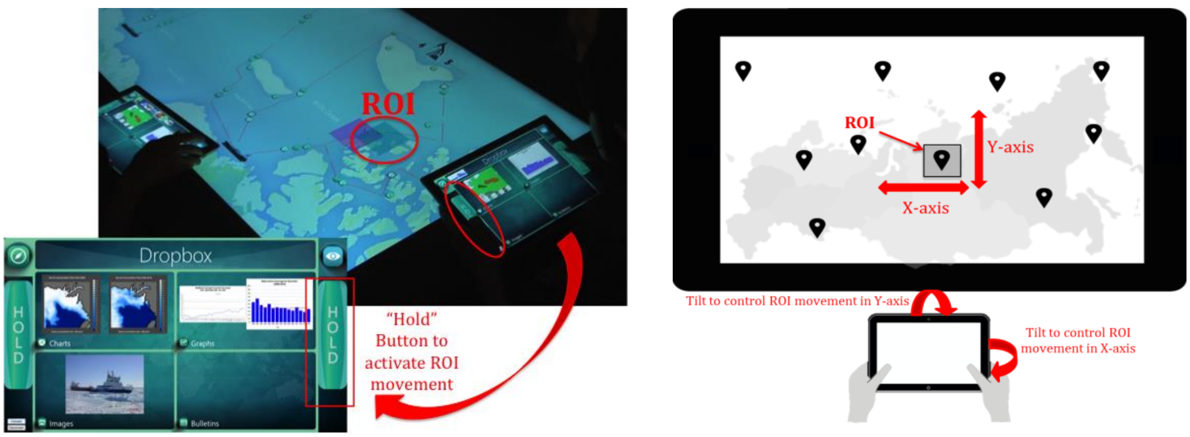


Figure 3.3: Illustrates movement of ROI using the TOUCH technique



(a) **(b)**

Figure 3.4: (a) Tablet interface showing the "Hold" button to initiate TILT gesture for moving the ROI on the table, (b) The TILT direction control to move ROI in X and Y-axis on the table.

3.2.2 Movement of ROI in TILT

The movement of the ROI in TILT was initiated by pressing a "hold" button on the tablet interface (see Figure 3.4(a)) and simultaneously tilting the tablet while the button was still in a depressed. As long as the button was held down, the ROI movement became activated, and 3D tilting of the tablet determined the direction of ROI movement, along the X and Y-axes (with respect to the seating position) on the tabletop interface (see Figure 3.4(b)). For example, for the long side (LS) participants, if the tablet was tilted with respect to the top or bottom side, the ROI on the table was moved in the Y-axis. Similarly, when the tablet was tilted with respect to either the left or right side of the tablet, the ROI moved in the X-axis.

3.2.3 Defining TILT Rotation Gesture

The physical movement of the device was designed to correspond to the direction in which the ROI was moving. Informal user-testing was conducted to test the control of the ROI with respect to the 3D rotation of the tablet. The factors considered in these tests were, having an unobstructed view of the tablet interface, and the accuracy of hitting the target. During the pilot tests two ROI control schemes were tested to identify an effective way of controlling the ROI movement every time the hold button was pressed. First, the ROI control was relative to the last saved tablet position. Second, the ROI control was relative to the current position of tablet (position just after pressing the hold button). These tests revealed that the second method of controlling the movement of the ROI was particularly useful for making minor adjustments to the ROI, after making long movements. For example, Figure 3.5 illustrates various steps involved in completing a TILT gesture interaction to move from one location to another within the tabletop screen. The first intention of the user was to get the ROI closer to the target (Step 1 to Step 2). The next action was making minor adjustments to position the ROI box onto the exact target location (Step 3 to Step 4). Since the goal of this thesis was to design an O+D visualization to facilitate data exploration, it was important that the detail view was always available. Hence, resetting the initial tablet position to the current position, ensured that the user could adjust their tablet in an ergonomically comfortable and viewable position (see Step 4, Figure 3.5(A)) even while performing a tilting gesture on the tablet, whereas if the last held position of the tablet is retained during ROI movement, it could create an obstructed data view (see step 4, Figure 3.5(B)). The next section will explore the interface design of the tablet and the tabletop in static mode, when the situation required users to collaborate and make sense of the given dataset.

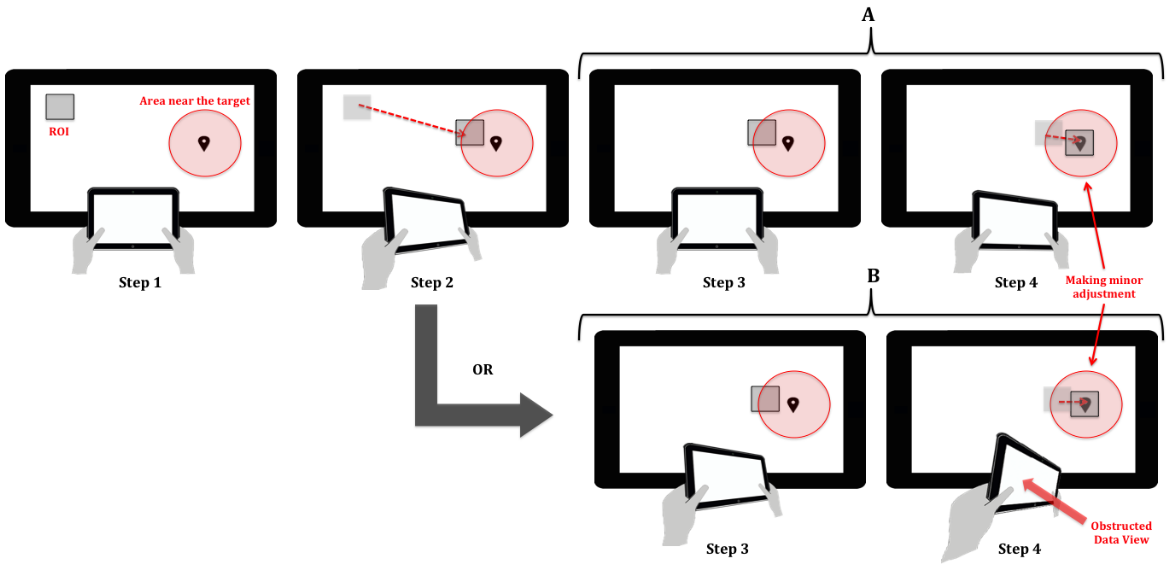


Figure 3.5: Illustrates steps involved in moving ROI from a point to the exact target location. (A) Setting the current tablet position to the starting position keeps the table view viewable. (B) Retaining the last saved position of the tablet obstructs the data view.

3.3 Interface Design Connecting Detail and Overview in a Geotagged Context

A user-centered design process was adopted to design the tablet and tabletop interface. Therefore, each design went through a number of design iterations before reaching the final design. Informal testing was conducted throughout the design cycle, and based on the feedback collected at each step; design modifications were made to enhance the effectiveness of the interface.

To incorporate workspace navigation, the workspace was split into a personal view (tablet) and a shared view (tabletop). Feedback in the form of visual clues such as a "glow" effect and colour codes (will be discussed in section 3.3.2) were provided on the tabletop for action indication that incorporates artifact manipulation. The flexibility of moving the ROI box provided view representation, where the location of the ROI box provided the ability to point to and communicate about the artifacts. The design of each of these elements will be described in detail in the following sections.

3.3.1 Tablet Interface Design

Figure 3.6 demonstrates the evolution of the tablet wireframe interface during the iterative design process. The main goal throughout the design process was to modify the tablet interface design to support O+D data exploration. During early wireframe testing on the scrolling layout design (A), it was found that the users were preoccupied interacting with the tablet interface for visualization data. This preoccupation on the tablet interface thus led to "attention tunneling". Attention tunneling is an occurrence when the users tends to focus their primary attention on an information in a specific region of an overall visual scene and exclude the information presented outside of highly attended areas (Wickens & Christopher, 2001; Bortolaso et al., 2013 2013). While using the scrolling layout interface, users focused their attention solely on the detailed tablet view, and lost the overview displayed on the table. Thus, the later wireframe designs (B and C) were transformed into a grid layout, consisting of a categorical arrangement (A→B). This design provided more efficient use of screen space and supported O+D visualization, where users could peek into more data at once instead of scrolling through it. This modification helped overcome the attention tunneling observed in early pilot tests.

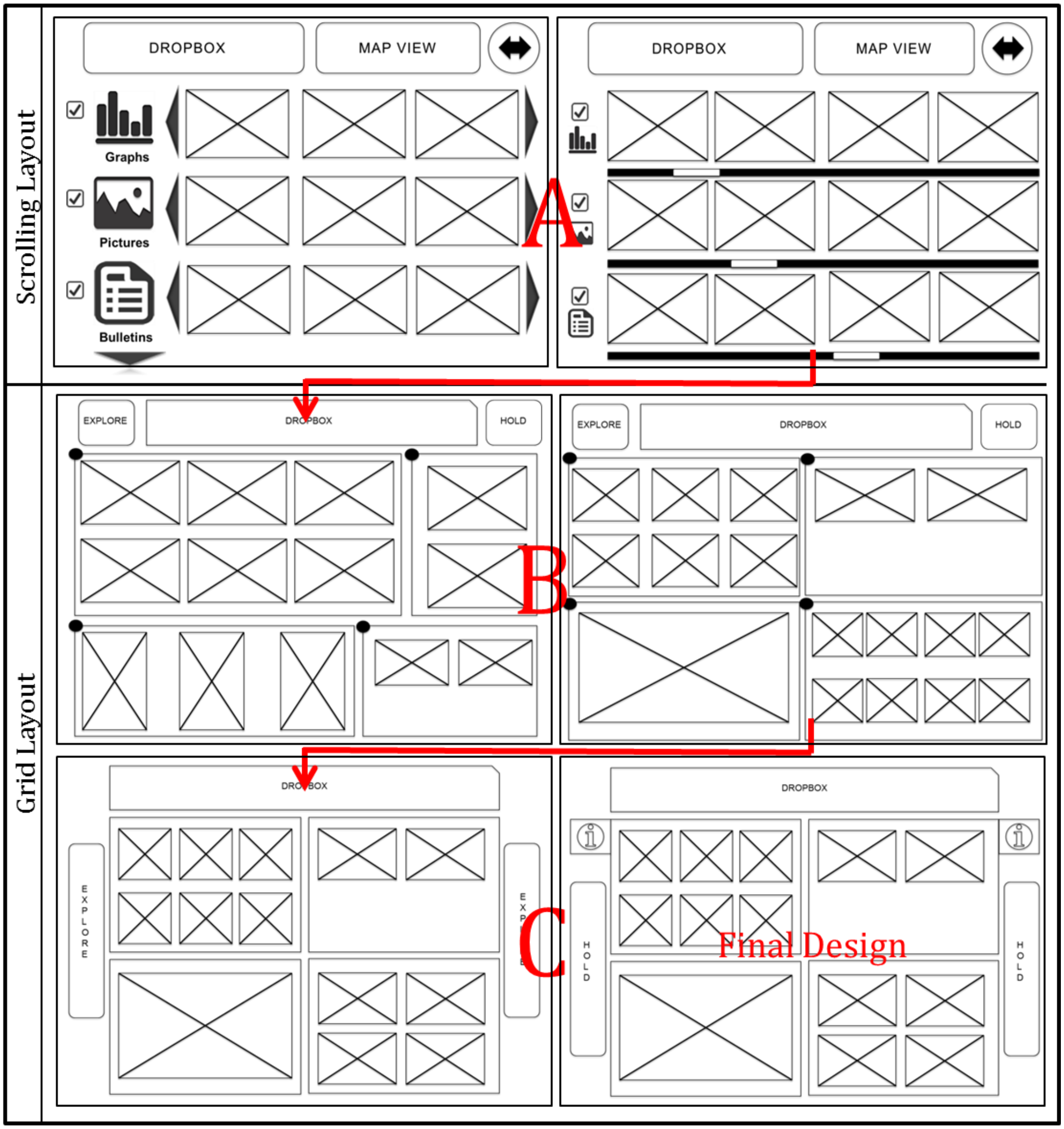


Figure 3.6: The evolution of tablet interface illustrating step-by-step transformation from scrolling layout to grid layout.

The grid layout wireframe design was further modified to improve the ergonomics of holding the device. This was done by changing the position of the hold button from the top right of the interface to both sides of the interface (B→C). The new layout provided better control and supported interaction for both the right- and left-handed users. Moreover, the size of the container where users could drag box items into the “dropbox” was increased to improve thumbnail viewing space.

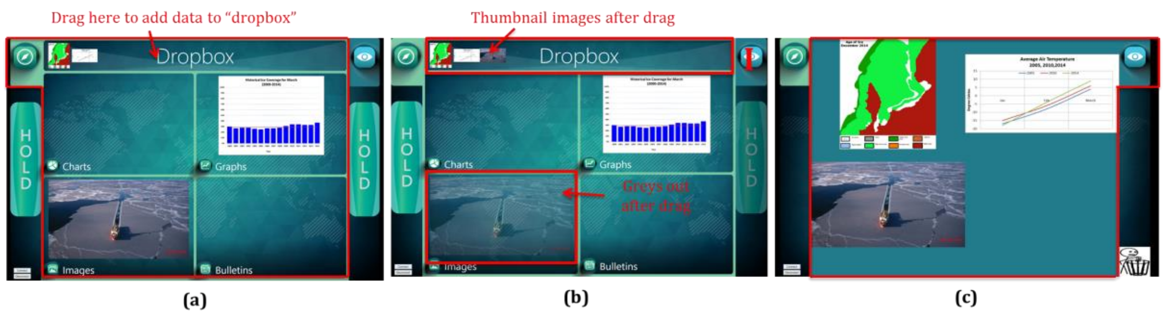


Figure 3.7: (a) Explore view before dragging the data, (b) Explore view after dragging the data adds a thumbnail images, (c) dropbox view showing all the data that is dragged to dropbox.

The “explore view” with the grid layout (see Figure 3.7(a and b)) on the tablet allowed users to get a sneak peek into the dataset by driving the ROI located on the tabletop. However, certain situations may require further data exploration (for an insightful discovery), either to be viewed independently or to discuss with the group. Previously, researcher have found that the performance of a collaborative task can be enhanced when group members share their independent findings (Goyal et al., 2014). Hence, the dropbox feature provided a mechanism for such deeper explorations, where data could be moved into the dropbox by simple dragging the data to a container on top of the tablet screen (a). Once the data is dragged onto the dropbox, a thumbnail image of the dragged item appears in the container, indicating that the data has been moved to dropbox, and this action greys out the dragged item from the grid view (b), hence providing users with additional feedback. Users can switch to “dropbox view” anytime by clicking on the “I” icon, and the data located on the dropbox is available for deeper exploration (c).

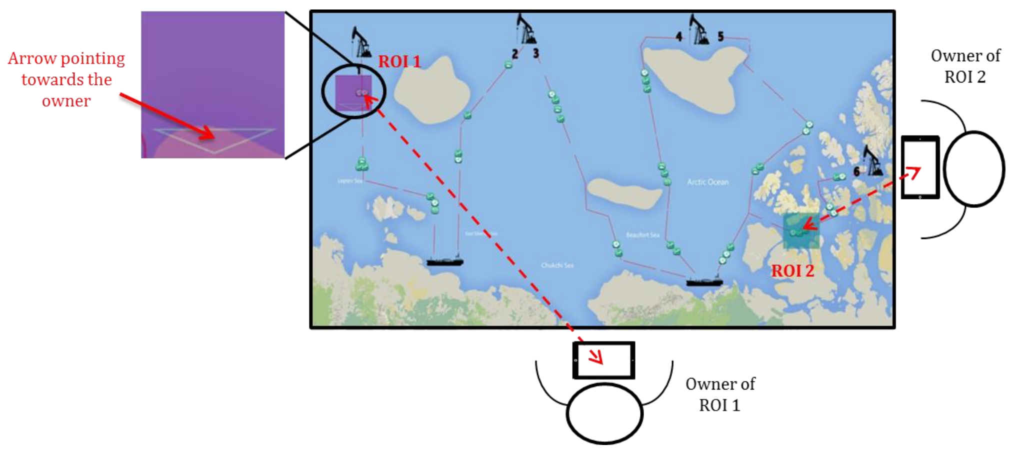
3.3.2 Supporting Awareness and Feedback

In the past, researchers have identified that workspace awareness reduces effort, increases efficiency, and reduces error during collaboration (Gutwin & Greenberg, 1998; Gutwin & Greenberg, 2002). Moreover, workspace awareness plays a vital role in a mixed-focused environment that requires users to switch back-and-forth between tightly coupled and loosely coupled interaction during sensemaking (Gutwin & Greenberg, 1998). When a group is engaged in tightly coupled interaction, awareness about other partners' actions helps members understand what others are referring to during conversation. Furthermore, during loosely coupled interaction, workspace awareness helps overcome conflicts that may arise when collaborators are interacting in the same physical (or virtual) space. Hence, the tabletop interface was designed to support workspace awareness by providing visual feedback as follows:

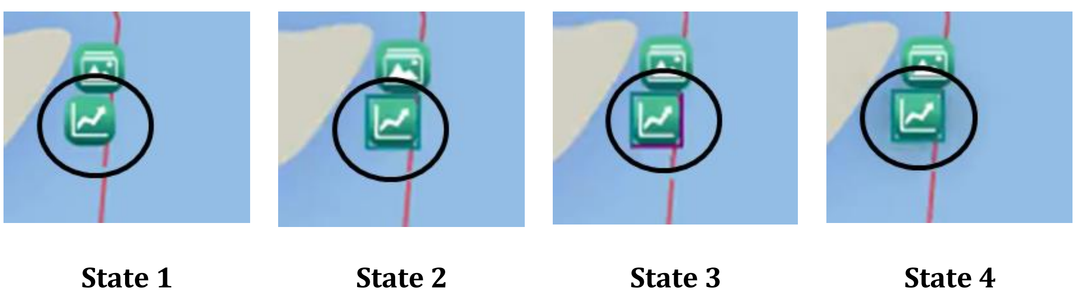
1. As Figure 3.8(a) illustrates, two ROI boxes (ROI 1 and ROI 2) had a unique colour code that was associated with its owners, and a small arrow was displayed inside the ROI box pointing in the direction of the owner's seating position (for experimental purposes, seating positions were fixed and configured during study set up).

2. Once a data item was dragged onto the dropbox, a coloured outline was displayed around the icon on the tabletop indicating the data item that was present in the dropbox. The outline colour was the colour associated with that "owning" user. For example, Figure 3.8(b) illustrates the change of state cycle of a data icon on the tabletop. State 1 is the regular state without any action. State 2 occurs when the owner of ROI 2 drags some data (on their tablet) into the dropbox, and hence a green outline appears on the icon (on the tabletop) that is associated with the data being dragged, indicating

the user of the drag action. State 3 occurs when the owners of both ROI 1 and 2 have dragged data associated with a particular icon into their dropbox, hence both green and purple outlines appear around an icon on the table. State 4 or the "glow" effect around the data icon was integrated to provide visual attention and enhance workspace awareness. This feature was activated on the tabletop interface in two scenarios, either when the user was interacting on a tablet in explore view and decided to enlarge a data item, or when user was interacting in dropbox view and decided to highlighted a data item (by tapping on it).



(a)



(b)

Figure 3.8: (a) Owner specific feedback provided by ROI box using colour coding and arrow pointing towards the owner, (b) Data icon state change cycle on the tabletop interface when user is interacting with the geotagged data associated with the icon on the tablet.

3.4 Chapter Summary

This chapter outlined the design of two data exploration techniques, TOUCH and TILT, and described the design evolution process of tablet and tabletop interface to support the O+D visualization. Based on informal testing, the design went through a number of iterations before producing the final design used in the study. Hence, this chapter elaborated on the second research objective of extending the existing data exploration designs and adapting them to allow the control of a personal view of geotagged data. The next chapter describes the study design and methodology used for data analysis.

Chapter 4

Study Methodology

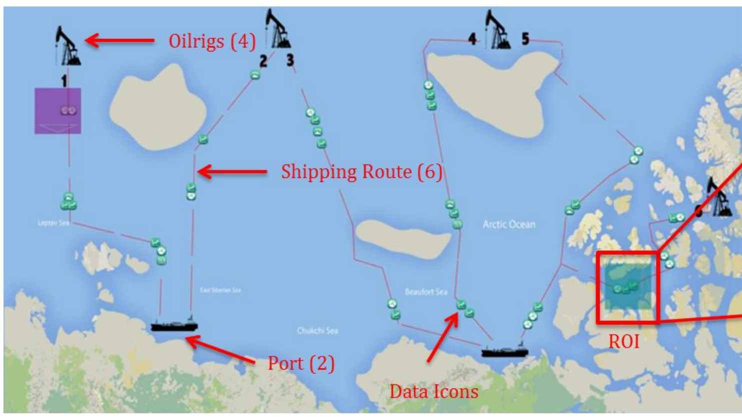
This chapter describes the study methodology used to test the effectiveness of two data exploration techniques. One of the primary objectives of this thesis is to examine how the proposed techniques were used to explore geotagged data during a sensemaking collaborative task. A human-centered research methodology was adopted where the data exploration techniques were verified through user-based testing in a controlled laboratory setting. During the study, the participants were asked to complete a sensemaking collaborative task in groups of two using the data exploration techniques. The task given to each test group was gamified into a collaborative puzzle, which was designed to imitate a real world geotagged data-driven sensemaking scenario. The goal of the task was to enhance user-engagement, and collect feedback on using the two data exploration techniques.

4.1 Study Scenario and Task

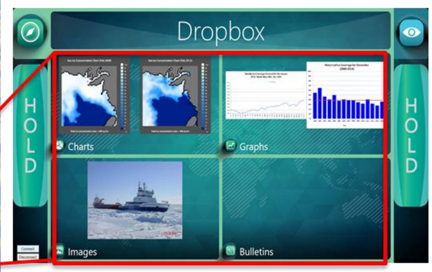
Figure 4.1(a) illustrates a map of the Arctic Ocean with six shipping route options that connect four oilrigs with two ports. The map was overlaid by geotagged data icons representing the graph, chart, photographs and bulletin data associated with the locations, and the geotagged data associated with these data icons could be viewed on the personal tablet (see Figure 4.2(b)) by moving the ROI box over these icons (Section 3.2). The case scenario that was given to each test group consisted of the following:

"Imagine you are a group of data-analysts who work for an oil extraction company, and your goal is to find the most feasible oilrig around the Arctic Ocean. Your company needs to target the

best oilrig based on the accessibility to/from the nearest shipping ports. To help with the analysis there is a map of potential oilrigs and enormous regional data from various webpage sources. Your goal for this study is to explore the geotagged data displayed on a digital map on a tabletop and with the help of your personal tablet navigates this information, and find the best solution for a given scenario."



(a) Tabletop View



(b) Tablet View

Figure 4.1: (a) Tabletop interface showing a map of the Arctic Ocean with four oilrigs, two ports, six shipping routes and two ROI boxes (b) A tablet view showing the tablet interface with geotagged data associated with the icons displayed below the ROI box.

The main task of the collaborative puzzle was to collaboratively explore geotagged data points on the map (see Figure 4.1(a)), and discover the most effective navigation route (out of the six routes) on the map from any port (out of the two) to any oilrigs (out of the four). Within the Artic context, an effective route would be one that is most likely to have open-water (or thin ice) most of the year. The data exploration process entailed moving the ROI box on the tabletop map (either using the TOUCH or TILT technique), and viewing the geotagged data associated with data icons on a personal tablet.

Each group was timed and given twelve minutes to solve the collaborative puzzle. To accomplish the task, participants were given clues associated with data that assisted them to uncover factual and insightful findings. *Facts* are pieces of information that provided explicit knowledge towards solving the task; whereas *insights* provide implicit knowledge, and hence may require collaborative sensemaking. For example, an insightful discovery could be the one made by comparing a historic sea ice coverage graph with a time-stamped aerial view photograph of a region, which was not possible when these two data types were viewed independently. Hence, the task involved the following steps: exploring geotagged data using personal tablets, uncovering relevant facts and insights, and finally, coming up with an answer that was agreeable by the group.

4.2 Study Design

A within-subjects group study was conducted to study the impact of the data exploration techniques while solving a collaborative sensemaking task. This section describes the independent and dependent variables included in the study.

4.2.1 Independent Variables

The study included two independent variables, summarized in Table 4.2. The first independent variable was interaction technique. The study used three levels of this factor to create three within-subjects conditions: TOUCH (Touch Gesture only), TILT (Tilt Gesture only) and BOTH (Tilt and Touch gestures together).

During the study, the order of the first two conditions (TOUCH and TILT) was counter-balanced, and then groups always completed the BOTH condition last. Within the BOTH condition, both the TOUCH and TILT techniques were available to use as described to control the ROI. The BOTH condition was introduced to measure the impact on collaborative sensemaking process when both forms of ROI control mechanisms were available to the group at the same time. Thus, the two possible sequences were: TOUCH→TILT→BOTH or TILT→TOUCH→BOTH. Further, three unique test cases were developed for the study to reduce the impact of learning effect. Two out of three test cases were used for the TOUCH and TILT condition, and the order of these cases was randomized. The third test case was always used for BOTH. A detailed description of three test cases can be found in Appendix A.

Table 4.1: Dependent Variables

Dependent Variables	
Quantitative Measures	**Source**

Perceived Awareness
    Awareness of Spatial Relationship between O+D
    Awareness of Partners Interaction
Perceived Collaboration
    Interference of Actions
    Coordination with Partner
Perceived Workload
    NASA-TLX
Perceived Ease of Use
    Attention/Distraction
    Confidence in the System/Decision Making
    Overall Preference
	Likert-scale rating from questionnaires

Interaction Performance
    Interaction Counts
    Accuracy of ROI Placement
    Spatial Interaction
	Interaction logs

Qualitative Measure	**Source**

Collaborative Behaviour
    Coupling Behaviour
    Territoriality
Task Completion Strategy
    Independent and Collective Task Work
Ease of Use of Technology
    Open-ended comments on study technology
	Open-ended questionnaire
	and Video Analysis

Table 4.2: Independent Variables

Independent Variables	

1. Interaction Techniques:
    TOUCH
    TILT
    BOTH
	2. Seating Position:
	    Long side
	    Short side

A second independent variable used as a between-subject factor in the study - the seating position of each participant in the group (see Table 4.2). One of the two participants was seated on the long side (LS) of the table whereas the other participant was seated on the short side (SS) of the table (as illustrated in Figure 4.2). Participants were instructed to remain on their (self-) assigned sides for the duration of the study.

4.2.2 Dependent Variables

To study the impact of the data exploration techniques on independent and collective exploration in collaborative sensemaking environment, a mixed-method study methodology (combining quantitative and qualitative data analysis) was adopted. The quantitative data collection consisted of 7-point Likert-scale survey questions and interaction logs, and qualitative data collection consisted of open-ended survey questions and video data. Based on the existing themes in the literature on multi-surface environments and collaborative sensemaking, and the domain knowledge from previous studies on cross-device interactions, the goal of this study was to examine the dependent variables listed in Table 4.1. The perceived quantitative measures were awareness, collaboration, workload, and ease of use. The awareness measures included awareness of the spatial relationship between the overview and detail view, and awareness of partners' interactions. For instant, whether the participants were aware of their own actions, their partners' actions and their spatial workspace while performing the task. Awareness during sensemaking is important for both an individual and for the group, to mitigate social conflicts and overcome technical limitations that may arise during collaborative sensemaking.

The perceived collaboration included interference and coordination within group members. These were mainly to test if participants felt interfered with their partner, or if they felt that they interfered with their partner while performing the task. The perceived workload was computed using a NASA-TLX (Cao et al., 2009) questionnaire measuring the mental and physical workload that was required to perform the task. The ease of use measures included attention/distraction, confidence in the system, and preference of technique. The interaction performance measures was computed using the interaction log data, and included the number of interaction counts, accuracy of positioning the ROI, and the spatial interaction on the tabletop interface.

The qualitative measures were analyzed using the video data and the open-ended survey questions, which included the following measures: collaborative behaviour, employed task completion strategy, and the ease of use of technology. The collaborative behaviour explored the groups' coupling behaviour exhibited during the task sessions, and if there was any territoriality that may have existed while performing the task. Next, the task completion strategy measure explored the task strategies employed by the group, such as independent or collective task work. Lastly, the ease of use of technology examined participants' reported comments on whether the technology helped or hindered task completion.

4.2.3 Test Case Design

As previously mentioned, there were three conditions, and each condition required a unique test case to run a within-subjects comparison. Each case consisted of a situation description and few clues specific to the situation to uncover factual and insightful data from all the given data. For example, a situation would include, *"Global warming has led to changing temperatures and* *has affected ice conditions in various regions in the Artic. These changes can impact the ability to predict routes for future travel…… find the best route for transporting oil during the winter period (December–March) considering changing ice conditions as the main factor.",* and the following clue, *"Comparing Ice charts within a given region over a period of time can provide helpful information on ice change."*

These case situations emulated a real-world problem designed around the collaborative sensemaking environment, where data analysts have some background knowledge of the problem and they convene with other data analysts to get a deeper sense of the data.

4.2.4 Data Selection and Testing

The dataset used for the study was adapted and modified from the Arctic sea ice data gathered from *Canadian Sea Ice Service (CSIS)* [1] and *National Snow and Ice Data Center* (*NSBOTH)*[2] website. The three test cases were developed through an iterative testing process. The goal of iterative testing was to avoid any unconscious bias towards the use of a particular exploration technique. The testing process started with the three researchers splitting up, as each worked independently on a separate test case, involving creation of data, consistent spreading of data on the map, and selection of facts and insights. The splitting technique was adopted to illuminate overlap between the cases and get a new perspective on each case.

A pilot study was conducted after every modification, and the data was readjusted (made more difficult or easier) to match the difficulty level of all the three cases. During pilot testing if

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[1] https://www.ec.gc.ca/glaces-ice/

[2] http://nsidc.org/

the participants were unable to solve the case within a time limit, the numbers of facts were increased and insights were decreased, and vice-versa. The same process was repeated for all the three cases until the task completion time for all cases was in the same time range. To match the three cases, the correct answers were evenly spread around the map. Therefore, a correct answer (best route to oil rig) to case 1 was route one or six, case 2 was route three or four, and case 3 was route five or six (six available routes are illustrated in Figure 4.1(a)).

4.3 Participants

The study was conducted with 24 participants (12 groups with two participants in each group), with 12 male and 12 female participants, within the age range of 18-45 years old. They were recruited by an invitation email or recruitment poster (see Appendix A), and were either students or employed in the technology field. All participants were frequent users of touch-based computing devices, and a few of them had prior console gaming experience that requires the use of a joy stick or direction control. One of the requirements for taking part in the study was that the two participants (or a group) know each other prior to the study, hence it was expected that they would be comfortable working together to solve a collaborative task.

4.4 Equipment and Setting

The study took place in a human-computer interaction laboratory at the University of Waterloo from July 6th to July 20th of 2015. The setup consisted of a custom-built multi-touch digital tabletop and two *Microsoft Surface Pro*[3] tablet devices. The digital tabletop incorporated a 4K (3840x2160 pixels) resolution 55-inche flat-panel LED display fitted with a PQLabs infrared

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[3] https://www.microsoft.com/surface/en-ca/devices/surface-pro-3

multi-touch frame. The arrangement of setup and participants is illustrated in Figure 4.2. To evaluate the impact of the rectangular dimensions of the tabletop, the two participants were seated at adjacent sides of the table, while researchers observed their actions from a few meters away. The first participant was seated on the long side of the table, and second was seated on the short side of the table. Therefore, most long-side participants (LS) could physically reach the entire tabletop screen, whereas it was physically impossible for a short-side participant (SS) to interact with the far end of the table or the "out-of-reach" region, as shown in the Figure 4.2. A video camera was installed on top of the tabletop for recording physical interactions, and a microphone for recording audio conversation between the participants.

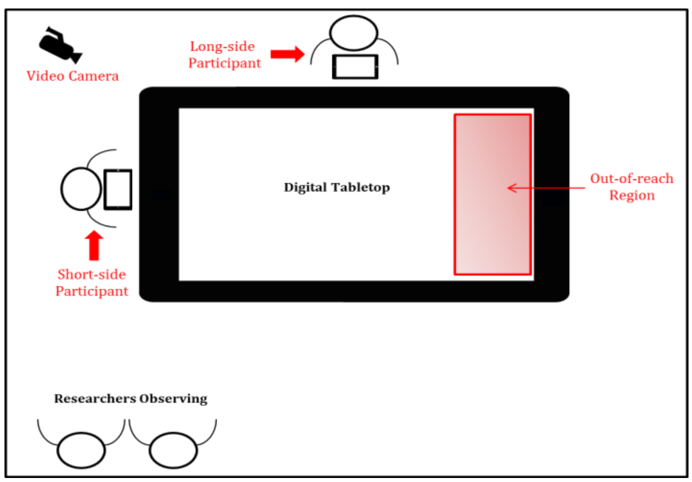

Figure 4.2: Experimental Setup

4.5 Procedure

Figure 4.3 illustrates the steps involved in the procedure of each study session, lasting for approximately 90 minutes. All participants were welcomed by the researchers by handing out a letter of information, consent form and background questionnaire. Next, the study began with the training that consisted of four steps. First, the participants were instructed about the user interface elements (i.e. buttons, menus, viewing modes and dropbox) and different feedback features (like data outline, glow effect, and highlight). Second, they were trained to interact with the multi-touch digital tabletop and the *Microsoft Surface Pro*. Third, they were educated on comprehending the data, by giving an example of factual and insightful findings. Finally, the group performed a short practice exercise prior to using the first condition. The training step was only required before the TOUCH and TILT conditions, because for the BOTH condition, participants were already trained in using all the required features.

The training and practice steps were followed by either the TOUCH or the TILT condition, whereas BOTH condition was always the last condition. During each condition, the group was asked to solve a unique test case. The first two conditions (TOUCH and TILT) were counter-balanced, and the first two test cases were randomized, whereas the third case was always used during the BOTH condition. The condition was always followed by a separate post-condition questionnaire. Towards the end of the study, participants filled out a post-experiment questionnaire, followed by a short group interview.

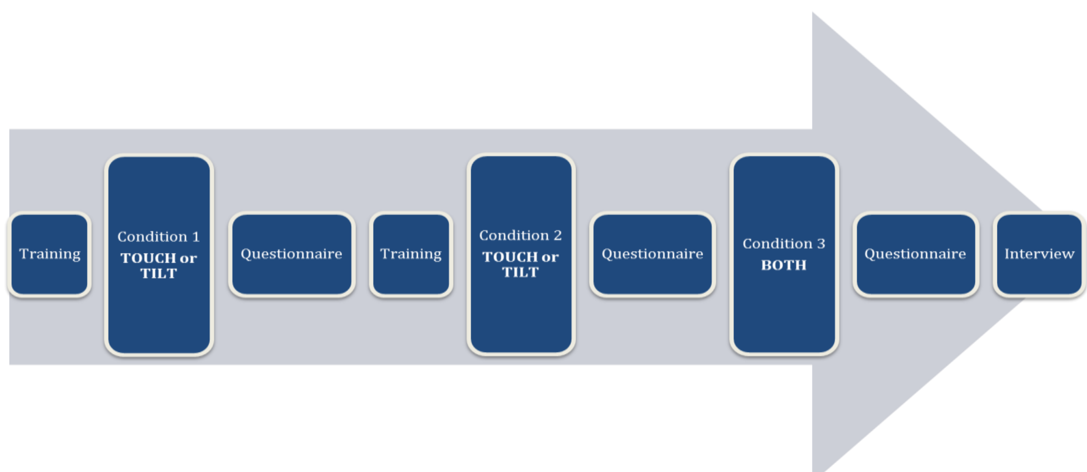

Figure 4.3: Study Procedure

4.6 Data Collection

During the study participants' actions were recorded digitally via screen capture computer software, and their physical actions and spoken words were recorded using a video camera and audio recording. There were various types of data that were collected, including observation notes, survey results, computer logs, video recording and group interviews. First, the researchers took observation notes during the study. The observation procedure aimed at analyzing groups' interaction and collaborative effort to solve the sensemaking task.

Second, a post-condition survey was a combination of 7-point Likert-scale questionnaire, NASA-TLX and open-ended questionnaire for measuring various dependent variables (see Table 4.1).

Third, the software automatically recorded users' interactions with the tabletop and tablet interface in computer log files. Stored interaction included interaction times, position (exact coordinates) and movements of the ROI box (from one coordinate to another). Separate log files were created for each condition.

Fourth, a video camcorder was affixed above the table at an angle that captured the entire working area around the table (Figure 4.4). The camcorder recorded the physical interactions and information being viewed (on tablet and table) by participants. Their conversations were recorded using an additional audio recording microphone. This helped understand how participants positioned themselves and their handheld device during a collaborative sensemaking process.

Finally, a short post-experiment unstructured group interview was conducted for obtaining verbal feedback from participants. The interview was also video recorded to capture physical gestures of participants (explaining their interaction with the system) as they answered each question.

Figure 4.4: Video Recording Capturing participants' physical actions

4.7 Data Preparation/Analysis

The primary objective of the study was to investigate the utilization of the data exploration techniques to support a collaborative sensemaking task, and the secondary objective was to observe the impact from the seating position of the participants on collaborative interactions. Therefore, the data analysis process consisted of examining group interactions during the collaborative sensemaking task, and investigating the variation in the group interactions while exploring data. Based on the knowledge about physical limitations of a tabletop (due to their rectangular dimensions), it was expected that LS had an advantage over SS for physically interacting with the table in the TOUCH condition. Hence, the LS participant was expected to prefer TOUCH over the TILT condition, as the TOUCH condition offered easy access to the entire tabletop screen with minimal learning that was required while using the TILT condition.

To validate the quantitative data, statistical tests were run on the post-condition and post-experiment survey results. A 2x2 analysis of variance (ANOVA) was conducted to measure any impact from both condition and table-side. In ANOVA, the tabletop side distinction (LS and SS) was considered as between-subjects variable, and the study conditions were treated as a within-subjects variable. The data-analyzed included all 24 participants (12 SS and 12 LS). An alpha value of α=0.05 was used to determine the significance for the ANOVA test results. Detailed finding of these test have been included in Appendix B and C.

The results from quantitative analysis were further validated by amalgamating the collected data including videos, log data, observation notes, interview and survey results, and were compared against each other. To better understand log data, the recorded numeric log information was converted into interaction visualization maps using *Processing (p5.js)*[4]. This form of log visualization map illustrating a spatial representation of the tabletop interactions during the task cycle is a common practice to study tabletop interaction behaviour (Nacenta et al., 2007) .

The number of facts and insights that were uncovered by the participants during each task condition were not used for data analysis. This is because the task was primarily a time-constrained data exploration task, which involved a quick scanning of data and making sense out of data in a given time. Hence, participants used the elimination strategy (instead of in-depth analysis) to filter out the best information from the given data. In the process they missed various facts and insights even though they were successful in finding the correct answer.

4.8 Chapter Summary

To fulfill the third research objective of evaluating the effectiveness of the proposed data exploration technique, this chapter elaborated on the study design, and the data analysis methodology applied to study the findings. Using a human-centered design methodology, a

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[4] http://p5js.org/

user-based study was conducted to test the utilization of two data exploration methods. The study was run in a controlled lab environment consisting of a digital tabletop and two handheld tablets. The participants performed the study in a group of two, while researchers unobtrusively observed them and their actions were video and audio recorded. The data collected was analyzed using mixed-methods (qualitative and quantitative) technique. The next chapter will present the qualitative and quantitative findings of this thesis.

Chapter 5

Findings

The sensemaking process employed by participants in the study was consistent with previously observed sensemaking behaviour (Pirolli & Card, 2005; Yi et al., 2008; Wallace et al., 2013). Most groups started the task by working independently to get an overview of the data, and to detect useful patterns within the data. This was followed by a collaborative phase where participants merged their activities, to reach a common ground with their partner. Overall, it was observed that the TILT condition better facilitated independent interactions, whereas the TOUCH condition better facilitated collaborative interactions. Moreover, the expected impact of seating arrangement discussed in Section 4.4 was observed only in some situations, and was largely mitigated by the collaborative nature of the task. As this chapter will show, both the TOUCH and TILT techniques offered different benefits, and were utilized differently for the data exploration during the sensemaking process, as teams were able to use both techniques to successfully complete the given collaborative sensemaking task. The particular effectiveness of each technique was highly dependent upon a group's preferred task strategy, and coupling state.

This chapter first reports on the quantitative analysis of participants' subjective and preference data, and performance measures across condition and seating arrangement. Then, the findings from the qualitative analysis are presented, based on the collected video data, participant comments, and analysis of interaction map visualizations produced from the computer log file. These findings highlight the impact that group strategies, such as coupling styles and territoriality had on groups' use of the TOUCH and TILT techniques during data exploration. The chapter first focuses on the observed differences between the TOUCH and TILT trials, and then reports on the observed use of the two techniques in the BOTH condition. The latter section focuses on how having both techniques available helped groups' overcome some of the respective usability issues of each individual method.

5.1 Quantitative Analysis

Previous research has found that collaboration and awareness measures play a key role in analyzing the effectiveness of a collaborative systems (Gutwin & Greenberg, 2002). Moreover, the task used in this study was a time-dependent task, which was expected to add an additional complexity (both mentally and physically). Thus, the following quantitative analysis section details the impact of awareness, collaboration, workload and performance, on the TOUCH and TILT techniques as observed by participants seated on both long and short side of the table.

5.1.1 Perceived Awareness, Collaboration and Workload

A series of 2x2 mixed factor design repeated measure ANOVA tests were conducted on the post-experiment questionnaire data, and this section reports on the significant findings from those tests for awareness, collaboration and workload measures. The complete analysis can be found in Appendix B. Table 5.1 summarizes the data and ANOVA results. The test on the awareness measure question, *"I found viewing the data on the tablet while moving the ROI on the table at the same time to be – easy (rating: 1) or difficult (rating: 7)"* yielded a significant effect for the technique factor ($F(1,22)=5.85$, $p=0.024$, $\eta 2=0.21$), but a non-significant effect for seating position ($F(1,22)=0.287$, $p=0.598$, *n.s.*) nor was there a significant interaction effect ($F(1,22)=0.936$, $p=0.344$, *n.s*). These results indicate participants (in both seating positions) were more aware of the relationship between ROI and data displayed on the tablet when using the TOUCH condition compared to the TILT condition.

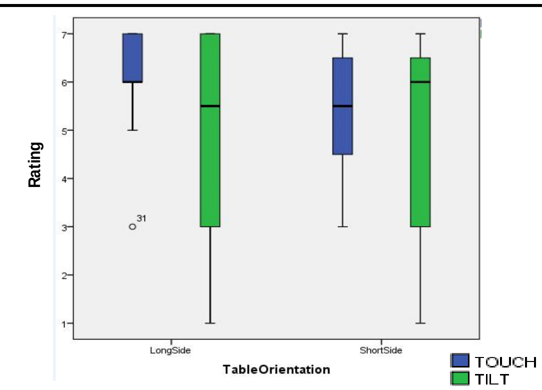
The test on the collaboration measure question, *"I felt my partner interfered with my actions while browsing data"* yielded a significant effect for both main factors, the technique ($F(1,22)=13.48$, $p=0.001$, $\eta 2=0.38$) and the seating position ($F(1,22)=5.92$, $p=0.024$, $\eta 2=0.21$), and a non-significant interaction effect ($F(1,22)=2.237$, $p=0.149$, *n.s*). Similarly, for the question, *"I felt that I interfered with my partner's action while browsing data*", the test yielded significant effect for both main factors, the technique ($F(1,22)=7.77$, $p=0.011$, $\eta 2=0.26$) and the seating position ($F(1,22)=5.883$, $p=0.024$, $\eta 2=0.21$), and non-significant interaction effect ($F(1,22)=1.74$, $p=0.2$, *n.s*). Together these results indicate that both LS and SS participants felt they were more interfered with their partners' actions and also that they interfered more with their partners' actions in the TOUCH condition than in the TILT condition. Further, in both cases, the LS participants reported more interference compared to their SS partners in the TOUCH condition than in the TILT condition.

Some significant results were found on the workload measures from analysis of the NASA-TLX questionnaire. The test for *physical effort required to accomplish a task* yielded a non-significant effect for technique ($F(1,22)=0.957$, $p=0.339$, *n.s*), but a significant effect seating position ($F(1,22)=4.409$, $p=0.047$, $\eta 2=0.16$), and a non-significant interaction effect ($F(1,22)=0.012$, $p=0.914$, n.s). These results indicate that both techniques required similar levels of physical effort but that across techniques SS participants reported both techniques to be more physically effortful than LS participants. The test for *frustration to accomplish a task* yielded a marginally significant effect for the technique ($F(1,22)=3.254$, $p=0.085$, *n.s*) and a non-significant effect for seating position F(1,22)=0.01, p=0.921, *n.s*), and non-significant interaction effect (F(1,22)=0.242, p=0.628, *n.s*).

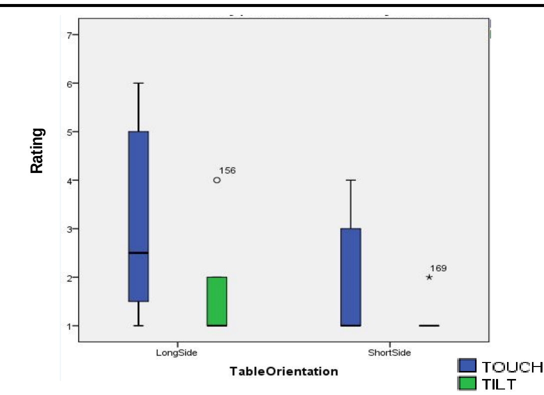
Table 5.1: Post-condition Likert questionnaire results comparing awareness, collaboration and workload measures. (*significance at α=.05)

Factors	Questions	TOUCH		TILT		RM-ANOVA
		LS	SS	LS	SS	
		Mean (SD)		Mean (SD)		
Awareness	*I found viewing the data on the tablet while moving the bounding box [ROI] on the table at the same time to be:*	6.08(1.16)	5.41(1.31)	4.91(2.15)	4.91(2.1)	* Sig Contrast Condition: F(1,22)=5.85, p=0.024
Collaboration	*I felt my partner interfered with my actions while browsing data.*	3.17(1.94)	1.75(1.13)	1.58(0.9)	1.08(0.29)	* Sig Contrast Condition:F(1,22)=13.48, p=0.001 * Sig Contrast LS vs SS:F (1,22)=5.92, p=0.024
	I felt that I interfered with my partner's action while browsing data.	3.25(1.91)	1.75(1.21)	2.08(1.31)	1.33(0.49)	* Sig Contrast Condition: F(1,22)=7.77, p=0.011 * Sig Contrast LS vs SS:F (1,22)=5.883, p=0.024
Workload	Effort	4.67(2.9)	6.33(1.92)	5.08(2.11)	6.67(1.15)	* Sig Contrast LS vs SS:F (1,22)=4.409, p=0.047
	Frustation	4.67(2.9)	6.33(1.92)	5.08(2.11)	6.67(1.15)	F (1,22)=5.92, p=0.024

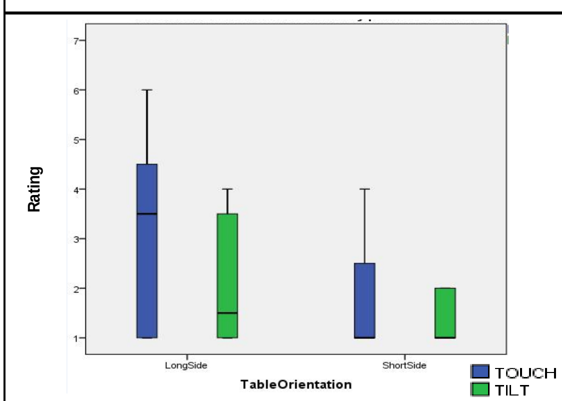
I found viewing the data on the tablet while moving the bounding box [ROI] on the table at the same time to be:



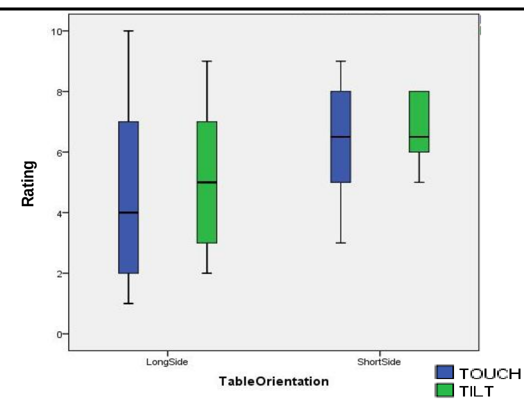
I felt my partner interfered with my actions while browsing data.



I felt that I interfered with my partner's action while browsing data.



Effort



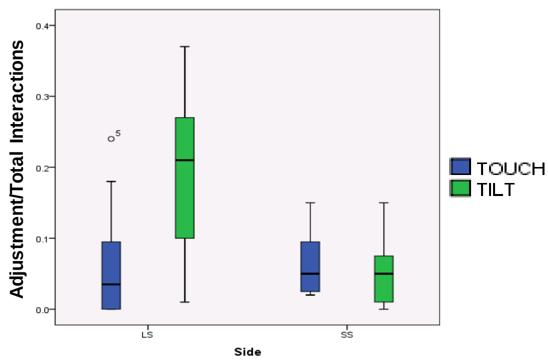
5.1.2 Accuracy of Positioning the ROI

Data gathered from the interaction logs revealed that 2300 interactions took place in the TILT condition compared to only 1174 interactions in TOUCH. The significant amount of TILT interactions partially resulted from different data exploration strategies used with the two techniques. However, observations made during the study and initial review of video data indicated that the greater number of interactions may have been the result of some usability issues (like overshooting or undershooting of target) participants encountered while positioning the ROI accurately. Thus a more in-depth investigation was conducted on the accuracy of each of the techniques using the interaction log data.

As a representative measure of targeting accuracy (i.e. how accurately a user could position the ROI over the desired data points), the log files were analyzed to identify occurrences in which the user immediately readjusted a location of ROI after an ROI move, for instance, where they may have overshot or undershot the desired target location. An ROI movement was considered a "correction" if it met the following two conditions: 1) it followed within 0.38 seconds of a previous ROI movement, 2) it covered a very short distance (physical moment of ROI<150 pixels). These numbers were determined on the average time and distance calculated by observing the adjustment interactions made in the video data. Thus, a 2x2 repeated measure ANOVA was conducted on these numbers to compute the adjustment interactions required to accurately place the ROI. The test yielded a significant effect on both main factors, the technique ($F(1,22)=7.753$, $p=0.01$, $\eta^2=0.26$) and the seating position ($F(1,22)=10.129$, $p=0.04$, $\eta^2=0.315$), along with a significant interaction effect ($F(1,22)=9.49$, $p=0.05$, $\eta^2=0.301$). As Table 5.2 shows, during the TILT condition there were more adjustments made to the ROI (12.4% of the total interactions - LS: 6.2%, SS: 6.3%) compared to the TOUCH condition (6.3% of the total interactions - LS: 19.3%, SS: 5.7%). The complete analysis can be found in Appendix B.

Table 5.2: Adjustment made per total interactions in the TOUCH and TILT condition by LS and SS participant. (*significance at α=.05)

Factor	TOUCH		TILT		RM-ANOVA
	LS	SS	LS	SS	
	Mean (SD)		Mean (SD)		
Adjustments per Total Interactions	0.06(0.08)	0.06(0.04)	0.19(0.11)	0.06(0.05)	* Sig Contrast Condition: $F(1,22)=7.753, p=0.01$ * Sig Contrast LS vs SS: $F(1,22)=10.129, p=0.004$ * Sig Contrast Interaction: $F(1,22)=9.49, p=0.005$



As expected, the majority of Long-Side (LS) participants ranked TOUCH above TILT in their preferred condition ranking in the post-experiment questionnaire (11 out of 12 preferred TOUCH and one preferred TILT). Less expected, was that six out of 12 Short-Side (SS) participants ranked TOUCH above TILT, and the remaining six ranked TILT above TOUCH. The findings from the qualitative analysis presented below provide insights into this unexpected finding.

To further investigate the preference and applicability of techniques for sensemaking, video analysis was conducted to identify emerging themes, and ROI interaction visualization maps were created for deeper analysis. The next section will discuss findings from these qualitative findings.

5.2 Qualitative Analysis

Initial review of the video data revealed two distinct phases of most groups' sensemaking session, consistent with previous collaborative sensemaking literature (Isenberg et al., 2012), Thus, each study session was split into two phases based on the predominant group coupling strategy used during the ongoing task activities - whether groups were predominantly interacting in a loosely or tightly coupled manner, as described in section 2.1.1. These changes in the group interaction closely aligned with different phases of the sensemaking process. Thus, framing the analysis using the broad task partitioning enabled the examination of the impact of the TOUCH and TILT techniques in different collaborative and task activity contexts. Consistent with Isenberg et al. (2012), the initial phase (Phase 1) was the *loosely coupled* phase where most groups worked independently with the occasional period of joint work. During this phase the primary activities included overviewing the data (viewing and filtering) and initial adjustment of the data, mapping to the first two stages of Yi et al.'s (2008) sensemaking model (see section 2.1). The second phase (Phase 2) was dominated by *tightly coupled* interactions with a brief loosely coupled interaction for verification before making a final decision. During this phase the groups continued to adjust the data and engaged in pattern detection and matching their mental model to the data, corresponding to the remaining stages of Yi et al.'s sensemaking model. These phase divisions during group interaction throughout the sensemaking task are illustrated in Figure 5.1(a). Further evidence of the phase division was provided by analyzing audio signals from the group conversation recorded during a task session. Figure 5.1(b) illustrates a typical audio conversation conducted by one of the 12 groups while solving the sensemaking task. As shown, the audio waveform starts with a burst of audio signal that signifies brief period of joint discussion, mainly for task strategizing. Next, the audio signal subsides, illustrating the loosely coupled Phase 1 with little communication between the two participants. Further, a huge burst of sound was recorded signifying the discussion between participants, during the tightly coupled Phase 2.

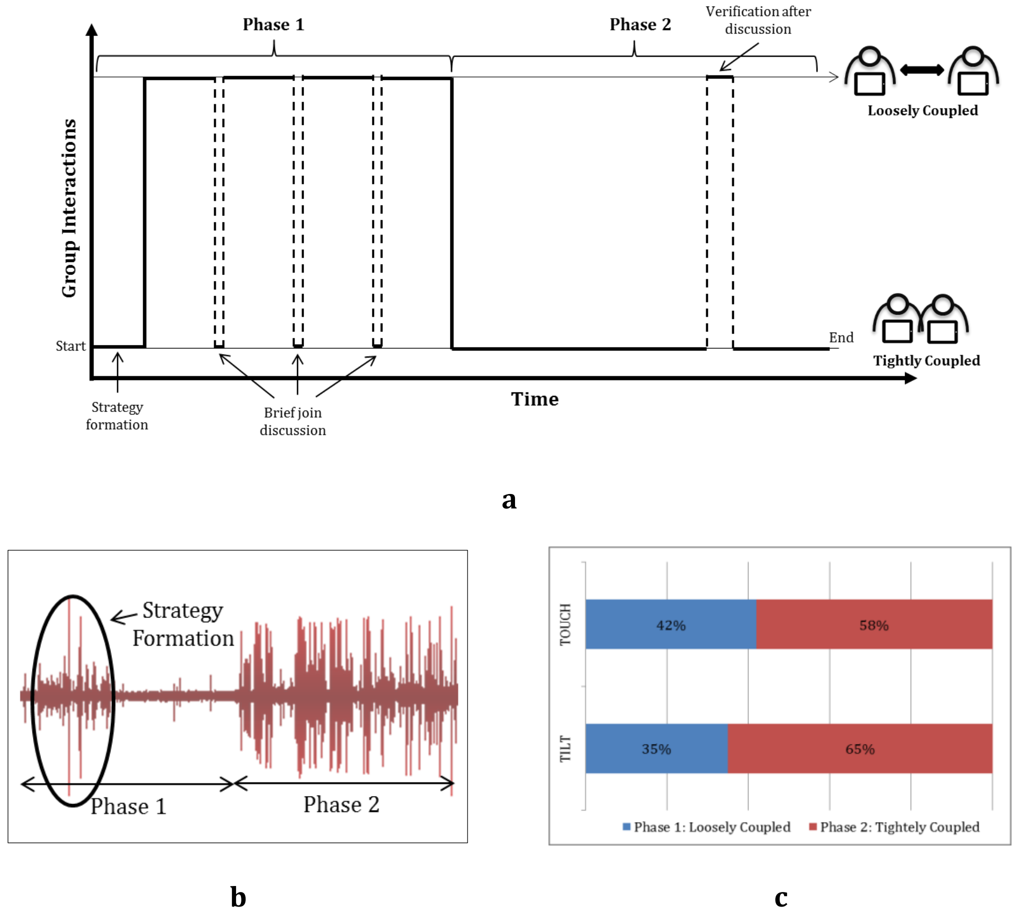


Figure 5.1: (a) Group interactions and phase division throughout sensemaking task, (b) Recorded audio signal from a group conversation illustrating phase division, (c) Phase division across TOUCH and TILT condition.

It was found that groups spent more time in Phase 2 than in Phase 1 and this difference was found to be statistically significant ($F(1,22)=6.75$, $p=0.016$, $\eta 2=0.235$). Even though there was a trend for groups to spend more time in Phase 2 in the TILT condition compared to the TOUCH condition (during TOUCH condition groups spend on average 42% of their task completion time in Phase 1 and 58% in Phase 2, and in TILT condition they spent 35% of their task completion time in Phase 1 and 65% in Phase 2 - see Figure 5.1(c)), this difference was not statistically significant ($F(1,22)=0.55$, $p=0.46$). A detailed analysis of RM-ANOVA can be found in Appendix B.

In addition to the observed differences in collaborative coupling, the video analysis also uncovered the differences in collaborative strategies, such as divide-and-conquer or overlapping data exploration. Moreover, it was observed that the participants' seating position during the study had a significant impact on use of each condition. While the TILT condition offered flexibility for long-distance independent explorations in Phase 1, the TOUCH condition provided support for cooperative interactions by offering flexible ownership during Phase 2, especially when a group operated in an extremely tightly coupled fashion, exploring the same data together. The remainder of this chapter will elaborate on how the TOUCH, TILT and BOTH conditions were used during Phase 1 and Phase 2 interactions. The Phase 1 section will provide further detail into collaborative coupling to explore the impact of territoriality on use of the TOUCH and TILT techniques. The Phase 2 section will elaborate on various collaborative data exploration strategies observed based on the groups' collective or independent physical navigation interactions.

5.3 Examining Data Exploration Behaviour in Phase 1: Independent Overview and Adjustment of the Data

The data analysis revealed that most groups chose to engage in a period of independent data exploration following a brief period of strategy discussion. During this loosely coupled data exploration participants primarily overviewed the available data, and began the adjustment phase of the sensemaking process by saving some potentially useful data in the dropbox area of their respective tablets. This section describes the different data exploration behaviours that were observed during Phase 1. It focuses on the areas of the tabletop explored by respective groups, as this is representative of the "information space" given the geospatial task context used in the study.

In particular, after a brief discussion of groups' strategy formation phase, this section describes the observed territorial behaviour groups exhibited in the shared tabletop workspace during their independent data exploration, and the impact of TOUCH and TILT techniques on territoriality. Groups also had a brief period of tightly coupled interactions primarily to mention or highlight potentially interesting data to examine further during Phase 2. These groups' interactions are also described.

5.3.1 Strategy Formation

As mentioned, the sensemaking task was initiated by a brief discussion phase, where groups strategized their plan to solve the task. As the groups were required to finish the sensemaking problem within the given time limit, the most agreed on method employed by most groups was to split the tabletop screen, and hence the information space into two halves. This allowed each participant to independently explore their own data set, and then get together as a group to discuss the main findings. This "divide-and-conquer" approach was found to be very effective, as one participant commented, *"Aspects that helped was that [I] checked one side of the data and my partner did the other side. Then we came together to compare and come up with a solution."* (SS8).

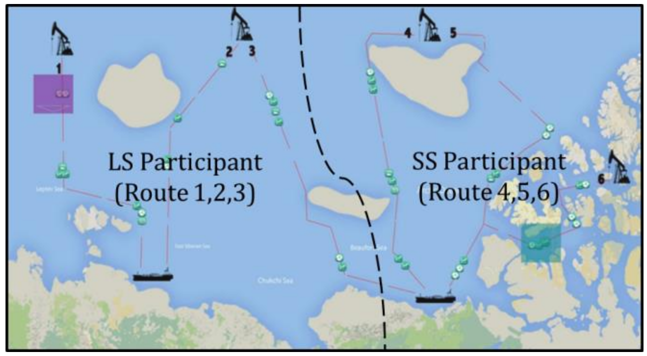


Figure 5.2: Implicit division of tabletop screen between LS and SS participants

It was found that most of the groups either explicitly strategized to use the divide-and-conquer approach, or in some cases the split occurred rather implicitly based on the physical proximity of the data. The most efficient task division was equally splitting the routes; hence the LS participant took routes one, two and three, and SS participant took routes four, five and six (see Figure 5.2).

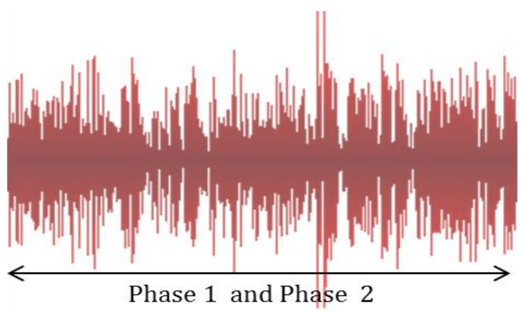


Figure 5.3: A typical audio group conversation waveform illustrating groups that did not use divide-and-conquer.

It was observed, in both the TOUCH and TILT condition, 10 out of 12 groups utilized the divide-and–conquer approach, and started the task by overviewing data independently in a loosely coupled manner. The remaining two groups chose, instead, to explore the data together, in a very tightly coupled manner throughout the whole sensemaking process. This was further evidenced by the omnipresent audio signal (see Figure 5.3) throughout the sensemaking task demonstrating a constant communication between group members, and also confirms the absence of Phase 1 for these groups.

5.3.2 Observed Tabletop Territoriality

By splitting the physical space into two territories, each participant was expected either explicitly or implicitly explore data within their own respective territories. Yet, it was observed that some participants did not remain confined to their own territory. While, most groups adopted a divide-and-conquer strategy, only few (six in TOUCH and seven in TILT) of these groups followed the plan. There were groups where participants confined their data exploration to their own territory, and hence exhibited *strong territoriality (ST)*. In contrast, in other groups, one or both participants explored data outside the explicitly or implicitly defined territory, and thus exhibited *weak territoriality (WT)*. Hence, out of the 10 groups who employed the divide-and-conquer strategy, there was a further division of groups based on the groups' territoriality.

In the TOUCH condition, six out of 10 groups exhibited ST, and four groups exhibited WT. Similarly, in the TILT condition, there were seven groups that exhibited ST (five of which exhibited ST in TOUCH) and three groups exhibited WT (all of which exhibited WT in TOUCH). The fact that five common groups exhibited ST and three common groups exhibited WT across the TOUCH and TILT condition, demonstrates that condition had minimum impact on territoriality, but rather that it was determined by groups' social dynamics and strategy.

To better understand territoriality, ROI movement interaction maps (see Figure 5.4) were generated for the ROI movements that occurred on the tabletop interface during Phase 1 of TOUCH and TILT condition. As illustrated, the WT groups were exploring data across the entire tabletop screen, and for ST groups, exploration occurred within their implicit territory (illustrated by ROI traces only on one side of the table interface). The yellow boxes depict self-interactions using the TOUCH condition, blue boxes depict self-interactions using the TILT condition, and brown boxes depict “helped by partner” interactions (only possible in TOUCH). The “helped by partner” interactions refer to the event when the ROI movement was not controlled by the owner but instead, by their respective partner. This behaviour will be elaborated on further in section 5.4.

5.3.3 Impact on Accuracy of placing the ROI

To explore geotagged data on the tablet, participants had to place their ROI at the correct location of associated data icon on the tabletop. Therefore, moving the ROI to accurately target the exact data icons on the tabletop was a significant factor during the study. Data analysis revealed that the ROI movements conducted using the TOUCH condition offered more accurate targeting of icons compared to the TILT condition (see section 5.1.2). Figure 5.4 further illustrates this lack of accuracy in the form of additional “jitter” interactions in the TILT condition compared to the TOUCH condition. In the TILT condition, ROI movements were controlled by the tilting motion of the tablet in the direction of ROI movement (see section 3.2.2), which was often hard to learn (especially for participants with limited console gaming experience) compared to the direct touch based TOUCH condition. During pilot testing, the impact of placing the ROI at an exact location was anecdotally observed to be more tedious for some participants using the TILT condition. Moreover, the accuracy issue during the TILT condition was observed more with the LS participant than the SS participant. Recall from the quantitative analysis (section 5.1.2) where the LS participant conducted more adjustment interactions during the TILT condition.

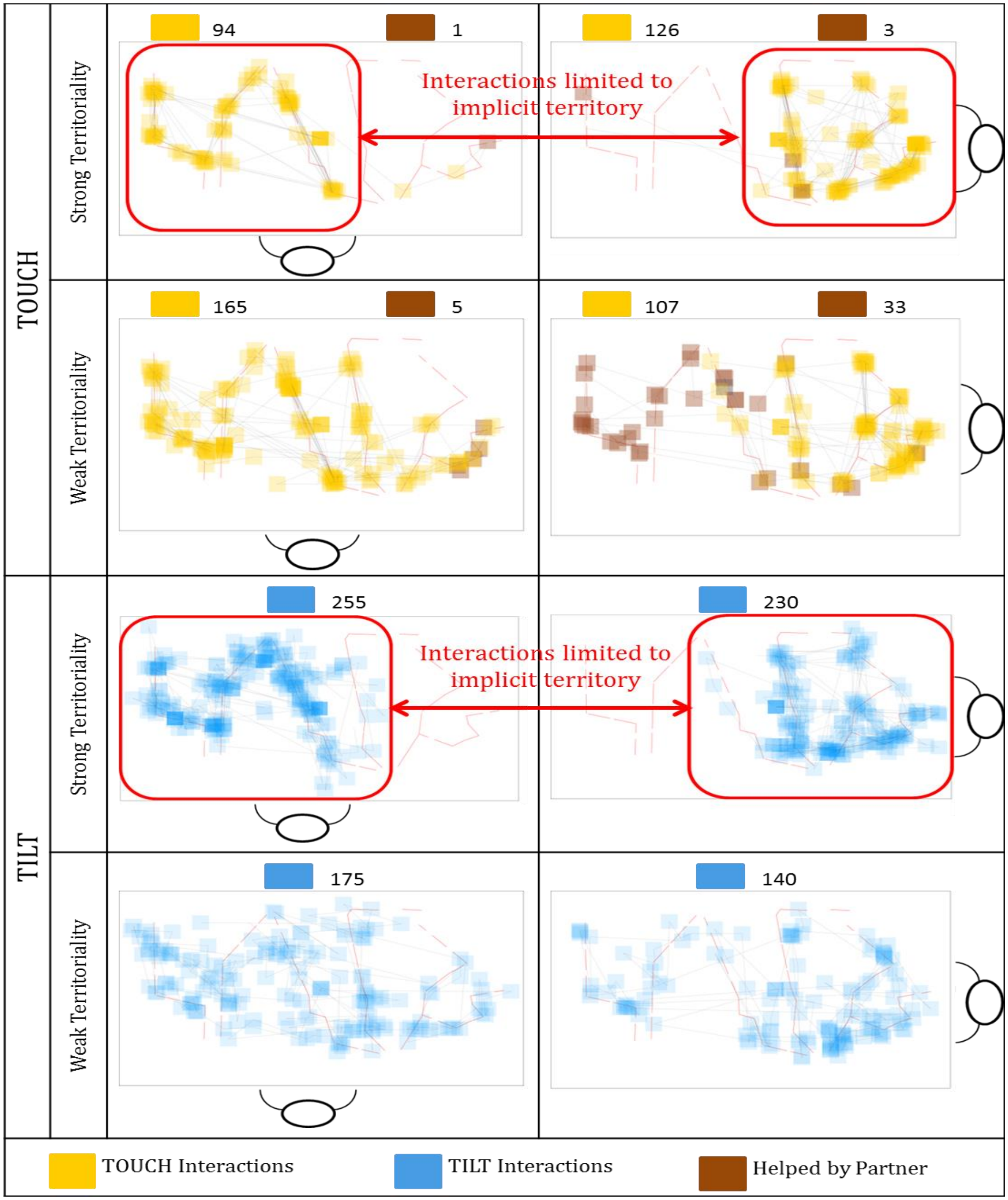


Figure 5.4: ROI Interaction map visualizing group interactions in TOUCH and TILT during Phase 1. ST interactions primarily occurred within the implicit territory.

5.3.4 Impact of TILT versus TOUCH on Territoriality in Phase 1

For groups that exhibited strong territoriality in Phase 1, participants, even after exploring all data points within their territory, stayed patiently in their own territory until their partner finished exploring their side (territory). For such groups, the lack of reachability of the TOUCH method had little impact on participants' data exploration behaviour, since they chose to explore the data only in their immediate, reachable tabletop area in both the TILT and TOUCH conditions. This behaviour can be observed in Figure 5.4, which shows very few interactions outside of each participant's territory for ST groups, in both the TOUCH and TILT conditions. It also shows fewer "helped by partner" interactions in the TOUCH condition. Furthermore, recall from quantitative results, six out of 12 groups preferred the TILT condition. It was further noted that five out of these six groups that preferred TILT, exhibited weak territoriality.

In contrast, groups that exhibited weak territoriality in Phase 1, were more impacted by the direct touch nature, and hence the lack of long-distance data exploration of the TOUCH method. As expected this particularly hindered the data exploration capabilities of the SS participant, but the data shows a significant impact on the LS participant also. Because the SS participant had limited reachability of the far tabletop interface, when they wanted to explore this area, they were forced to ask their partner to move their ROI. This dependence on the LS participant can be seen in the numerous "helped by partner" interactions in WT groups in the TOUCH condition in Figure 5.4. This perception was evidenced by the negative comments in the TOUCH condition and positive comments in the TILT condition by SS participants in response to an open-ended question, *"What aspects of technology (table and tablet) hindered the completion of the task?"*, including:

- *"Reaching across the long dimension of the screen when seated on a short end was not possible. Had to rely on partner to view distant icons further away from me…." (SS4 TOUCH),*
- *"I could get to the other side of the table, without interfering with my partner by having to ask for help to move my boundary box [ROI]." (SS2 TILT).*

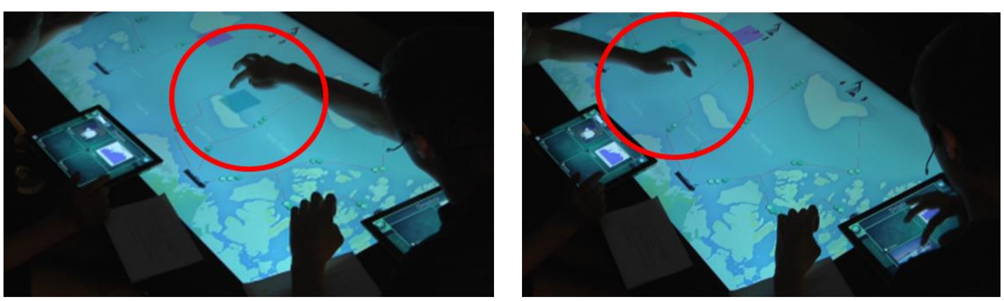
Even LS participants agreed that the TOUCH condition limited their partners' ability to reach the entire screen which impacted task performance, as one of the LS participants commented, *"partner not being able to reach the desired location since they were on the [short] side of the table hindered the group's ability to accomplish task." (LS3 TOUCH).*

However, since Phase 1 was a loosely coupled phase with little tight interactions between the partners, the dependency of SS participants on their partner to achieve their data exploration goal led to some social awkwardness due to the need to interrupt their partner. When either participant tried to move their ROI at a position close to their partner, it would sometimes lead to arm-crossing and overlapping of ROI as illustrated in Figure 5.5, and evidenced by the comment, "*have to avoid boxes overlapping when dragging them on the table. (SS11).*

Figure 5.5: Overlapping of ROIs during Phase 1

On the other hand, in the TILT condition, groups could easily move their ROI to far tabletop locations without disturbing their partner, which better facilitated the data exploration of the whole tabletop for both LS and SS participants. This observation is consistent with the previously reported significant increase in reported interference in the TOUCH condition compared to the TILT condition (Section 5.1.1).

The level of territoriality (weak or strong) exhibited by participants was not universally consistent within all groups. The data analysis revealed that one of the SS participants attempted to explore data outside his territory on the far end of the table by moving his ROI into this area (Figure 5.6(a)). However, the LS participant "defended" her territory by immediately moving the ROI back into SS's territory (Figure 5.6(b)). In the post-experiment questionnaire, the SS participant reported preferring TILT and his comment to the open-ended question, "*Why did you like one condition over the other?*" included, *"..being at the side of the table made it difficult to access the far side routes."(SS10 TILT).* However, this mixed territorial behaviour was rare in most groups as both partners were typically exhibiting the same (strong or weak) level of territoriality.



(a) **(b)**

Figure 5.6: WT behaviour exhibited by group 10, (a) SS participant tries to explore data outside his territory (b) LS partner moves his ROI back to his territory

5.3.5 Brief Periods of Tightly Coupled Interaction in Phase 1

During Phase 1, there were occasional instances when participants exhibited brief periods of tightly coupled interactions (as discussed in section 5.2), mainly to inform their partner of something interesting for discussion during the next phase. These short tightly coupled interactions typically consisted of one partner showing the other their tablet (Figure 5.7), or the participants talking out loud to share what they were seeing or thinking. Moving a partner's ROI was rare in Phase 1 beyond helping them reach a distant location in the case of WT groups.

Figure 5.7: SS participant shows their partner an image on their tablet during a brief period of tightly coupled interaction in Phase 1.

5.4 Examining Data Exploration in Phase 2: Collaborative Adjustment of Data, Pattern Detection, and Mapping of Mental Model

After overviewing the data independently in Phase 1, group members started working together to further adjust the data, discuss emerging patterns, and verify hypotheses through arranging and comparing key data to map the data to their mental model of their working conclusions. Hence, Phase 2 was dominated by tightly coupled group interactions between the participants. Moreover, it was observed that different groups adopted different tightly coupled interaction styles. These coupling styles emerged mainly based on the groups' approach to physically navigating the ROI on the tabletop, and the synchronous or asynchronous exploration of data on the tablet.

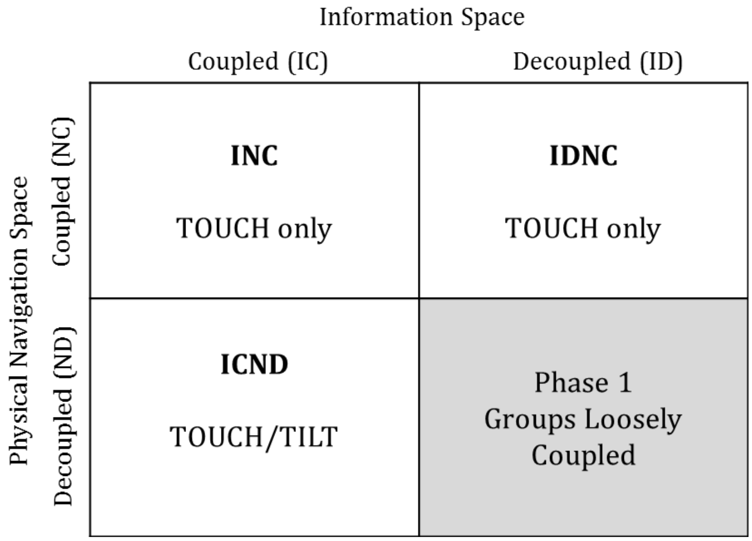


Figure 5.8: Observed collaborative data exploration strategies, based on physical navigation of ROI and the viewed information space. Some strategies were only possible in the TOUCH condition as indicated.

The data analysis revealed several approaches groups used to physically navigate the ROI, and also to navigate the information space. In some groups one partner controlled the movement of both ROIs; these groups were considered to be *navigation space* coupled (NC). In contrast, if both participants were independently navigating their own ROIs, they were considered to be *navigation space* decoupled (ND). Similarly, if both the participants were viewing the same information synchronously, they were considered *information space* coupled (IC), otherwise they were considered *information space* decoupled (ID). Figure 5.8 illustrates the four coupling quadrants based on physical navigation space and information space. These quadrants will be discussed in detail in the next section.

5.4.1 Observed Collaborative Data Exploration Strategies

The employed collaborative data exploration strategies resulted from how a group adapted to a given condition, and the different group interaction styles they adopted while interacting with the data. Data exploration strategies were categorized based on the level of coupling groups exhibited with respect to the physical navigation space and the information viewing space of viewed data. If the participants were decoupled in both navigation space and physical space, they were independently exploring the data, characterized by Phase 1 interactions. This leaves three other possible collaborative data exploration strategies, as shown in Figure 5.8. Two of these data exploration strategies, *information and navigation coupled* (INC), and *information decoupled and navigation coupled* (IDNC) were possible only with the TOUCH condition, whereas *information coupled and navigation decoupled* (ICND) was possible with either TOUCH or TILT condition. These three collaborative data exploration strategies will be explained in detail in the next section.

5.4.1.1 Information & Navigation Space Coupled (INC)

When groups explored and discussed the data using a strategy that coupled both the information and navigation spaces, they would place both ROIs on the same data icon(s) so that both tablets showed the same or overlapping data (i.e. information coupled). For convenience, groups who employed this strategy delegated one partner to physically navigate (or "drive") both ROI's on the table (i.e. navigation coupled). Groups with good coordination, cooperation and mutual understanding, chose this form of data exploration strategy. Since the physical navigation coupling was possible only with touch gestures, this strategy was limited to the TOUCH condition only. It was found that seven groups used INC strategy during Phase 2 in the TOUCH condition. Figure 5.9(a) shows a group where the LS participant moved both ROIs, and both participants were viewing the same information synchronously.

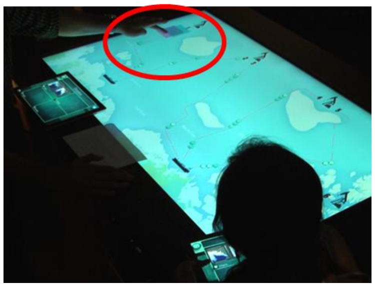
5.4.1.2 Information Space Decoupled & Navigation Coupled (IDNC)

In other groups, one partner was responsible for moving both ROIs (i.e. navigation coupled), for some period in Phase 2, but the partners were exploring different information (i.e. information decoupled). This strategy primarily occurred to facilitate a participants' ability to reach far data points. Similar to INC, this strategy was only possible in the TOUCH condition. Groups who employed the IDNC strategy, coordinated well in the physical space but there was not much discussion between them. For example, Figure 5.9(b) illustrates the LS participant driving both ROIs, and the SS participant is gesturing where to place his ROI as they were not viewing same information. This collaborative exploration strategy was employed in both Phase 1 and Phase 2. It was found that five groups used IDNC strategy during Phase 1 and two of these groups also used it in Phase 2, while using the TOUCH condition.

5.4.1.3 Information Space Coupled & Navigation Decoupled (ICND)

The final collaborative data exploration strategy involved partners viewing the same information (i.e. navigation coupled) but each partner was responsible for moving their own ROI (i.e. navigation decoupled). This strategy occurred naturally in TILT condition due to the tablet-control movement of ROI for both partners. It also, occurred in the TOUCH condition when participants wanted to retain control of their own ROI, especially with LS participant since they had ROI access most of the time. It was found that three groups used ICND strategy during Phase 2 in TOUCH condition. Figure 5.9(b) illustrates a group where both participants are driving their own ROI in the TOUCH condition.

The following section discusses the use of these collaborative data exploration strategies in detail, and how they impacted data exploration in the TOUCH and TILT condition.



(a) INC: LS participant physically navigate both ROI's while the group explores data synchronously in his territory.

(b) IDNC: LS participant physically navigates both ROI's in NC. SS participant gestures his partner on where to place his ROI.

(c) ICND: Group is exploration same information but since they are ND, both participants are holding their ROI's resulting in ROI overlap.

Figure 5.9: Observed collaborative data exploration strategies

5.5 Comparing TOUCH and TILT in Phase 2

As mentioned, the NC arrangement was possible only in the TOUCH condition. Hence, TOUCH supported more flexible collaborative data exploration strategies like INC and IDNC; whereas in the TILT condition, groups were limited to using the ICND strategy. The groups' selection of a coupling strategy (INC, IDNC or ICND) had a significant impact on the use of both the TOUCH and TILT method. The following section elaborates on these impacts, and how this influenced preference of one condition over another.

5.5.1 Impact of "Ownership" of ROI

Following the implicit division of tabletop workspace in Phase 1, the data analysis revealed an extreme form of territoriality in the TOUCH condition in Phase 2 for some groups. In these groups, a participant would become a "temporary owner" of their partners' ROI when it was located in their territory, and vice versa. The fact that the TOUCH method did not enforce ownership – that is, the system did not track who was moving the ROIs - allowed such unique territorial behaviour.

5.5.2 "Flexible Ownership" Helped Hypothesis Validation

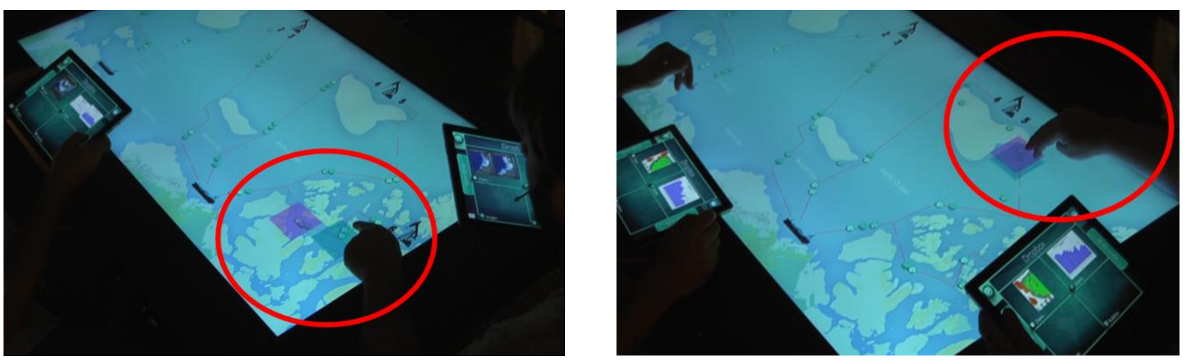
As mentioned previously in Phase 2, participants came together to discuss their independent findings from Phase 1, and this step was required to make a final decision. Thus, Phase 2 entailed "hypothesis validation" or "showing" the knowledge gained from an independent exploration phase to reach common ground among partners. To perform hypothesis validation in the TILT condition, participants had to gesture at a location of interest on the tabletop, and wait for their respective partner to move their ROI to that position for further discussion. On the other hand, the TOUCH condition offered the "flexible ownership" feature discussed above, where both participants were free to move any ROI irrespective of who "owned" the ROI. The perceived benefit provided by this flexible ownership was evidenced by many positive comments participants (both SS and LS) made regarding the utility of the TOUCH technique in response to the open-ended question, *"What aspects of the technology (table and tablet) helped in completion of the task/ group collaboration?",* including:

- *"I could also move my partner's square if I wanted to show her a specific piece of data that she had not seen to make sure we were viewing the same image." (LS9 TOUCH),*
- *"The touch controls allowed my partner to control if she wanted to show me a particular data point (or vice versa)." (SS3 BOTH),*
- *"the ability to move my partners box and show him what I was viewing assisted me in presenting my ideas as well as giving him confirmation of my hypothesis." (LS10 TOUCH),*

On the other hand, participants missed having the flexible ownership feature when using TILT, as illustrated by the negative comments:

- *"… could not show my partner quickly what I was seeing since I could not move his box." (LS10 TILT),*
- *"….I wasn't at times sure what my partner was referencing or the data was misconstrued if I was talking about a certain part of data when looking at another." (LS12 TILT).*

Furthermore, flexible ownership was found to be extremely useful when participants were discussing an insightful finding, and required constant reference to a data point. If one partner wanted to show the other partner certain data, they could simply move their partner's ROI to the desired location, which caused the data to appear on their partner's tablet. Figure 5.10 illustrates an example comparing the use of TILT and TOUCH during Phase 2. In TILT, the SS participant gestures to the LS participant to indicate where to move his ROI. In TOUCH, he simply grabs the partner's ROI and moves it to the point of interest for further discussion.



(a) **(b)**

Figure 5.10: (a) In TILT, SS pointing at a location where he needs LS to move his ROI, (b) In TOUCH, SS uses "flexible ownership" feature to drive LS's ROI to desired location.

5.5.3 "Flexible Ownership" facilitates cooperation and assistance by "Territorial Navigation"

Due to the different seatings position of the participants (as discussed in Section 4.4), the LS participant could reach the entire table on their own, whereas the SS participant had to depend on their partner to position their ROI to reach the far end of the table. Hence, LS participants were expected to control both ROIs during majority of the task in the TOUCH condition. However, it was observed that some groups (those with good coordination) adopted a new navigation strategy that minimized the extra work load (of driving both the ROIs) from the LS participant. In this strategy, proximity to the ROI and natural tabletop territoriality determined who should drive both the ROIs; hence it was defined as the *Territorial Navigator (TN)* strategy. As illustrated in Figure 5.11, the LS participant controls both ROIs when the group was exploring left half of the table and the SS participant controls both the ROIs for the right half. TN form of navigation was possible only with groups that were navigation coupled either by exhibiting the INC or the IDNC strategy.

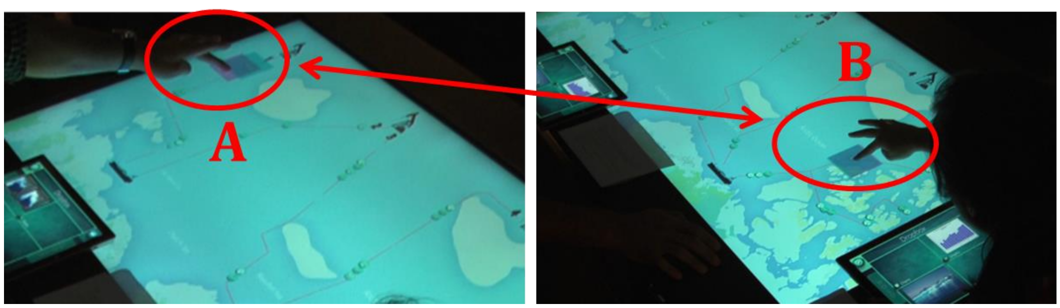


Figure 5.11: Illustrates Territorial Navigator strategy, (A) LS participant moves both ROIs, (B) SS participant moves both ROIs.

When groups were decoupled in information space (during IDNC), exhibiting TN would often encourage group to couple, which resulted in better coordination between the partners. For example, group 10 started working in ICND in TILT, but in TOUCH, they exhibited TN which encouraged them to couple in information space, exhibiting INC. This perception could be further evidenced by the following comments, to open ended question: *"What aspect of technology helped in the completion of the task?"*, including*:*

- *"Ability for one user to move both ROI together using multi-touch."(LS4 BOTH)*

- *"Moving the viewing moving box [ROI] together so that both my partner and i can see the same data and give views together to better assist the route" (LS7 TOUCH)*

Although, participants agreed that TN strategy was an efficient way of ROI navigating, having to move both the ROI simultaneously was reported to be "time consuming". Some participant's event suggested to "merge" (or "*snap",* LS7) both the ROIs together to simplify the TN interaction, which was evidenced by the following comment:

"...It would also be better if the boxes [ROI] could be locked together or a button on the tablet to SNAP my partner's bounding box [ROI] to my box view location..." (SS4 TOUCH).

Data analysis revealed that TN strategy was more common in the groups where SS participants preferred TOUCH; five out of six groups that preferred TOUCH exhibited the TN strategy during Phase 2. The TN strategy was only possible when the ROI was controlled by the other partner; hence more "helped by partner" interactions would imply a strong TN exhibition, and result in preference for the TOUCH condition. This perception was verified by computing the number of "helped by partner" interaction in Phase 2 and comparing the ROI movement map illustrated in Figure 5.12. As shown, there are more brown squares (131 helped by partner: 39 for LS and 92 for SS) for groups where SS participants preferred the TOUCH condition in comparison to others who preferred TILT (53 helped by partner: 10 for LS and 43 for SS) in Phase 2. Further, on examining the total number of interactions, it was found that groups where the SS participant preferred the TOUCH condition had on average more "helped by partner" interactions than the groups where SS participants preferred TILT (TOUCH Average: 63% "helped by partner" interactions of the total number of interactions, 71% for LS and 55% for SS, TILT Average: 37% "helped by partner" interactions of total number of interactions, 29% for LS and 45% for SS).

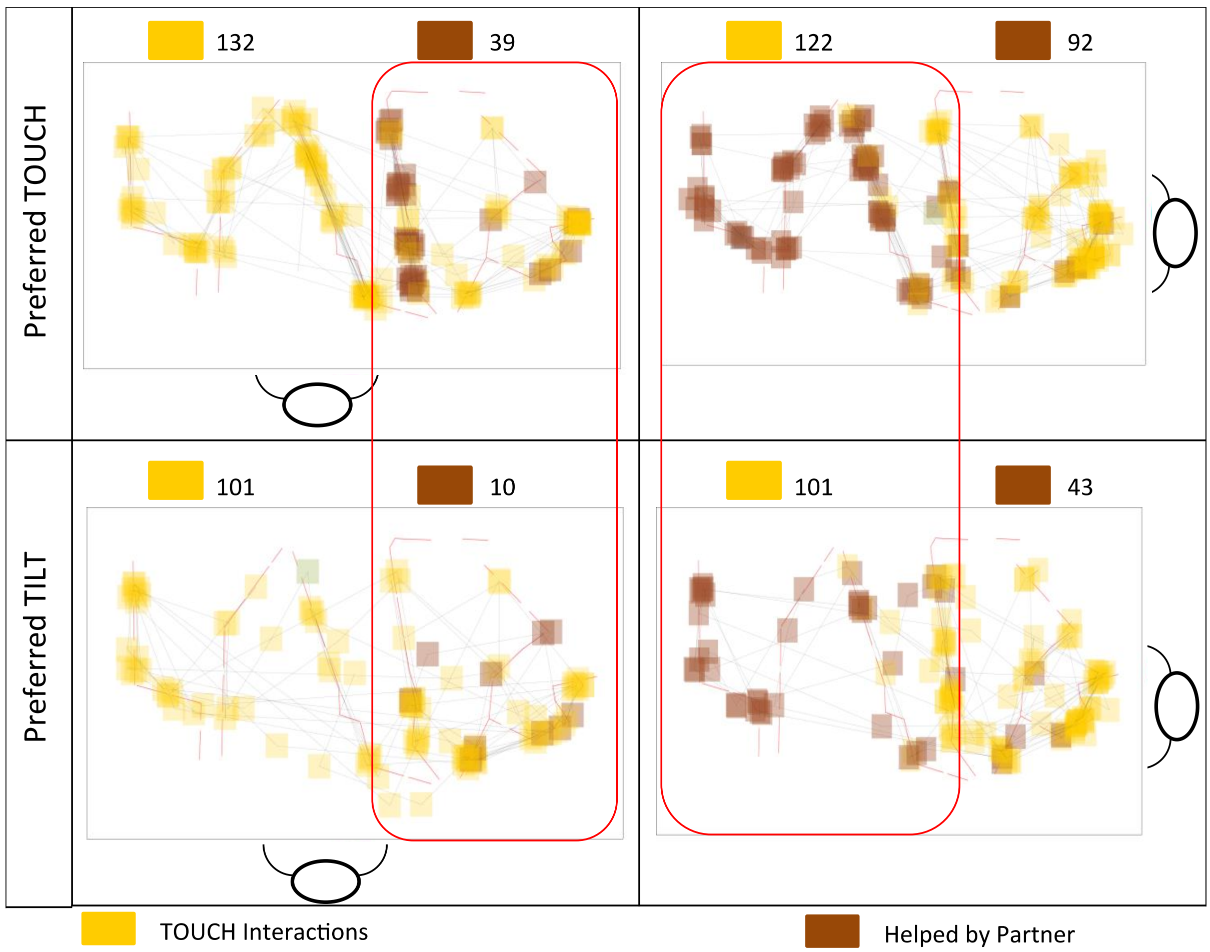


Figure 5.12: TOUCH data exploration interactions by SS participants' that preferred TOUCH and TILT in Phase 2

5.5.4 Impact of "Helping Interactions" in Phase 2

The data analysis revealed that the LS participants conducted more "helping by partner" interactions than the SS participants during Phase 2. Both Figures 5.12 and 5.13 illustrate that LS participants were responsible for more helping interactions than SS participants (SS helped by LS: 135, LS helped by SS: 49). Further, the groups where SS participants preferred the TOUCH condition were helped more by their respective partner (SS helped by LS: 92, LS helped by SS: 39) than the ones that preferred the TILT condition (SS helped by LS: 43, LS helped by SS: 10).

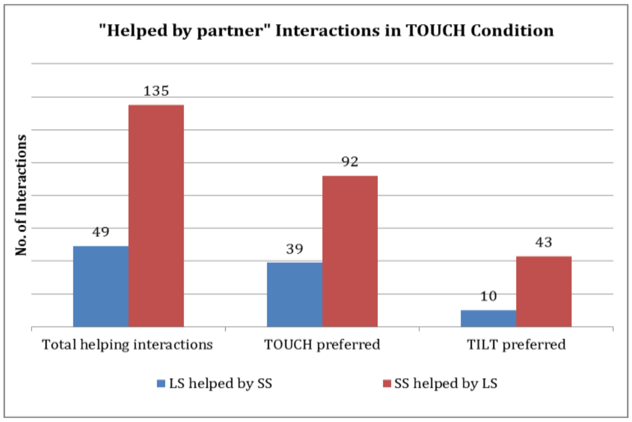


Figure 5.13: Helping Interactions in TOUCH (Phase 2 only)

5.5.5 Impact of Tablet Position and Control of ROI

The data analysis revealed that the different control mechanisms for positioning the ROI offered by the TOUCH and TILT method impacted how participants positioned their tablet while solving the sensemaking task. Some participants preferred to place their tablet in their hands; irrespective of the condition, while other participants preferred to place it on the table edge in front of them or in some cases even on the table edge closer to their partner. The following section, discusses how positioning of participants' tablets and the respective ROI control mechanism offered by the TOUCH and TILT method, impacted data exploration.

5.5.6 Impact on 'Tableaux' Formation

As discussed in section 2.1.2, Wallace et al. (2013) previously observed that groups performing a sensemaking task in a table-centric multi-surface environment arrange their tablets together on the table in a "tableaux" format to help pattern detection and to gain insights from the data. Arranging data side-by-side can provide a visual context from the group conversation, making communication more efficient (Brennan et al., 2006). The data analysis revealed that, when possible, participants' positioned their tablets in different orientations to improve visualization and comparison of the data. As participants placed their tablets in different orientations, the formation of a tableaux where tablets were positioned side-by-side along the table edge between participants (see Figure 5.14) was the most commonly observed positioning pattern that participants used to facilitate adjustment of the data, pattern detection and mental model matching.

Since TOUCH allowed the ROI to be positioned without moving the tablet, tablets were free to be positioned anywhere around the tabletop, without interfering with the ROI control. On the other hand, for the formation of tableaux in the TILT condition, participants had to position their tablets either in their hands (instead of resting it on table) or by first putting data into dropbox, and then doing side-by-side comparisons with data in the dropbox (see Figure 5.14(b)).

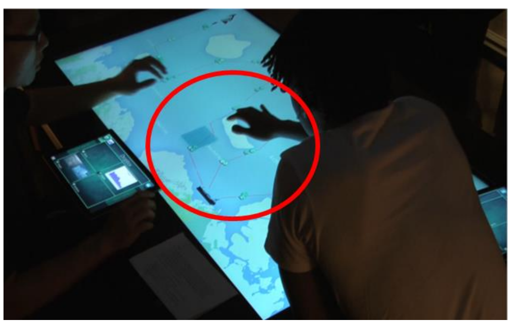
Thus, having the flexible ownership feature in TOUCH offered more flexibility to place tablets in various orientations for comparison in comfortable positions, and as a result better supported the formation of a tableaux. This is evidenced by the participant comment, *"Sometimes it was hard to hold & view the tablet [in TILT] while also viewing the table at the same time." (LS9 TILT).* The data analysis revealed that eight (out of 12) groups engaged in tableaux formation, and out of these groups, three of them chose not to form a tableaux when using the TILT condition.

(a) (b)

Figure 5.14: Illustrates the tableaux formation in TOUCH and TILT, (a) TOUCH supports uninterrupted tableaux, (b) Switching to "dropbox view" in TILT for tableaux.

5.5.7 Impact of Usability Issues in Phase 2

During Phase 2, the TOUCH condition worked well for seven groups exhibiting the INC collaborative strategy. The remaining five groups, exhibiting decoupled exploration strategies, such as ICND or IDNC, experienced a number of collaboration issues. For instance, decoupled navigation led to "hesitation" to ask their partner to move the ROI (Figure 5.15(a)), and "snatching" of ROI when one partner took control of the other partners' ROI to show them something without their permission (Figure 5.15(b)).



(a) When navigation decoupled: SS instead of asking his partner for help, stands to move his ROI. [G8]

(b) When information decoupled: LS moves SS's ROI without permission to show him something and SS gets angry

Figure 5.15: Usability Issues during the decoupled state

In groups exhibiting IDNC, although participants explored different data points, they helped each other with the ROI movements. Hence, when participants interacted in "unknown territory" (common area on the table that was accessible to both partners) there was confusion about who should be driving the ROI in this region. Since, LS participants had access to the entire tabletop they often kept control of their partner's ROI in "unknown territory", even though they were looking at different data. Such scenarios resulted in "ambiguity" on the right moment to hand back the ROI controls to the SS partner, without interfering with their actions. This ambiguity was evidenced by the quantitative findings, where LS participants reported that they felt *"they interfered with their partners' actions"* (see section 5.1.1).

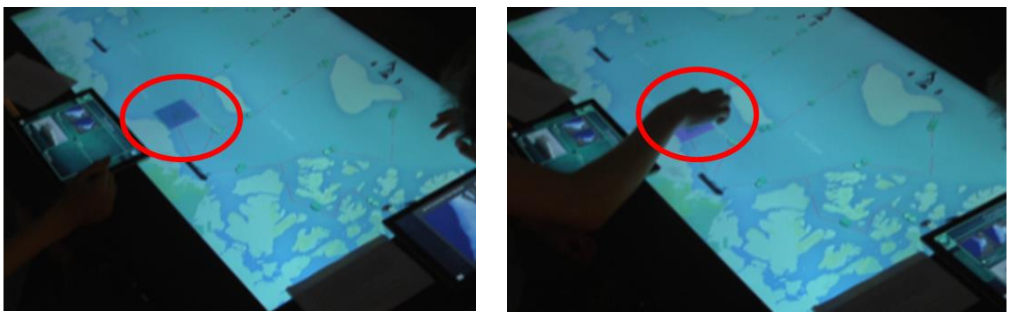
On the other hand, in groups exhibiting ICND, participants were decoupled in navigation space but they were looking at the data together. Hence, to continue a discussion, SS participants had to interrupt LS participants to get their help to move their ROI to access the far end of the table. Hence, such interference led LS participants to report; *"I am interfered with my partner action"* in the post-condition questionnaire (see section 5.1.1).

Overall, in groups with poor coordination and weak territoriality, the TOUCH condition led to awkwardness, crossing of arms, unwanted obligation, overlapping of boxes and interference. Hence, recall from the post-condition questionnaire data when participants were asked if they felt their *partner interfered with my actions while browsing data* and *if they felt they interfered with their partners actions.* For both questions, the TOUCH condition was found to have more interference over TILT for both LS and SS participants. This perception is further evidenced by the following negative comments:

- *"Hit detection on the boxes was annoying if they overlapped, made it difficult not to interfere with partners data viewing" (LS2 TOUCH)*

- *"Sometimes I got my box confused with my partners." (L10 TOUCH)*

Figure 5.16 illustrates an example of confusion arising due to one ROI overlapping another ROI in ICND strategy. As shown, the group is interacting in the TOUCH condition where both ROIs are overlapped (see Figure 5.16(a)), and the LS participant accidently moves his partners' ROI (see Figure 5.16(b)). Later, he realizes and comments, *"I keep moving your box"*. The SS participant from this group preferred the TILT condition.



(a) **(b)**

Figure 5.16: Illustrates ROI overlapping due to ICND strategy, (a) ROIs are overlapped (b) LS accidently moves his partners' ROI

In the TOUCH condition, when groups explored "out-of-reach" points on the table and one participant helped the other participant drive their ROI, they would often forget to hand back the ROI control to its owner (see Figure 5.17). This issue was more commonly observed for groups that exhibited the IDNC strategy, due to bad coordination in physical navigation. In contrast, groups exhibiting the INC strategy overcame this issue with good communication.

Figure 5.17: After moving from tightly to loosely coupled interaction, LS forgets to hand back SS's ROI. Hence, SS participant gestures her partner to help bring back her ROI.

5.5.8 Social Impact of ROI Control

Since Phase 2 was dominated by tight collaborative interaction, coordination, and cooperation, territoriality, sharing view-points and smooth transfer of the ROI control (in the case of flexible ownership in TOUCH) had a significant impact on the group behaviour. In this phase, group discussions involved constant "referring to" and "comparing" data points at different locations on the tabletop. Thus, it required participants to make quick movements of ROI. Consequently, the accuracy of placing the ROI at a specific location became more significant than in Phase 1. For example, when both partners were going over data together, and one participant invited the other participant to *"come have a look"* (SS5). The discussion was stalled until both participants were viewing the same information (or had ROI's at the same location). This is further evidenced by a positive comment from a participant about using TOUCH, *"We could just show each other what we're referring to [data points] instantly instead of having to wait for the other to hover over the data and to correctly position it over." (TOUCH SS9).*

5.6 Examining the BOTH Condition

To better understand the utility of TOUCH and TILT techniques and their respective benefits and user appeal for supporting the data exploration process, groups performed the experiment task using a version of the software that provided both TOUCH and TILT ROI control mechanisms. It was found that in BOTH condition there were in total 1087 TOUCH interactions and 527 TILT interactions. This section examines groups' data exploration behaviour in this condition, with a focus on how the techniques complemented each other and helped resolve the respective usability of TOUCH and TILT techniques.

5.6.1 Impact of "TOUCH plus TILT" Controls

The data analysis revealed that eight out of 12 groups started the task independently (i.e. four groups did not have a separate Phase 1). The "TOUCH plus TILT" controls in BOTH condition offered participants with flexibility to explore data independently and collectively, and also unlike TOUCH it reduced the extra work load of driving both ROIs from the LS participant. This was evidenced by the following comments, to the open-ended question, *"What aspects of the technology helped, in particular, to explore all the available data?"*,

- *"Having both touch drag and HOLD button to move the box was helpful." (SS4 BOTH),*
- *"having both movement options available was helpful and meant less movements for me [BOTH reduced extra work of driving both ROI]." (LS2 BOTH).*

However, it was found that the groups where SS participants preferred the TILT condition controlled the ROI more often using the TILT method, particularly to explore "out-of-reach" data points, rather than asking their partner for help, as illustrated by fewer "helped by partner" (Total: 27 interactions, LS: 2, SS: 25 in Figure 5.18). In contrast, groups where the SS participant preferred the TOUCH condition, participants still depended on their partner for controlling their ROI movements (see Figure 5.18), as there were 188 "helped by partner" interactions (LS: 105 interactions, SS: 83 interactions). It was observed that the "helping by partner" interactions were defined by the territoriality adopted by the groups in Phase 1 (brown squares present on one side of the table marking participants' territory). Further, as evidenced by data, the LS participants were helped more by their partners than the SS participants (105 "helped by partner" interactions for LS versus 83 helped by partner interactions for SS) even though they had access to most of the table throughout the task. Hence, the "helped by partner" interaction or the TN strategy was not entirely based on the needs of the task (due to physical limitations) rather it was dependent on the territoriality and the division of work load.

While using the BOTH condition, participants had an option of choosing either the TOUCH or TILT method of control, and participants utilized both controls based on the situation. The data analysis revealed that participants used the TILT method to reach the far end of the table, and they used the TOUCH method to place ROI accurately at a specific location. Figure 5.18 illustrates more blue squares (illustrating TILT interactions) towards far end of participants, and yellow squares (illustrating TOUCH interactions) closer to their territory. This perception can be further evidenced by the following participants' comment:

- *"…Using the hold button [TILT] helped when viewing distant icons, but I prefer touch and drag when the box is within reach [TOUCH]."(SS4, BOTH),*
- *"The ability to use both motion and touch controls was useful for traveling long distances and doing precision work respectively." (SS10 BOTH).*

Further, an example from the study illustrates (see Figure 5.19) the use of the TOUCH and TILT methods in the BOTH condition of group 9, where the SS participant is using the TILT method to reach far away points, and she switches to the TOUCH method for closer interactions.

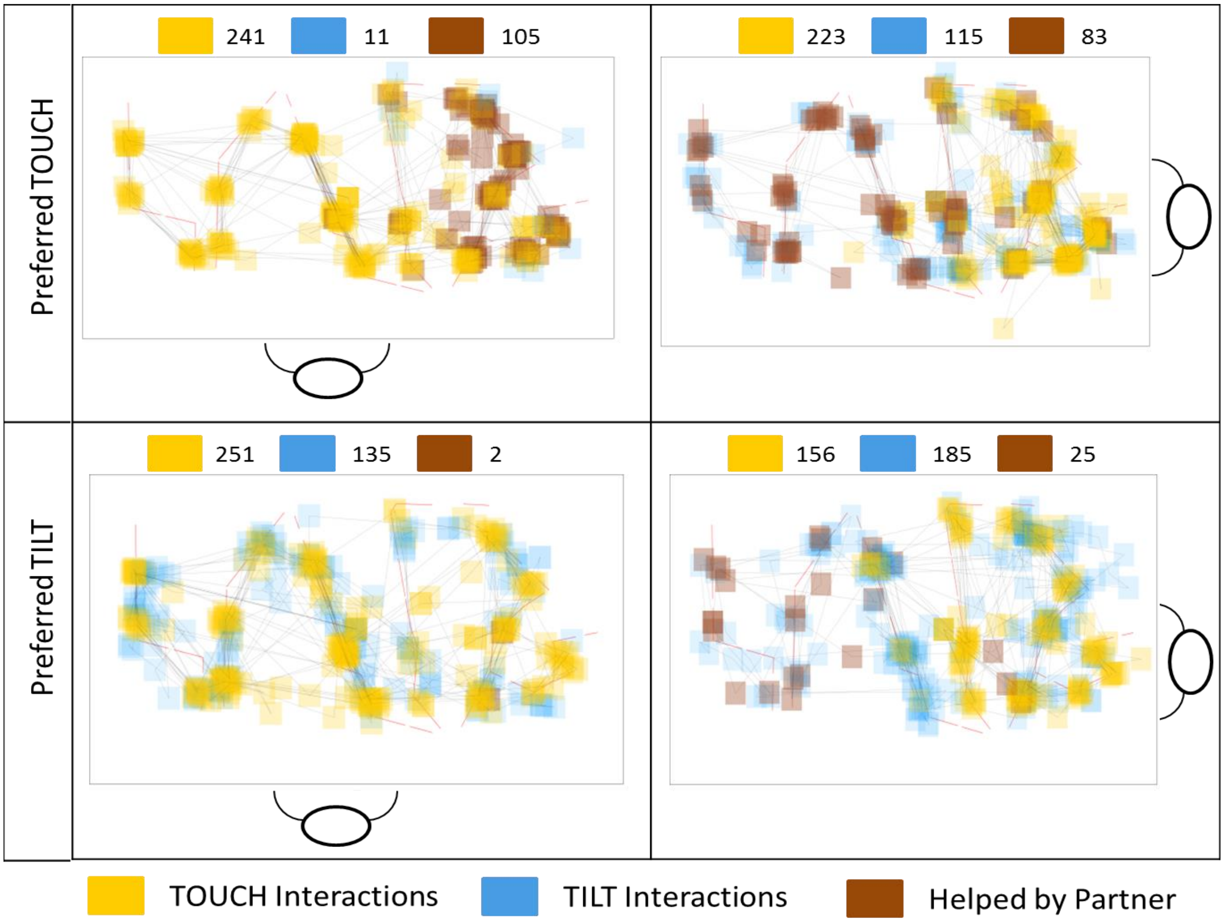
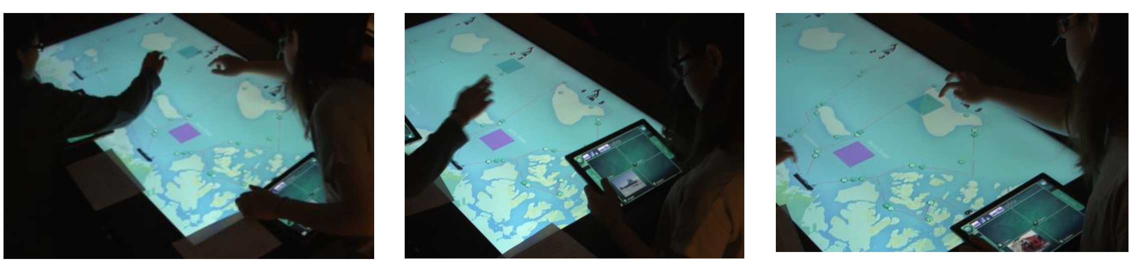


Figure 5.18: Interactions comparing SS participants' that preferred TOUCH and TILT in BOTH conditions (Phase1 + Phase 2 combined)

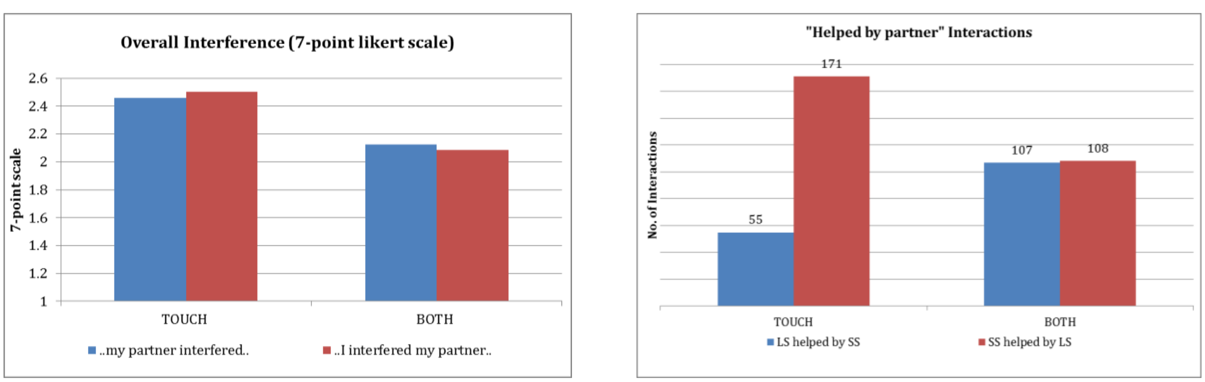


(a) **(b)** **(c)**

Figure 5.19: (a) SS tries to reach her ROI across the table. Despite some help from her partner she is unable to reach her ROI, (b) She switches to tilt gesture control after realizing that she can get access to her ROI using tilt, (c) Switches back to touch gesture for in-reach data.

5.6.2 Usability issue resolved in BOTH

As discussed in section 5.5.7, groups exhibiting a ND strategy in the TOUCH condition faced various usability issues that impacted the flow of data analysis and overall sensemaking. Data analysis revealed that providing both TOUCH and TILT methods together helped participants overcome these limitations. Figure 5.20(a) compared the average reported interference in the BOTH and TOUCH condition, and found that the interference was reduced in the BOTH condition compared to the TOUCH condition. Further, the total number of "helped by partner" interactions were equally divided between the two participants in the BOTH condition, in comparison to the TOUCH condition (see Figure 5.20(b)). These interactions were increased where LS was helped by the SS (from 55 in TOUCH to 107 in BOTH) and reduced where SS was helped by the LS (from 171 in TOUCH to 108 in TILT). This perception of reduced interference in the BOTH condition can be further evidenced by the following comment, *"using both the tablet and touching the table [BOTH condition] helped me not getting distracted by my partner." (LS3 BOTH).*



(a) **(b)**

Figure 5.20 (a) Compared the average Likert-scale interference in the BOTH and TOUCH conditions, (b) Comparing the average "helped by partner" interactions in the TOUCH and BOTH conditions (Phase 1+ Phase 2).

Figure 5.21 illustrates an example from the study that evidenced the use of the TOUCH and TILT methods together (in the BOTH condition), to overcome technical limitations related to the overlapping of ROIs. As illustrated in Figure 5.21(b), both the LS and SS participants are exploring the data on the left half of the table, and in the process their ROIs get overlapped. At first, the LS participant attempts to use the TOUCH method to move his ROI. Later, after viewing the overlapped ROIs, he decides to switches back the controls to the TILT method (see Figure 5.21(b)).

(a) (b)

Figure 5.21: (a) LS attempts to use TOUCH but back out after viewing overlapped ROI's, (b) LS switches to TILT to avoid moving his partners' ROI.

5.7 Chapter Summary

An observational lab study was conducted to examine the impact of data exploration techniques on the collaborative sensemaking process. The quantitative and qualitative data analysis revealed that different groups employed various collaborative strategies while solving a sensemaking task, and these strategies impacted SS participants' preference for the data exploration method. Hence, this chapter meets the third research objective of evaluating the impact of two data exploration techniques on collaborative sensemaking. The following chapter will summarize and discusses the implications of these findings.

Chapter 6

Discussion

This chapter summarizes the results, and discusses the implication of the findings presented in the previous chapter. While discussing the utilization of the two techniques during the sensemaking task, this chapter elaborates on the impact of group strategy on use of the studied techniques, and its consequential impact on participants' preference of one technique over the other. Then, design recommendations are discussed for improving the two techniques to help address current design limitations, specifically to enhance collaborative sensemaking.

6.1 Impact of Flexibility (of TOUCH) versus Reachability (of TILT) on Sensemaking

One of the goals of this thesis was to evaluate the impact of tabletop seating position while conducting collaborative interactions. The length of the tabletop used in the study made it physically impossible for participants seated on the short side (SS) to reach the far end of the tabletop without leaving their assigned location (which they were instructed not to do). Hence, one data exploration techniques (TILT) had a clear advantage over the other (TOUCH), if the task was done independently instead of as a group. But the study revealed that groups came up with different innovative strategies to overcome this limitation. Groups that strategically planned the task and exhibited effective coordination and cooperation throughout the task were able to overcome the "reachability" limitation in the TOUCH technique. The "flexible ownership" feature of the TOUCH technique (see section 5.5.2) allowed cooperative groups to adapt the use of the technique from "personal" data exploration to "group" exploration by allowing participants to freely move the ROI, regardless of its actual "ownership". As a result, the TOUCH technique improved coordination between participants, as they were prompted to help each other while working together. The participant comment, *"...now that it's a two-person game, we can help each other to view different parts of the table, so this isn't a shortcoming [talking about reachability]." (SS 11 TOUCH),* illustrates that the reachability shortcoming of the TOUCH technique could be overcome by groups collaborating in their navigation space.

However, a collaborative sensemaking task may require group members to branch out to work independently. Hence, there should be an option of independent exploration without interfering with other group members' actions. The TILT technique offered the "independence" of exploration without interfering with a partner, or in other words, the ability to explore the out-of-reach data points. This was, particularly important for the SS participants, as evidenced by the comment by one SS participant, *"The motion controls [TILT] allowed me to access the data my partner was looking at without having her move the box." (SS10 TILT)*. Additionally, the TILT technique was perceived to allow faster exploration without interfering with the partner, as illustrated by the participant comment,

> *"I preferred the fluid motion-sensor [TILT] because it enabled me to transfer between different points much faster without reaching across the table or asking my partner to move it for me. It eliminated steps of communication and made obtaining the pieces of information much more instant." (SS12 TILT).*

6.2 Impact of Group Strategy on Preference

The data analysis revealed that there was a strong correlation between the groups' initial strategy formation (see section 5.3.1) and how groups chose to use the two techniques. It was found that different groups adopted different collaboration strategies in Phase 1 and Phase 2. The most commonly adopted strategy by groups was *divide-and-conquer,* in which they would split the tabletop interface in half, and each participant would be responsible for exploring the data independently in their own territory. Some groups exhibited strong territoriality, whereas some exhibited weak territoriality. If a group adopted a divide-and-conquer strategy, and if both participants exhibited strong territoriality in Phase 1, they typically reported preferring TOUCH over TILT on the post-experiment questionnaire. This was evidenced by the preference result of SS participants, where five out of six SS participants that preferred the TOUCH technique exhibited strong territoriality. Hence, this raises a question, did territoriality in Phase 1 influence the way groups interacted in Phase 2? It can be implied that respecting "partners" territory in Phase 1 helped participants to build trust and cooperation between each other. Therefore during Phase 2, these groups chose a working strategy where they were coupled in the physical navigation space, and resolved the interference issues (that may arise in the TOUCH technique) by exhibiting collaborative strategies like flexible ownership and territorial navigation discussed in section 5.5.3.

The remaining groups that started the task with divide-and-conquer and exhibited weak territoriality were more likely to prefer the TILT technique. In these groups, either one or both partners did not follow the groups' plan of working in their respective territories. Crossing their partners' territory in Phase 1 may have given their partner an impression that they were not confident in their partners' judgment of the viewed data. As a result of such behaviour, this may have impacted the group interaction in Phase 2. Thus, the lack of trust from Phase 1 may have carried over into Phase 2, where the participants were then reluctant to coordinate with each other, or ask for help in moving the ROI in the TOUCH technique. Hence, for these groups the "reachability" feature of the TILT technique became a significant factor.

Besides divide-and-conquer, there were a small number of groups that adopted a completely different strategy. These groups, instead of splitting the tabletop screen, completed the whole task by "jointly" exploring data on the entire tabletop (refer to section 5.3.1). These groups did not exhibit any territorial behaviour. Therefore, their information space was coupled for the majority of the sensemaking task, and there was very limited independent interactions (see Figure 5.3). Hence, for these groups, the factor that derived preference of technique was the coupling behaviour in the physical navigation space. Since there were no defined territories, the transfer of control of ROI was important when groups were exploring out-of-reach points during the TOUCH interactions. If the transfer of control was smooth and there was no interference issues (like ROI overlapping, arm crossing, etc.), the TOUCH technique became a favorable option. On the other hand, if there was awkwardness and interference in the physical navigation space, the TILT technique was favorable. The following example from the study illustrates this issue.

Example: Group 12 exhibited tightly coupled joint collaboration across all three conditions. They chose to work decoupled in the physical navigation space. Hence during the TOUCH technique, they encountered a number of usability issues, such as overlapping ROIs. During one such incident, the LS participant said to his partner that he would give him a low score for interference on the survey questionnaire (in a sarcastic way) since he (the partner) kept moving his ROI. Later on a questionnaire, the same participant expressed his in the following comment: *"..the boxes could be moved by touch hindered my abilities because my partner kept tending to drag my square [ROI]."(SS 12).*

6.3 No Observed Impact of Map Orientation

Our previous experience with tabletop collaboration suggested that orientation of the map may impact participants' performance, and hence, it was expected that the SS participant (being at a 90 degree viewing angle to the map) may find it hard to view the data on the map. However, the data analysis did not reveal any significant impact from orientation of the map on participants' performance. In the post-condition questionnaire, when asked if *"..locating data icon(s) on the tabletop map that represented the data shown on the tablet"* [was] easy or difficult, no significant difference was found between the LS and SS participants' responses. This lack of seating position effect may have been due to the fact that, unlike many previous tabletop studies, in this study the tablet interface view displayed completely different information from the tabletop interface rather than, for instance, a full or partial view of the tabletop contents. That is, in earlier studies where orientation had an impact on performance, the tablet interface displayed a full or partial replicated view of the tabletop interface, e.g. a zoomed area of a large map. This required users to cognitively map related views being viewed at different orientations.

In this study participants appreciated having the overview tabletop screen as it was perceived to be useful for collaboration by providing a broad overview (or a "big picture"). This was evidenced by the comment, *"..seeing the big picture [tabletop] at all times on the table helped a lot - allowed for ease of collaboration with my partner, was able to break the task down into two areas of investigation." (LS3 TILT).*

6.4 Impact of Attention Tunneling and Physical Ergonomics on Sensemaking

Two key factors in providing a usable multi-surface data exploration technique include its ability to provide fluid interactions with minimum workload and to minimize attention tunneling. In the TILT technique, movement of the ROIs was directly controlled by the tablet interface. Hence, it supported viewing of data and moving the ROI simultaneously. In contrast, the TOUCH technique the ROI movements were controlled by physically touching the tabletop screen. Hence, viewing of data on the tablet was an additional step. Thus, in theory the TILT technique should support a more ergonomically friendly interaction by reducing the extra physical effort required to reach the data points located on the table, as in the case of the TOUCH technique (specifically for the SS participant). Additionally, the TILT technique was expected to minimize the attention tunneling effect, unlike the TOUCH technique where participants' attention was constrained to either moving the ROI on the table or viewing information on the tablet, but not both at the same time. However, since the task was performed collaboratively, the results revealed that, in practice, this was not always the case.

During the discussion phase (Phase 2), participants positioned their tablets in various orientations to facilitate the sensemaking process (e.g. tableaux formation – see section 5.5.6). With the TILT technique, they were constrained to continuously position the tablet in their hands, whereas, with the TOUCH technique, they were free to position the tablets as desired to enhance collaborative viewing. This explains the results of the post-condition questionnaire (see section 5.1.1) when participants were asked if "*viewing the data on the tablet while moving the ROI on the table at the same time"* was easy or difficult. Data viewing was found to be much easier using the TOUCH technique than in the TILT technique. This perception was further evidenced by the following participant comment:

> *"..I found the touch screen feature of the table much easier to use than the hindering "HOLD" feature on the tablet, because it is easier for me to just place the tablet against the side of the table for viewing images and diagrams, then to hold the edge of the tablet and tilt it to move the bonding square."(LS9).*

However, as mentioned previously (see section 5.5.6) the TILT technique did support formation of tableaux, once the data was moved into the dropbox. But this additional step (of moving the data into the dropbox) delayed data analysis during the collaborative discussion phase and hence the completion of the sensemaking task. In contrast, if the sensemaking task was completed independently, it is expected that the TILT technique may be a better option, as discussion with other collaborators and tableaux formation would not be necessary. In the pilot testing conducted involving a single user, anecdotal observations revealed that participants utilized the TILT technique more often in the BOTH condition. When the same participants solved the task in a group setting, they utilized the TOUCH technique more often in the BOTH condition.

6.5 TOUCH Facilitates "Least Collaborative Effort"

It was expected that independent exploration and reachability offered by the TILT technique would provide an advantage for data exploration in a tabletop environment. However, the findings revealed that the flexible ownership of the TOUCH technique enabled the group to utilize a wider variety of collaborative strategies to cooperatively explore data. The dependency on the partner for positioning the ROI in some tabletop locations encouraged more cooperative interactions in TOUCH, including one member moving both ROIs for the group during some periods of the collaboration. Both the SS and LS participants agreed that moving the ROIs together in TOUCH helped them collaborate and jointly explore data, as illustrated by the comments:

- *"I used to move both viewing boxes [ROI] together so that my partner and I, both can see the available information on that point."(LS7 TOUCH)*
- *"The table's touch screen helped in group coordination, because it allowed me to move my partner's bonding square [ROI] so that I viewed the same image and could then voice our opinions on it." (LS9 BOTH)*
- *"Moving the viewing moving box [ROI] together so that both my partner and I can see the same data and give views together to better assist the route."(LS7 BOTH)*
- *"..able to move my partner's box [ROI] that saves much more time"(SS3 BOTH)*
- *"The tablet helped in storing bits of info at once [referring to TILT technique] but it did not necessarily help group coordination as you did not know if you were looking at the same picture or graph."(LS9 TILT)*

The above behaviour of collective movement of ROI (observed in the TOUCH condition) was consistent with Clark & Brennan's (1991) theory of "least collaborative effort", which states that, "the participants try to minimize their collaborative effort—the work that both do from the initiation of each contribution to its mutual acceptance" (p. 135). Further, Gutwin and Greenberg (2002) have stated that an advantage of workspace navigation is that, "collaboration is simplified when people see the same artifacts at the same time" (p. 1). The flexible ownership of TOUCH allowed for shared navigation, which consequently, simplified the artifact's viewing with minimal collaborative effort.

Therefore, a group engaged in a collaborative activity will try to minimize their effort and the work done by each collaborator, helping each other as possible to reduce the overall amount of work the whole group has to perform. Using TOUCH required less effort to create a "coupled information space" to facilitate a group discussion compared to TILT, where one participant had to wait for the other partner to position their ROI to start a group discussion. This may have been a factor in why participants reported TILT being more frustrating to use than TOUCH (see section 5.1.1).

6.6 Impact of Loosely versus Mixed-Focused Coupling on Analysis

As mentioned, TOUCH encouraged groups to work tightly coupled and work together cooperatively. Considering Clark and Brennan's (1991) grounding in communication theory (refer to section 2.1.1), when groups work together and build on common ground, moment by moment, it can lead to efficient decision making. It was anecdotally observed that when groups worked together they would carry a longer discussion leading to insightful findings. For example, Figure 6.1 illustrates a group carrying out an insightful discussion, where one partner is trying to convince the other partner why certain data should be considered in their decision. When working independently such insightful data exploration would often go unnoticed or sometimes result in incorrect interpretation.

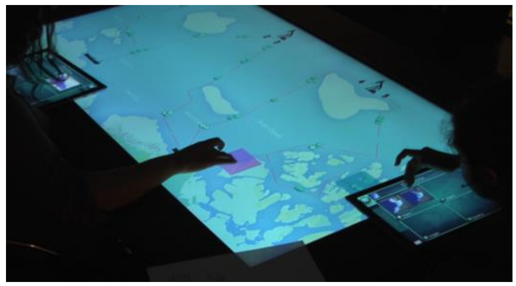


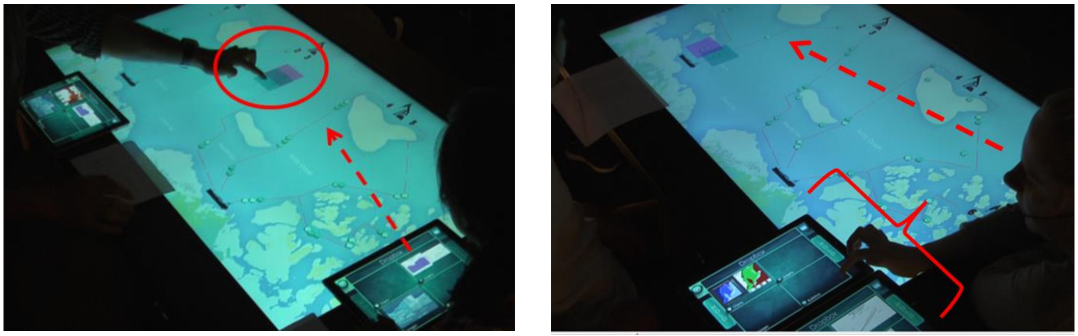
Figure 6.1: SS points out insightful data to convince LS (G5)

However, the mixed-focused collaboration in the TOUCH technique, sometimes led to an obligatory collaboration which impacted verification of data. This situation occurred when one of the participants was not fully convinced of their partner's decision, and they wanted to branch-out from the group (often for a short duration) to verify the results. It was observed that participants in the BOTH condition switched to the TILT technique for independent verification during the discussion phase (as illustrated in Figure 6.2, where the SS participant switched from TOUCH to TILT technique to perform data verification). This perception was also confirmed by the comment, *"..able to revisit the charts/graphs/pictures/bulletin again."(SS3),* where the participant is referring to the fact that TILT allows her to "revisit" the out-of-reach points for verification without disturbing her partner.

Figure 6.2: SS participant switching from TOUCH to TILT (in BOTH condition) for verification

6.7 Loss of Spatial Correlation between "Focus View" and "Map Context"

Previous research has shown that humans retain information better when they perceive data that has a direct spatial correlation (Cockburn, 2004). As discussed previously, the TOUCH technique allowed a single group member to control the movement of both ROIs. Such single-user controlled interaction used least collaborative effort, and thus was better suited for a collaborative data exploration. However, this interaction behaviour disconnected the non-controller (partner not controlling movement of their ROI) from the spatial location of their ROI on the tabletop, as they were engaged in data-viewing on the tablet. This led to "attention tunneling" (refer to section 6.4) and also violated the O+D visualization design. Moreover, there were a few instances when the non-controller was engaged in discussion with their partner on the data points that were not being displayed on their tablet because the controlling partner (moving both the ROIs) accidently did not place their partners' ROI at the exact location on the table. For example, Figure 6.3 illustrate such a case were partners were spatially disconnected leading to confusion.



(a) **(b)**

Figure 6.3: Illustrates spatial disconnection for groups exhibiting TN strategy, (a) few data points are missing on SS's tablet, and she asks LS to move her ROI at exact location, (b) SS loses spatial correlation with the table as LS moves both ROIs.

6.8 Impact of Positioning Accuracy

Similar to Brown and Hong's (2006) observation, in this study, when groups were asked to complete the task using the BOTH condition, TILT was used to cover long distance ROI movements, and TOUCH was primarily used for accurately placing the ROI at an exact location. It was observed that participants would often switch from the TILT to the TOUCH technique just for making minor adjustments. Participants liked having both methods together as evidenced by the following comments after using the BOTH condition:

- *"The ability to use both motion and touch controls was useful for traveling long distances and doing precision work respectively."(SS10 BOTH)*
- *"Using the hold button helped when viewing distant icons, but I prefer touch and drag when the box is within reach."(SS4 BOTH)*

However, in our pilot sessions, anecdotally, users with previous experience with console gaming had better control of the ROI in the TILT technique, and hence, the accuracy of placing the ROI at an exact location was no longer an issue. It is know from all the emerging touch devices that as people get used to using new technology, they get more comfortable using it, and hence it can be anticipated that the accuracy issue in the TILT technique may be reduced in future studies as people become more familiar with the input paradigm of controlling screen content via device movement .

6.9 Applicability of TOUCH and TILT beyond Geospatial Task

In this research, the motivation of designing the TILT and TOUCH techniques was the overview-plus-detail interface to support the geotagged data exploration in a collaborative sensemaking environment. However, these techniques are not limited to be used in this environment. These techniques would likely be equally useful in any task that involves connecting the spatially located information on a tabletop interface to the sematic detailed information on the secondary tablet interface. Although the main contribution of this thesis is applied and tested in a geotagged data context but the study results would likely extrapolate to more general overview-plus-detail task scenarios. For example, the TOUCH and TILT techniques could be applied for data analysis in a construction domain, where these techniques can be used for sensemaking of floor plans, layouts, building information model, etc. In such scenarios an architect or a structural engineer could explore sematic data that is spatially connected to a building schematic.

6.10 Study Limitations

This work provides an in-depth discussion on how different group styles and group dynamics impacted the use of the TOUCH and TILT techniques in a collaborative sensemaking environment. Yet, as these techniques were tested in a controlled laboratory environment, there are a number of limitations that need to be acknowledged. First, this study consisted of a gamified task, with the majority of participants being students at University of Waterloo; whereas in a real-world scenario the data analyst would face a more stressful decision-making environment. Second, the TILT technique was observed to be much harder to use compared to the TOUCH technique. With the popularity of touch devices, more people are trained in using direct manipulation gesture. On the other hand, only some people (e.g. experienced console gamer) have existing expertise on mobile device movement as computer input. Third, this study was run with a group of two participants with one being on the short side and other being on long side of the table. A study done with more than two participants may greatly impact the group dynamics and use of the exploration techniques. Finally, the task context used in this study was a sea-ice Artic data task that consists of graphs, charts, images and bulletins, and these types of data are associated with the spatial context on the map. In other scenarios the type of data may need to be explored in a more multi-dimensional fashion. For example, a piece of data may be better explored when viewed in a temporal context in addition to a spatial context. Hence, the way the two data exploration techniques are used may differ for such multi-dimensional data exploration.

6.11 Technical Limitations

The two data exploration techniques were designed for the ROI movement to be controlled independently by their owner. In the TILT technique, ROI movement was controlled by its owner using their tablets; hence during an occurrence of a ROI overlapping, participants were able to move their ROIs without interfering with their partners' ROI. On the other hand, in the TOUCH technique, when the ROIs were overlapping exactly on top of each other (common with groups exhibiting ICND behaviour), it was physically not possible to move the bottom ROI without first moving the top ROI. Hence, this resulted in unavoidable interference.

As discussed in section 5.6.1, the TOUCH technique was widely used by the participants for short distance accurate movements, but it had technical limitations when making long distance ROI movements. During pilot testing it was anecdotally observed that participants felt tired after making long distance drags. Additionally, during long drag movements of the ROI, sometimes the ROIs got overlapped, and participants unknowingly took control of their partners' ROI after the overlap.

6.12 Design Recommendations

The main objective of this thesis was to study the impact of multi-surface interaction techniques on independent and collective data exploration of geotagged data during collaborative sensemaking. Based on observations and suggestions made by participants, there are number of design recommendations for potential future work related to the proposed design concept. The design recommendations have been divided into two parts. First, the design recommendation those need to be considered for improving multi-surface system supporting collaborative sensemaking. Second, the design recommendations for improving, specifically the TOUCH and the TILT interactions.

6.12.1 Design Recommendation for Improving Multi-Surface Collaborative Sensemaking

The findings from the study indicate that there were significant amount of mixed-focus collaboration between the participants in a group. The participants preferred working independently during initial phase and then working collectively during the discussion phase. Therefore, a well-designed multi-surface interaction technique should support tightly and loosely coupled collaboration by supporting both independent and collective activities.

Independent exploration requires for each participant to be able to reach the overview content (data) and control their personal view, without interrupting their group members, in order to reduce interference.

Furthermore, the system should provide collective data exploration to support the discussion phase of sensemaking. This includes supporting the lease collaborative effort for exploring data and one way to achieving this is by proving a flexible ownership. When a group works collectively, the system should allow each group members to control other member's view so that it is not enforcing a strict ownership. Moreover, the system should allow all group members to share views and discuss their individual findings effectively with other group members.

As observed in previous research and in this research, activities like formation of tableaux are commonly used by groups while conducting sensemaking. Hence, a well-designed system should support formation of tableaux by separating the control of the data view from where the data is being viewed.

6.12.2 Design Improvements for TOUCH and TILT Interaction

Based on the feedback reported on the post-condition questionnaire by the participants on the use of technology, and observations made during the study, the following design recommendations were made to improve the TOUCH and TILT interaction techniques.

6.12.2.1 Merging the ROI Together during Tightly Coupled Interactions

The study findings revealed that groups frequently used "flexible ownership" of the TOUCH technique, and used the territorial navigation (TN) strategy to overcome the physical limitations of the tabletop. To minimize effort and improve accuracy for groups that employed the TN strategy, it is recommended to have an option of merging both the ROIs together. This implication can be achieved by “locking” or “snapping” both ROI’s together when required, also suggested by one of the participants in the comment, “*....boxes could be locked together or a button on the tablet to SNAP my partner's bounding box [ROI] to my box view…” (SS4).*

6.12.2.2 Shared Common View on the Table or Tablet

The dropbox feature was integrated in the tablet interface to help group members with the discussion and insightful analysis, but study data indicate that participants missed having a feature where they can view the data being displayed on other partners’ tablets. This was confirmed by the following negative comment, *“..shared views of same data were harder to achieve….” (SS4).* Some groups overcame this limitation by simply dragging both the ROIs on the same data point, but the manual dragging was not accurate to position over the exact location of the ROI. Hence, it is recommended to have a feature where participants can share each other’s view, or perhaps make dropbox as a shared space between all the collaborators where they engage in discussion and analyze data cohesively.

6.13 Chapter Summary

This chapter discussed the findings presented in this thesis as they are applied to the context of data exploration in a collaborative sensemaking environment. Comparing the use of TOUCH and TILT throughout the sensemaking process, the chapter discussed how the application of each technique impacted groups’ performance. Finally, the technical limitations of the method and suggested design improvements were presented.

Chapter 7

Conclusions and Future Work

While researchers have previously investigated various data exploration techniques, much of this literature either focuses on the data visualization by providing magnified secondary views or by adding extra layers of information over existing interfaces. Few of these techniques were designed to support collaborative sensemaking, and none of them focused primarily on studying collaborative sensemaking environments involving geotagged data. Hence, to meet the demand of increasing geotagged data and fill a gap in the literature to support insightful sensemaking of such data, this thesis focused on designing a multi-surface collaborative sensemaking environment by utilizing TOUCH and TILT control mechanisms for exploration of geotagged data.

7.1 Research Objectives and Summary

Section 1.2 introduced the three research objectives of this thesis, namely: 1) to identify promising cross-device interaction and data exploration techniques for multi-surface environments from existing literature 2) to apply promising data exploration techniques to a multi-surface environment, that allow independent personal viewing of geotagged data during collaborative sensemaking and 3) evaluate the impact of the proposed techniques on collaborative sensemaking. The first objective was fulfilled by performing a literature review that examined the existing sensemaking models, both for individuals doing sensemaking and for groups engaged in collaborative sensemaking, and by exploring different data-exploration techniques involving single- and multi-surface environments (Chapter 2).

The second objective was addressed by designing the TOUCH and TILT control mechanisms to move a "region of interest" (ROI) widget in the tabletop interface, and hence to control the personal view of geotagged data on a peripheral tablet (Chapter 3). These interaction techniques were applied to a table-centric multi-surface environment aimed to support collaborative sensemaking involving Arctic-sea ice geotagged data. Finally, the third objective was addressed by conducting a mixed-methods laboratory-based study investigating the use of the TOUCH and TILT technique during a collaborative sensemaking task (Chapters 4 and 5). Hence, the main research objective of understanding the impact of overview-plus-detail (O+D) multi-surface interaction techniques on independent and collective data exploration of geotagged data during collaborative sensemaking has been address in this study.

As a result, the following main contributions were made:

- **Application of existing cross-device data exploration methods to support sensemaking.** The two techniques, TOUCH and TILT, were adapted from existing cross-device data exploration techniques and they were extended further to support the collaborative sensemaking task environment.
- **Comparing the use of two control mechanisms for data exploring during a collaborative sensemaking process.** Findings from the user study indicate that both TOUCH and TILT techniques helped to support collaborative sensemaking based on different stages of sensemaking or the strategy that groups employed. TILT provided reachability during loose collaborative phases, while TOUCH enhanced group collaboration during tight collaboration phases. Although TOUCH led to more interference due to the need for partners to help each other reach far tabletop locations,

its "flexible ownership" and accurate ROI placement facilitated communication and tight cooperation during sensemaking.

- **Examination of the impact of seating arrangement on the effectiveness of control mechanisms.** Even though the TOUCH technique limited participants seated at the short side of the tabletop to physically interact with the far end of the table, groups with good cooperation overcame this limitation by helping each other. This mitigated the expected negative impact of the TOUCH technique. However, the TILT technique supported independent data exploration more effectively than TOUCH.
- **Geotagged data exploration using the Overview + Detail visualization.** This research involved geotagged data that had a spatial context; hence analysis of such data required the need to create a spatial connection between the overview of the geographic map on the tabletop and geotagged data detailed on the tablet. The flexibility of TOUCH was perceived to be ergonomically friendly, but since it allowed the detail view to be controlled by the non-owner, it sometimes resulted in attention tunneling due to a disconnection between the overview and the detail view.

7.2 Future Work

This research suggests a number of opportunities for further investigation.

First, findings from this study identified that group dynamics and group strategies employed during the sensemaking task had a huge impact on the use of the TOUCH and TILT techniques. Hence, to study this impact further, future studies should look at comparing the use of techniques with larger groups (more than two members), and when the task is performed with group members who do not know each other prior to taking part in the study. Second, it was anecdotally observed that participants with limited experience of using tablet controls (or non-professional console gamers) found it much harder to use the TILT condition compared to the participants with prior experience using console-based games. Future studies could be conducted by recruiting participants only with prior console gaming experience to study the usability aspect of the TILT technique.

Third, during pilot testing and training of participants, it was also anecdotally observed that during the TILT condition some participants were more comfortable controlling the ROI movements when the tablet was tilted in the up-and-down direction compared to the left-and-right direction. This ergonomic limitation was more applicable to the LS participant as they required more left-and-right movements during the session, being seated at the longer side of the tabletop. Hence, future studies should focus on conducting benchmark testing on performance and accuracy of ROI placement using both the TOUCH and TILT techniques, and from both sides of the table, for instance, by conducting *Fitts's law* testing (Drewes, 2010). Finally, the context used in this study to test TOUCH and TILT techniques was a geotagged data exploration task. These techniques could be applied and tested in other task domains, such as, architecture, engineering design, etc.

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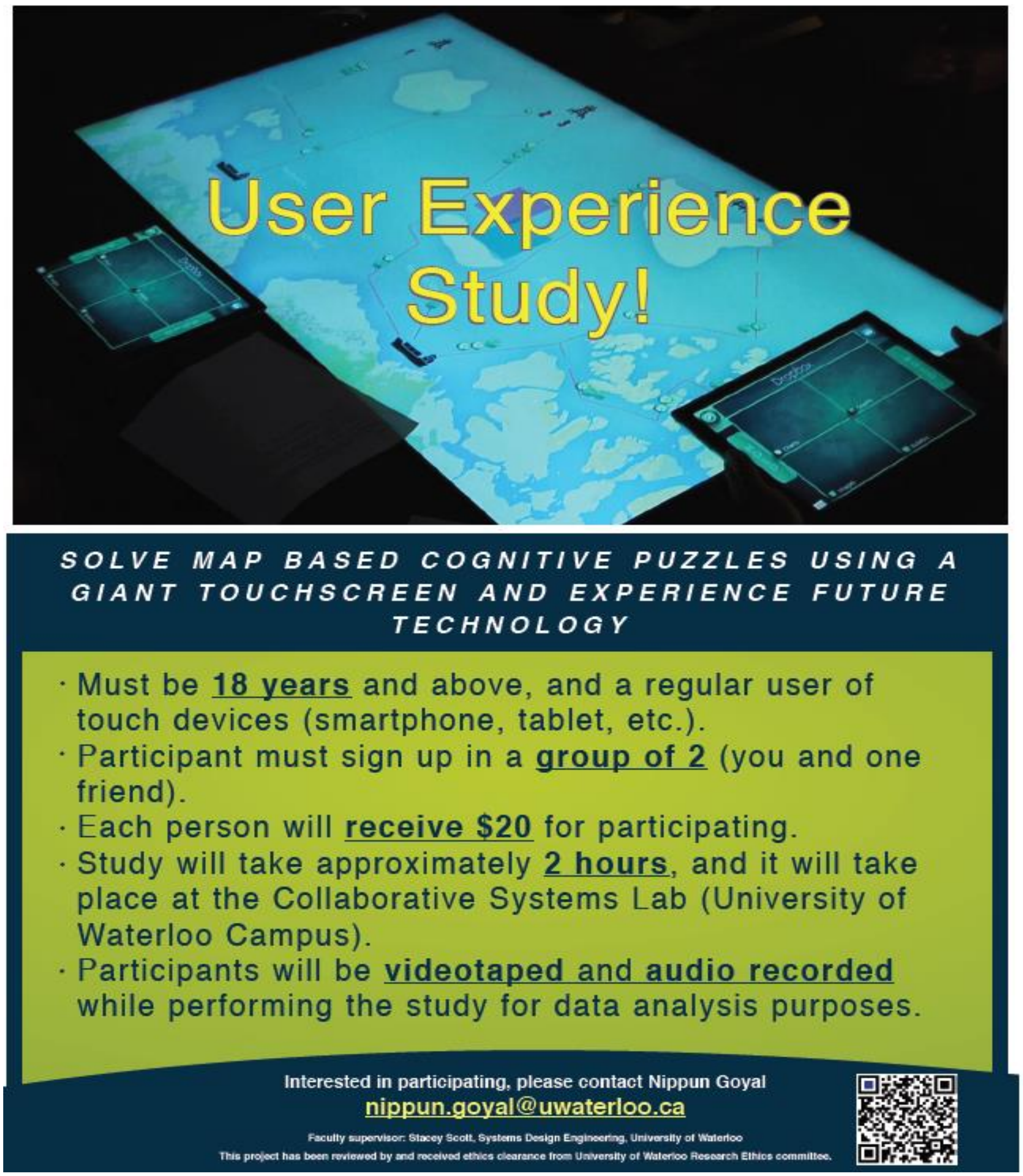
Appendix A
Study Material

A.1 Recruitment Material

Recruitment Poster



Recruitment Letter

Subject: USER EXPERIENCE STUDY: Solve map based cognitive puzzles using a giant touchscreen and experience future technology?

Hello,

My name is Nippun Goyal and I am a master's student working under the supervision of Dr. Stacey Scott in the System Design Engineering Department at the University of Waterloo. We are currently seeking participants for a study of group solving a map based cognitive puzzle using an interactive multi-touch tabletop and a tablet. As a part of study your group will be asked to solve a collaborative map based cognitive puzzles using a multi-touch interactive tabletop and tablet.

- Participants must sign up in a **group of two** (you and one friend).
- The study will take **approximately 2 hours.**
- Participants must be at least **18 years** old and be regular user of touch devices (smart phone, tablets, etc.).
- Participants will be asked to complete a questionnaire after each puzzle and take part in a group interview after the study session about their experience of using technology.
- Each participant will receive **$20 remuneration** for taking part in the study.
- Participants will be **videotaped and audio recorded** while performing the study for data analysis purposes.
- The study will take place at the Collaborative Systems Laboratory at the University of Waterloo Campus (200 University Ave W, Waterloo, ON).

If you are interested in participating please contact me (nippun.goyal@uwaterloo.ca).

This project has been reviewed by and received ethics clearance (ORE # 20790) from the University of Waterloo Research Ethics committee.

Sincerely,

Nippun Goyal

Faculty supervisor:

Dr. Stacey Scott, Systems Design Engineering, University of Waterloo

A.3 Study Material

LETTER OF INFORMATION

Data navigation techniques to study semantically overlaid geotagged data using tablet and a digital tabletop

Summary of the Project:

You are invited to participate in a research project directed by Nippun Goyal, Dr. Stacey Scott, Oluwademilade Olagoke and Raphael Cheng from Collaborative Systems Laboratory at the University of Waterloo. This research is a part of thesis project for Nippun Goyal towards completion of MASc. degree and the faculty supervisor on this project is Dr. Stacey Scott. We will read through this letter of information with you, describe our experimental procedures in detail, and answer any questions you may have. The research is being funded by NSERC- SurfNet

The study aims to explore the use of personal handheld tablet with a digital tabletop in a collaborative environment. The study will last approximately 2 (two) hours. During the study, you will be first asked demographic/background questions such as gender, age, occupation, game play, and use of touch-based devices. Then you will be asked to solve tasks in groups of two. At the end of each session and at the end of the study, we will ask you several questions about your experience with the task and the devices you used to accomplish those tasks. You can decline to respond to any question on the questionnaires by leaving it blank.

Procedure:

During the experiment, you will be asked to work as a group to complete a task of finding answer to question that will require you to navigate geotagged data using your tablet that has been overlaid on a map on digital tabletop. You will be asked to perform these task using three different conditions involving computer devices such as an interactive tabletop and personal tablet. After completing the task in each condition, you will be asked to fill in a questionnaire giving your opinions on the previously tested interactions. At the end of the study, we will interview you as a group and ask you to comment on the tasks completed and your approach to solve the task.

Throughout the task, you will be videotaped and audio recorded.

Your participation is voluntary. You may stop at any time by alerting the experimenter. Should you choose to withdraw; any data collected up to the point of withdrawal will be destroyed. If you wish to withdraw at a later date, you may contact the research team using the contact information provided below, and all data collected during your session will be destroyed.

Confidentiality and Data Security:

All information you provide is considered completely confidential. Your name will not appear in any publication resulting from this study; however, with your permission anonymous quotations may be used. In these cases participants will be referred to as Participant 1, Participant 2, … (or P1, P2, …) or collectively as a group (Group A, B, …). Data collected during this study will be retained for 5 years in locked cabinets or on password protected desktop computers in a secure location accessible only to researchers associated with this project and will be securely destroyed afterwards Electronic data will be de-identified before being stored.

You will explicitly be asked for consent for the use of photo/video/audio data captured during the study for the purpose of reporting the study's findings. If consent is granted, this data will be used only for the purposes associated with teaching, scientific presentations, and/or publications and you will not be identified by name. In any video recordings shown publicly, we will not blur your face.

While researchers will maintain confidentiality (unless permission is given to use video in public or semi-public venues) we cannot guarantee that other participants will do the same. Hence, we would like to remind all participants that confidentiality is expected regarding other participants in the study.

Risks and Benefits:

There are no known risks in participating in this study. The research community will benefit from a better understanding of the usability of multi-display environments and large interactive surfaces and their impact on collaborative work.

You will receive $20 to thank you for your participation. The amount received is taxable. It is your responsibility to report this amount for income tax purposes. Should you choose to withdraw, you will still receive $20.

Questions or Concerns:

This project has been reviewed by, and received ethics clearance through University of Waterloo Research Ethics Committee.

Any questions about study participation may be directed to members of the research team listed above. Any ethical concerns about the study may be directed to Dr. Maureen Nummelin, Chief Ethics Officer, Office of Research Ethics, University of Waterloo, at 519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Please retain a copy of the letter of information and consent form.

Data navigation techniques to study semantically overlaid geotagged data using Tablet and a digital Tabletop

I have read the letter of information describing this study being conducted Nippun Goyal, Dr. Stacey Scott, Oluwademilade Olagoke and Raphael Cheng from Collaborative Systems Laboratory at the University of Waterloo. I understand that I will be participating in a research project whose structure and procedures are described in the attached letter of information. I have had the opportunity to ask questions related to this study, and have received satisfactory answers to any questions.

Sometimes a certain image and/or segment of videotape clearly shows a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific presentation or in a publication.

I am aware that I may allow video and/or digital images in which I appear to be used in teaching, scientific presentations, publications, and/or sharing with other researchers with the understanding that I will not be identified by name. I further understand that my face or any other part of my body recorded in the video will not be blurred in any video recordings shown publicly. I am aware that I may allow excerpts from the conversational data collected for this study to be included in teaching, scientific presentations and/or publications, with the understanding that any quotations will be anonymous.

I am aware that my participation is voluntary and that I may withdraw my study participation at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through a University of Waterloo Research Ethics Committee. I understand that I may address any questions about study participation to Stacey Scott (stacey.scott@uwaterloo.ca), and Nippun Goyal (nippun.goyal@uwaterloo.ca) of University of Waterloo and that any ethical concerns about the study may be to the Director, Office of Research Ethics at the University of Waterloo at maureen.nummelin@uwaterloo.ca, 519-888-4567 ext. 36005.

Participant ID: _________

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

	Please Circle One		Please Initial Your Choice
With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.	YES	NO	__________
I consent to the use of non-identifying quotations in publications, and talks.	YES	NO	__________
I consent to being videotaped (body including my face) and audio recorded while participating in this study for the purposes of permitting accurate analysis of my actions during this session.	YES	NO	__________
I consent to the use of still images and short video recordings made during this study in publications, and talks.	YES	NO	__________
I consent to work in a pair or a group while performing task in the study.	YES	NO	__________
I consent to answer questionnaires at the end of each condition.	YES	NO	__________
I consent to give a group interview at the end of this study.	YES	NO	__________

Participant Name: ____

(Please print)

Participant Signature: ____

Witness Name: ____

(Please print)

Witness Signature : ____

Date : ____

Background Questionnaire

Please fill out this questionnaire as accurately as possible. None of the information will be personally linked to you in any way. Please do not write your name anywhere on the questionnaire.

1. What is your sex? (please circle one)

  ○ Female
  ○ Male
  ○ Other

2. What is your age?

  ○ 18-25
  ○ 26-35
  ○ 36-45
  ○ 46-55
  ○ 56-65

3. What is your occupation? ________________________________

If student, what degree/program are you in? _________________________________

4. On a scale of 1-5, Please indicate how often you have played Console game (Xbox, Play Station) over the past five years?

Never	Once or twice	Several times	Weekly	Daily
1	2	3	4	5

5. On a scale of 1-5, Please indicate how comfortable are you in using joy stick/direction controls on console game?

Not Comfortable				Very Comfortable
1	2	3	4	5

6. On a scale of 1-5, please indicate how often you have used a touch-based computing device (e.g., iPhone, iPad, Blackberry Storm, Microsoft Surface computer, digital tabletop computer, etc.)?

Never	Once or twice	Several times	Weekly	Daily
1	2	3	4	5

7. How well do you know the other participant?

Never Met				Very Well
1	2	3	4	5

Thank you Letter

"Data Navigation techniques to study semantically overlaid geotagged data using Tablet and a digital Tabletop"

We appreciate your participation in our study, and thank you for spending the time helping us with our research!

During this experiment, you were asked to work as a group to complete a task of finding answer to question that required you to navigate geotagged data using your tablet that was overlaid on a map on digital tabletop. You performed these task using three different conditions involving computer devices such as an interactive digital tabletop and personal handheld tablet. After completing the task in each condition, you were asked to fill in a questionnaire giving your opinions on the previously tested interactions. At the end of the study, we interviewed you as a group and ask you to comment on the tasks completed and your approach to solve the task.

Through this research project we designed two interaction techniques called direct and indirect, to browse geotagged data overlaid on digital tabletop using a handheld personal tablet and further explore that data using the dropbox feature available on the tablet. You performed the task using direct and indirect condition and in third condition both direct and indirect conditions were available together to navigate data on the table. A collaborative sensmaking task was used as a method of studying performance using both direct and indirect techniques. The goal was to analyze which technique offers more flexibility and is more effective for data browsing to solve a sensemaking task in a collaborative environment.

Please remember that any data pertaining to you as an individual participant has been collected confidentially. Once all the data are collected and analyzed for this project, we plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. If you are interested in receiving more information regarding the results of this study, or would like a summary of the results, please provide your email address, and when the study is completed (anticipated by September 2015) one of us will send you the information. In the meantime, if you have any questions about the study, please do not hesitate to contact me by email as noted below. As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through a University of Waterloo Research Ethics Committee. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Maureen Nummelin, Chief Ethics Officer, Office of Research Ethics, University of Waterloo, at 1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Thank you!

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Systems Design Engineering

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Post-Condition Questionnaire

Participant ID: ________________

Please fill out this questionnaire as accurately as possible. None of the information will be personally linked to you in any way. Please do not write your name anywhere on the questionnaire.

1. NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the mission easy or demanding, simple or complex, exacting or forgiving?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the mission easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Temporal Demand: How much time pressure did you feel due to the rate or pace at which the mission occurred? Was the pace slow and leisurely or rapid and frantic?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Performance: How successful do you think you were in accomplishing the goals of the mission? How satisfied were you with your performance in accomplishing these goals?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Frustration: How discouraged, stressed, irritated, and annoyed versus gratified, relaxed, content, and complacent did you feel during your mission?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

2. Awareness and Collaboration

Please circle the number on the scale from 1 to 7 that best represents your experience.

I found it easy to locate data icon(s) on the tabletop map that represented the data shown on the tablet.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

I found it easy viewing the data on the tablet while moving the bounding box on the table at the same time.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

I was always aware of what data my partner was exploring.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

Coordinating with my partners was easy.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

I felt my partner interfered with my actions while exploring data.

Never			Sometimes			Always
1	2	3	4	5	6	7

I felt that I interfered with my partner action while exploring data.

Never			Sometimes			Always
1	2	3	4	5	6	7

While viewing data on the tablet, I felt _________.

Distracted						Focused
1	2	3	4	5	6	7

I found dropbox feature on the tablet was useful.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

I am confident that my team considered all the relevant data.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

I am confident that my team got the right answer.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

3. Please answer the following questions.

What aspects of technology (table and tablet) hindered completion of task?

____

____

What aspects of the technology (table and tablet) helped in completion of task?

____

____

What aspects of the technology (table and tablet) helped in group coordination during the task?

____

____

What was your approach to solve the task?

____

____

Post-Experiment Questionnaire

Participant ID: ________________

Please fill out this questionnaire as accurately as possible. None of the information will be personally linked to you in any way. Please do not write your name anywhere on the questionnaire.

1. Out of first two condition rank condition in order you liked the most and explain why?

Condition 1	Condition 2
Rank___	Rank ___

Why?

____

____

____

____

____

2. Any additional remarks

____

____

____

____

A.3 Condition Test Scenario and Cases

Scenario:

Imagine a scenario where you are a data analyst who works for an oil company. Your company is planning to set up an oil extraction plant around few potential oil fields in artic where oil will be extracted for next 8-10 years. Based on past research, your company has information for 4 potential oil fields where oil extraction plant can be set up. These potential oil fields are accessible via oil tanker (ships) from nearest ports.

There are 6 different ship routes that can be used to reach the 4 potential oil fields and there 2 ports available where your company can set up base station for land transportation. Along each route there is geotagged information from Canadian Ice Service from their research and events that have occurred in the past. The information can be categorized into four different types, i.e. Ice chart, Ice Graph, Photographs and Ice Bulletin. This information is the only source you have to make a decision that will be best for your company.

Your goal for this study is to explore geotagged information, overlaid on a digital map on tabletop and with the help of tablet navigates the information, and find the best solution for a given scenario.

Case1:

Your goal for this round is to find the best route for transportation of ships to carry oil, taking into account that oil is transported in the month of **December**.

Here is some of key information that you should consider:

1. *Compare ice chart and ice graph between different routes.*
2. *Check for changing ice trends. Changing trend can often help Figure out future feasibility of route.*
3. *Pictures can often help provide some basic idea about the ice situation for a given period.*
4. *Ice Bulletins provide information on forecast.*

Case 2:

Global warming has led to changing temperatures and has affected ice conditions in various regions in Artic. These changes can impact the ability to predict routes for future travel. Since you are planning for the next few years, it is important to consider the changing ice conditions. Your goal for this round is to find the best route for transporting oil during winter period **(December –March)** considering changing ice conditions as the main factors.

Here are some of the keys that you should consider:

1. *Look for changing trends over last few years.*

2. *Comparing Ice charts within a given region over a period of time can provide helpful information on ice change.*
3. *Comparing images of a given region taken over a period of time.*
4. *Change in air temperature over time can often cause changes in ice condition.*

Case 3:

An icebreaker is a special-purpose ship designed to cut and navigate through ice-covered waters, and provide safe waterways for other boats and ships. Hence, considering the fact that an ice breaker can clear a path for oil tankers to move around is a very important factor to be considered for the winter season. From the geotagged information provided by Canadian Ice Service, your goal for this round is to find which oil field will be most feasible to set up an extraction plant taking into account that an ice breaker can create a clear path of travel in the winter season **(December-March).**

Here are some of keys that you should consider:

1. *An Ice breaker can easily cut through fresh/young ice compared to ice that has become denser over years of accumulation.*
2. *A trend of changing ice temperatures over the years can help ice breaker easily cut through as it will reduce the density of accumulated thick ice.*
3. *Any picture or news bulletin that provides information of failed mission or an ice breaker stuck at a place can be helpful towards your evaluation.*
4. *Look for signs of coast guard activity or coast guard stations around the route. Coast guard can launch rescue mission if an ice breaker gets stuck.*

Appendix B
Statistical Calculations

B.1 Statistical Analysis of Condition

Descriptive Statistics

Question		TableOrientation	Mean	Std. Deviation	N
I found locating data icon(s) on the tabletop map that represented the data shown on the tablet to be:	TOUCH	LongSide	6.3333	1.1547	12
		ShortSide	5.75	1.60255	12
		Total	6.0417	1.39811	24
	TILT	LongSide	5.8333	1.4668	12
		ShortSide	5.1667	1.64225	12
		Total	5.5	1.56038	24
I found viewing the data on the tablet while moving the bounding box on the table at the same time to be:	TOUCH	LongSide	6.0833	1.1645	12
		ShortSide	5.4167	1.31137	12
		Total	5.75	1.25974	24
	TILT	LongSide	4.9167	2.15146	12
		ShortSide	4.9167	2.10878	12
		Total	4.9167	2.08341	24
I am confident that my team considered all the relevant data.	TOUCH	LongSide	6.1667	0.71774	12
		ShortSide	5.75	1.54479	12
		Total	5.9583	1.19707	24
	TILT	LongSide	6.0833	0.79296	12
		ShortSide	6.1667	0.93744	12
		Total	6.125	0.85019	24
I am confident that my team got the right answer.	TOUCH	LongSide	5.8333	0.93744	12
		ShortSide	5.75	0.96531	12
		Total	5.7917	0.93153	24
	TILT	LongSide	5.75	1.21543	12
		ShortSide	5.9167	1.08362	12

		Total	5.8333	1.12932	24
I was always aware of what data my partner was exploring.	TOUCH	LongSide	4.9167	1.92865	12
		ShortSide	4.9167	1.92865	12
		Total	4.9167	1.88626	24
	TILT	LongSide	5.0833	1.88092	12
		ShortSide	5	1.59545	12
		Total	5.0417	1.70623	24
Coordinating with my partner was:	TOUCH	LongSide	6.0833	1.08362	12
		ShortSide	6.25	1.3568	12
		Total	6.1667	1.20386	24
	TILT	LongSide	6	1.59545	12
		ShortSide	6.1667	1.02986	12
		Total	6.0833	1.31601	24
I felt my partner interfered with my actions while browsing data.	TOUCH	LongSide	3.1667	1.94625	12
		ShortSide	1.75	1.13818	12
		Total	2.4583	1.71893	24
	TILT	LongSide	1.5833	0.90034	12
		ShortSide	1.0833	0.28868	12
		Total	1.3333	0.70196	24
I felt that I interfered with my partner's action while browsing data.	TOUCH	LongSide	3.25	1.91288	12
		ShortSide	1.75	1.21543	12
		Total	2.5	1.74456	24
	TILT	LongSide	2.0833	1.31137	12
		ShortSide	1.3333	0.49237	12
		Total	1.7083	1.0417	24
While viewing data on the tablet I was:	TOUCH	LongSide	5.5833	0.90034	12
		ShortSide	5.6667	0.88763	12
		Total	5.625	0.87539	24
	TILT	LongSide	5.8333	0.57735	12
		ShortSide	5.9167	0.28868	12

		Total	5.875	0.44843	24
I found dropbox feature on the tablet to be:	TOUCH	LongSide	4.4167	1.56428	12
		ShortSide	4.25	1.81534	12
		Total	4.3333	1.6594	24
	TILT	LongSide	4.1667	1.74946	12
		ShortSide	4.5833	1.88092	12
		Total	4.375	1.78916	24
Mental Demand	TOUCH	LongSide	6.1667	1.99241	12
		ShortSide	6.4167	2.06522	12
		Total	6.2917	1.98865	24
	TILT	LongSide	5.9167	1.56428	12
		ShortSide	7.0833	1.37895	12
		Total	6.5	1.56038	24
Physical Demand	TOUCH	LongSide	3.3333	2.80692	12
		ShortSide	3.0833	2.57464	12
		Total	3.2083	2.63718	24
	TILT	LongSide	4.3333	2.46183	12
		ShortSide	3.5	2.50454	12
		Total	3.9167	2.46571	24
Temporal Demand	TOUCH	LongSide	4.5	3.03015	12
		ShortSide	5.9167	2.31432	12
		Total	5.2083	2.73431	24
	TILT	LongSide	4.1667	2.24958	12
		ShortSide	5.0833	2.74552	12
		Total	4.625	2.49891	24
Performance:	TOUCH	LongSide	8.0833	1.50504	12
		ShortSide	7.6667	1.96946	12
		Total	7.875	1.72734	24
	TILT	LongSide	7.5833	1.62135	12
		ShortSide	7.6667	1.82574	12

		Total	7.625	1.68916	24
Effort	TOUCH	LongSide	4.6667	2.90245	12
		ShortSide	6.3333	1.92275	12
		Total	5.5	2.55377	24
	TILT	LongSide	5.0833	2.10878	12
		ShortSide	6.6667	1.1547	12
		Total	5.875	1.84891	24
Frustration	TOUCH	LongSide	3.4167	2.71221	12
		ShortSide	3.0833	2.46644	12
		Total	3.25	2.54097	24
	TILT	LongSide	4.0833	1.92865	12
		ShortSide	4.25	2.37888	12
		Total	4.1667	2.11961	24

Tests of Within-Subjects Effects

Question	Source	df	Mean Square	F	Sig.	Partial Eta Squared
I found locating data icon(s) on the tabletop map that represented the data shown on the tablet to be:	Condition	1	3.521	2.424	0.134	0.099
	Condition * TableOrientation	1	0.021	0.014	0.906	0.001
	Error(Condition)	22	1.453			
I found viewing the data on the tablet while moving the bounding box on the table at the same time to be:	Condition	1	8.333	5.851	0.024	0.21
	Condition * TableOrientation	1	1.333	0.936	0.344	0.041
	Error(Condition)	22	1.424			
I am confident that my team considered all the relevant data.	Condition	1	0.333	0.568	0.459	0.025
	Condition * TableOrientation	1	0.75	1.277	0.271	0.055
	Error(Condition)	22	0.587			
I am confident that my team got the right answer.	Condition	1	0.021	0.037	0.849	0.002
	Condition * TableOrientation	1	0.188	0.336	0.568	0.015

	Error(Condition)	22	0.559			
I was always aware of what data my partner was exploring.	Condition	1	0.188	0.105	0.749	0.005
	Condition * TableOrientation	1	0.021	0.012	0.915	0.001
	Error(Condition)	22	1.786			
Coordinating with my partner was:	Condition	1	0.083	0.108	0.745	0.005
	Condition * TableOrientation	1	0	0	1	0
	Error(Condition)	22	0.769			
I felt my partner interfered with my actions while browsing data.	Condition	1	15.188	13.477	0.001	0.38
	Condition * TableOrientation	1	2.521	2.237	0.149	0.092
	Error(Condition)	22	1.127			
I felt that I interfered with my partner's action while browsing data.	Condition	1	7.521	7.771	0.011	0.261
	Condition * TableOrientation	1	1.688	1.744	0.2	0.073
	Error(Condition)	22	0.968			
While viewing data on the tablet I was:	Condition	1	0.75	1.784	0.195	0.075
	Condition * TableOrientation	1	0	0	1	0
	Error(Condition)	22	0.42			
I found dropbox feature on the tablet to be:	Condition	1	0.021	0.007	0.935	0
	Condition * TableOrientation	1	1.021	0.333	0.57	0.015
	Error(Condition)	22	3.066			
Mental Demand	Condition	1	0.521	0.417	0.525	0.019
	Condition * TableOrientation	1	2.521	2.02	0.169	0.084
	Error(Condition)	22	1.248			
Physical Demand	Condition	1	6.021	1.964	0.175	0.082
	Condition * TableOrientation	1	1.021	0.333	0.57	0.015
	Error(Condition)	22	3.066			
Temporal Demand	Condition	1	4.083	0.815	0.376	0.036
	Condition * TableOrientation	1	0.75	0.15	0.702	0.007
	Error(Condition)	22	5.008			

Performance:	Condition	1	0.75	0.355	0.557	0.016
	Condition * TableOrientation	1	0.75	0.355	0.557	0.016
	Error(Condition)	22	2.114			
Effort	Condition	1	1.688	0.957	0.339	0.042
	Condition * TableOrientation	1	0.021	0.012	0.914	0.001
	Error(Condition)	22	1.763			
Frustration	Condition	1	10.083	3.254	0.085	0.129
	Condition * TableOrientation	1	0.75	0.242	0.628	0.011
	Error(Condition)	22	3.098			

B.2 Statistical Analysis of Table Orientation

Tests of Between-Subjects Effects

Question	Source	df	Mean Square	F	Sig.	Partial Eta Squared
I found locating data icon(s) on the tabletop map that represented the data shown on the tablet to be:	Intercept	1	1598.521	546.999	0	0.961
	TableOrientation	1	4.688	1.604	0.219	0.068
	Error	22	2.922			
I found viewing the data on the tablet while moving the bounding box on the table at the same time to be:	Intercept	1	1365.333	293.524	0	0.93
	TableOrientation	1	1.333	0.287	0.598	0.013
	Error	22	4.652			
I am confident that my team considered all the relevant data.	Intercept	1	1752.083	1083.255	0	0.98
	TableOrientation	1	0.333	0.206	0.654	0.009
	Error	22	1.617			
I am confident that my team got the right answer.	Intercept	1	1621.687	969.707	0	0.978
	TableOrientation	1	0.021	0.012	0.912	0.001
	Error	22	1.672			
I was always aware of what data my partner was exploring.	Intercept	1	1190.021	239.182	0	0.916
	TableOrientation	1	0.021	0.004	0.949	0

	Error	22	4.975			
Coordinating with my partner was:	Intercept	1	1800.75	708.492	0	0.97
	TableOrientation	1	0.333	0.131	0.721	0.006
	Error	22	2.542			
I felt my partner interfered with my actions while browsing data.	Intercept	1	172.521	92.666	0	0.808
	TableOrientation	1	11.021	5.92	0.024	0.212
	Error	22	1.862			
I felt that I interfered with my partner's action while browsing data.	Intercept	1	212.521	82.326	0	0.789
	TableOrientation	1	15.188	5.883	0.024	0.211
	Error	22	2.581			
While viewing data on the tablet I was:	Intercept	1	1587	2703.019	0	0.992
	TableOrientation	1	0.083	0.142	0.71	0.006
	Error	22	0.587			
I found dropbox feature on the tablet to be:	Intercept	1	910.021	293.161	0	0.93
	TableOrientation	1	0.188	0.06	0.808	0.003
	Error	22	3.104			
Mental Demand	Intercept	1	1963.521	389.312	0	0.947
	TableOrientation	1	6.021	1.194	0.286	0.051
	Error	22	5.044			
Physical Demand	Intercept	1	609.187	58.835	0	0.728
	TableOrientation	1	3.521	0.34	0.566	0.015
	Error	22	10.354			
Temporal Demand	Intercept	1	1160.333	135.543	0	0.86
	TableOrientation	1	16.333	1.908	0.181	0.08
	Error	22	8.561			
Performance:	Intercept	1	2883	731.838	0	0.971
	TableOrientation	1	0.333	0.085	0.774	0.004
	Error	22	3.939			
Effort	Intercept	1	1552.687	216.026	0	0.908

	TableOrientation	1	31.688	4.409	0.047	0.167
	Error	22	7.188			
Frustration	Intercept	1	660.083	79.427	0	0.783
	TableOrientation	1	0.083	0.01	0.921	0
	Error	22	8.311			

B.3 Statistical Analysis of Phase Comparison

Tests of Within-Subjects

Source	Phases	df	Mean Square	F	Sig.	Partial Eta Squared
Phases	Linear	1	0.621	6.754	0.016	0.235
Phases * Condition	Linear	1	0.051	0.553	0.465	0.025
Error(Phases)	Linear	22	0.092			

B.4 Statistical Analysis on Accuracy

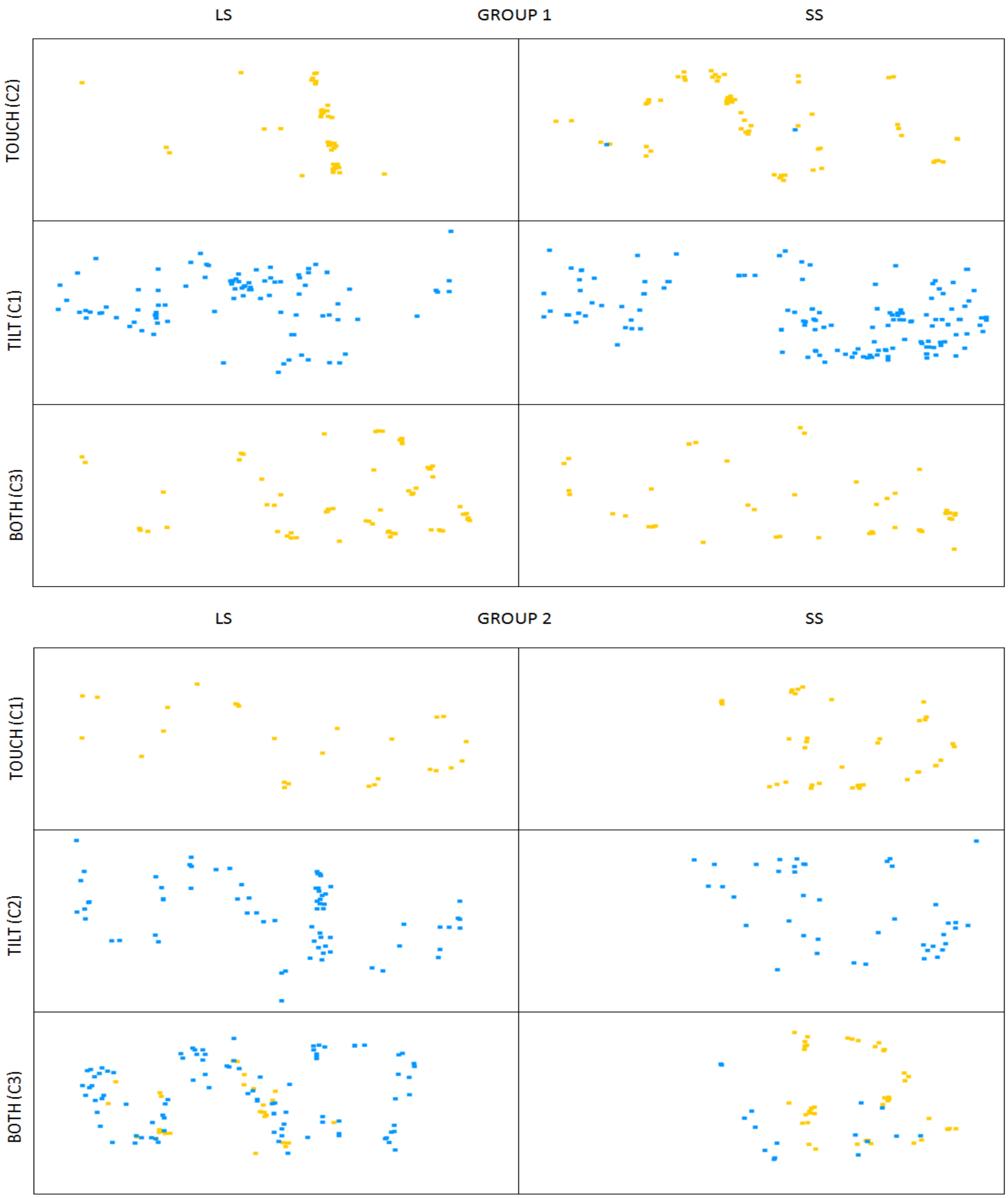
Tests of Within-Subjects on Condition

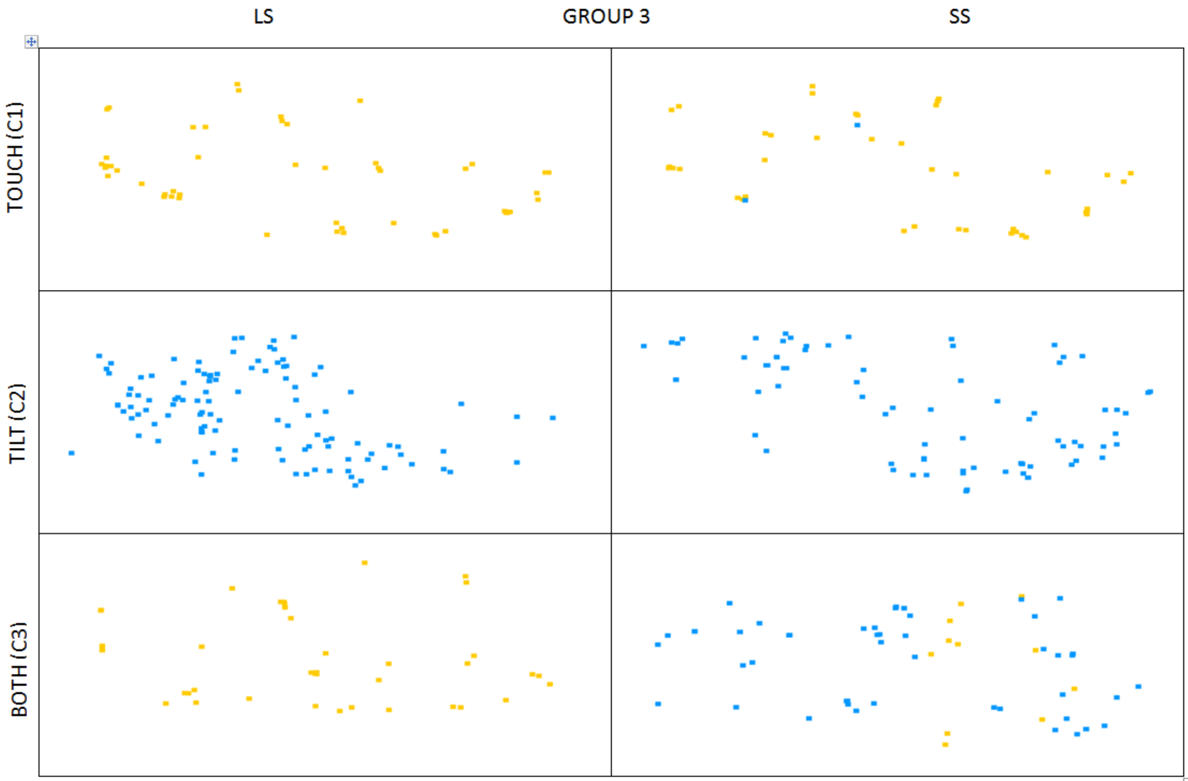
Source	Phases	df	Mean Square	F	Sig.	Partial Eta Squared
Condition	Linear	1	0.047	7.753	0.016	0.261
Condition * Side	Linear	1	0.047	9.495	0.465	0.301
Error(Phases)	Linear	22	0.047			

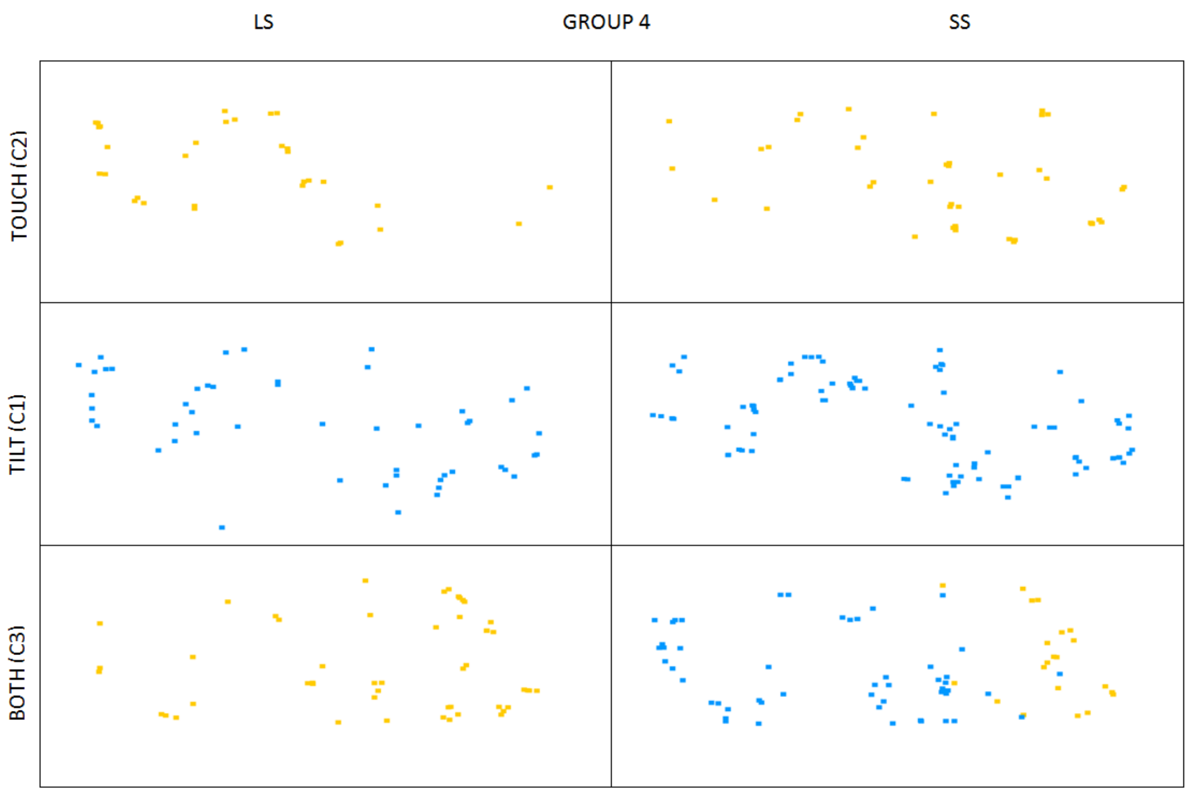
Tests of Within-Subjects on Condition

Source	Phases	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	Linear	1	0.422	78.158	0.000	0.780
Side	Linear	1	0.055	10.129	0.004	0.315
Error	Linear	22	0.005			

Appendix C
ROI Interaction Visualization Maps




LS
GROUP 3
SS
TOUCH (C1)
TILT (C2)
BOTH (C3)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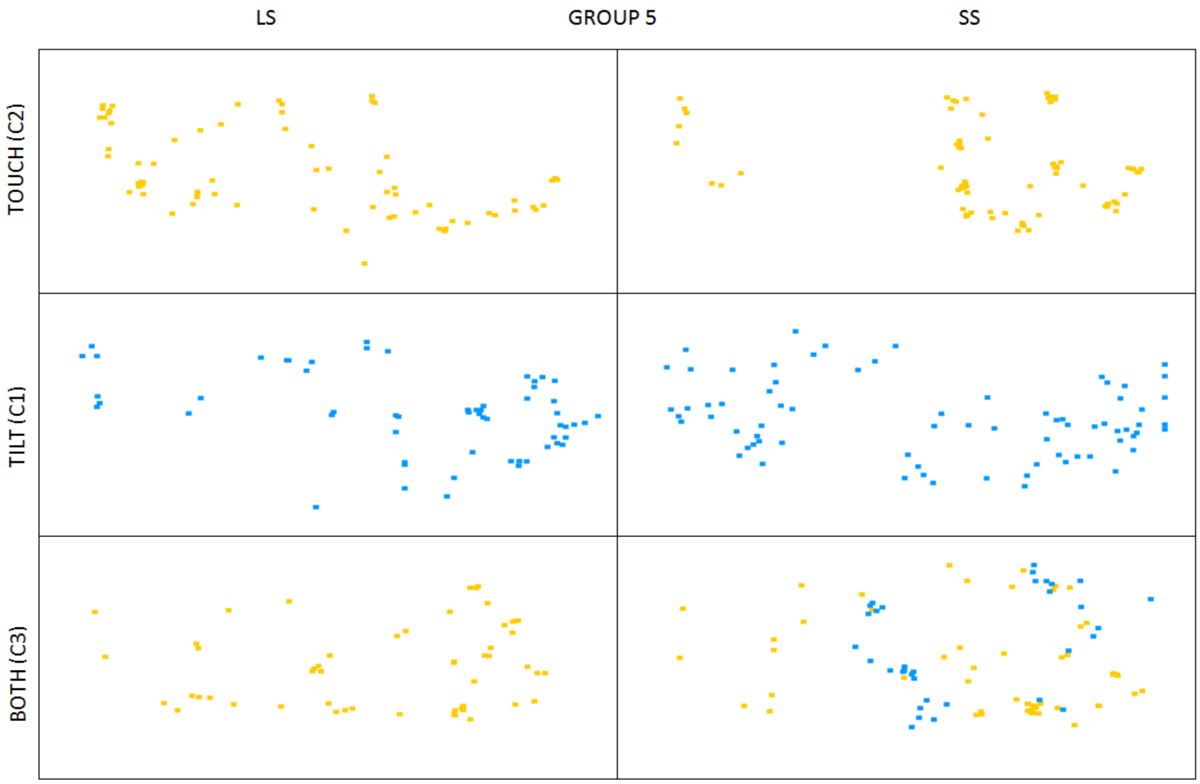
GROUP 4
SS
TOUCH (C2)
TILT (C1)
BOTH (C3)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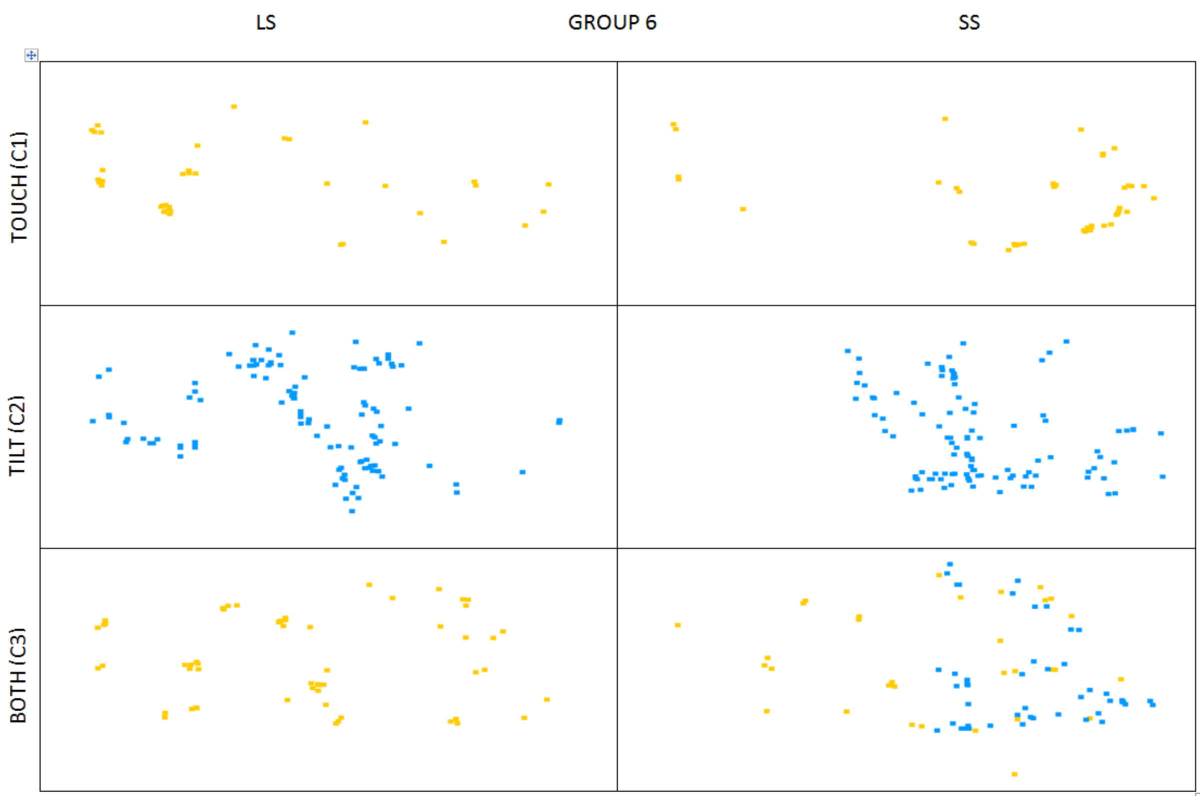
GROUP 5
SS
TOUCH (C2)
TILT (C1)
BOTH (C3)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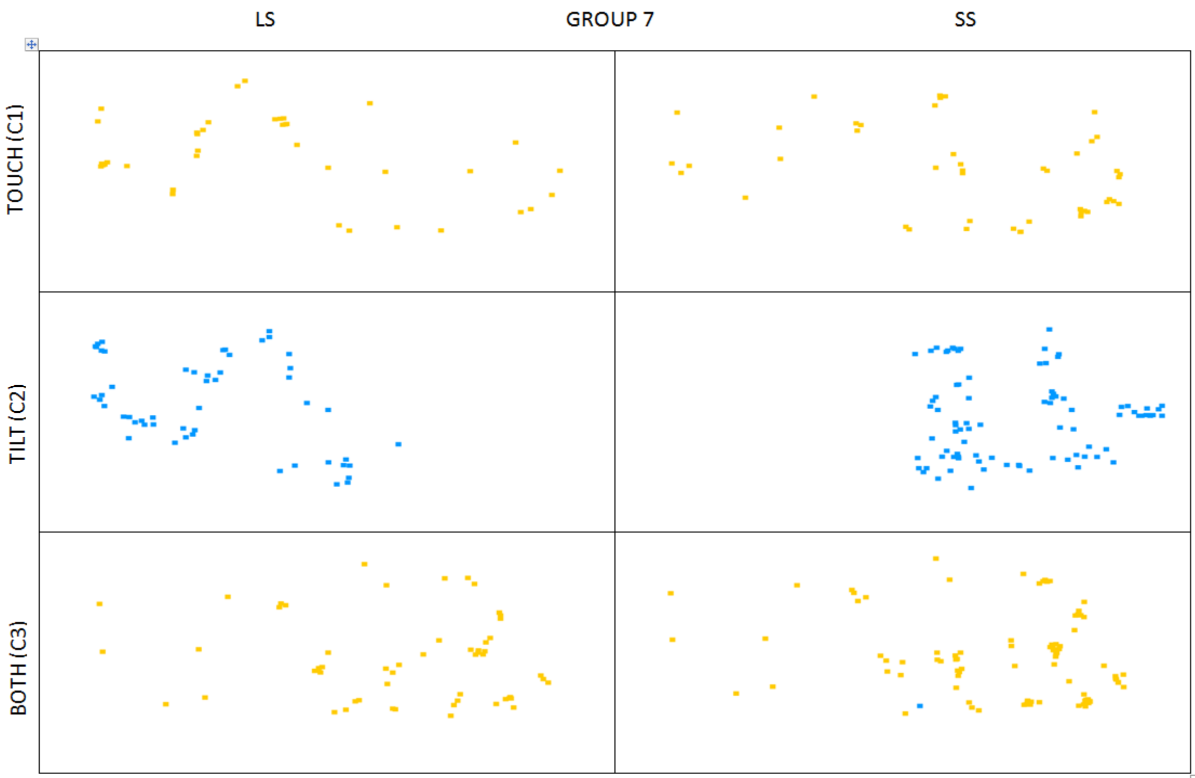
GROUP 6
SS
TOUCH (C1)
TILT (C2)
BOTH (C3)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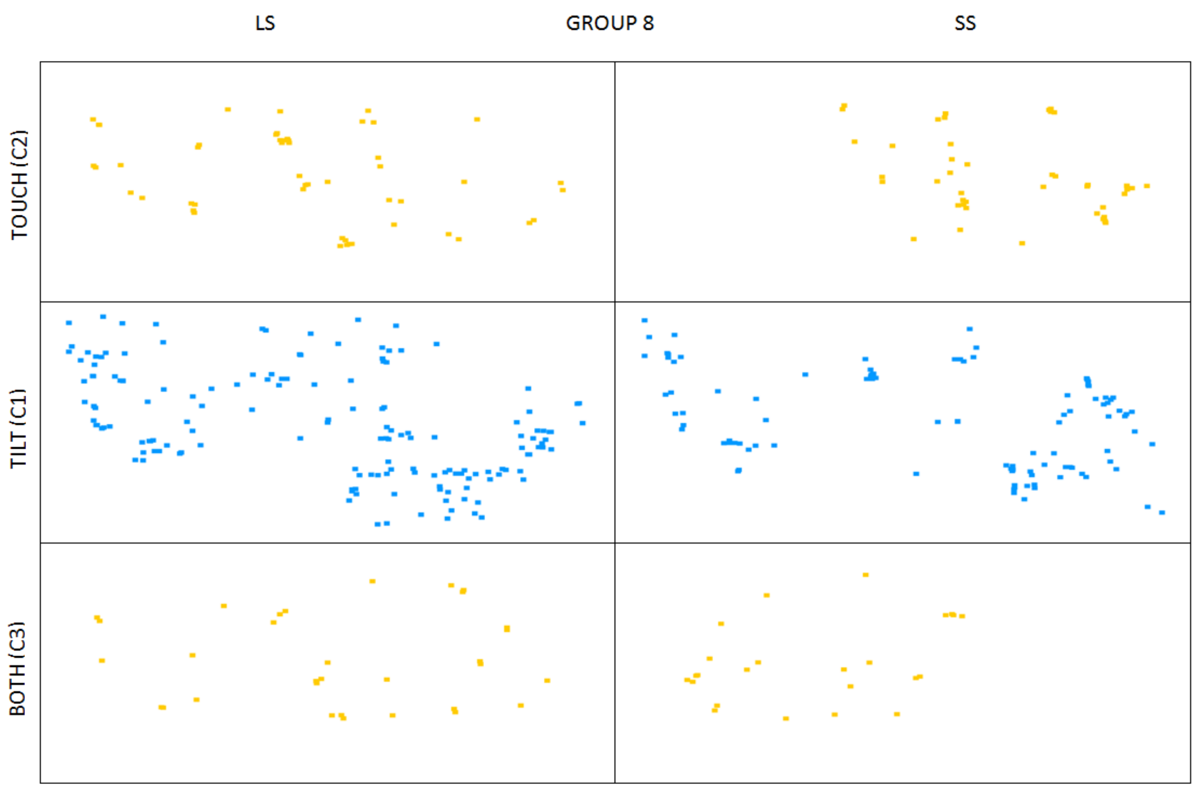
GROUP 7
SS
TOUCH (C1)
TILT (C2)
BOTH (C3)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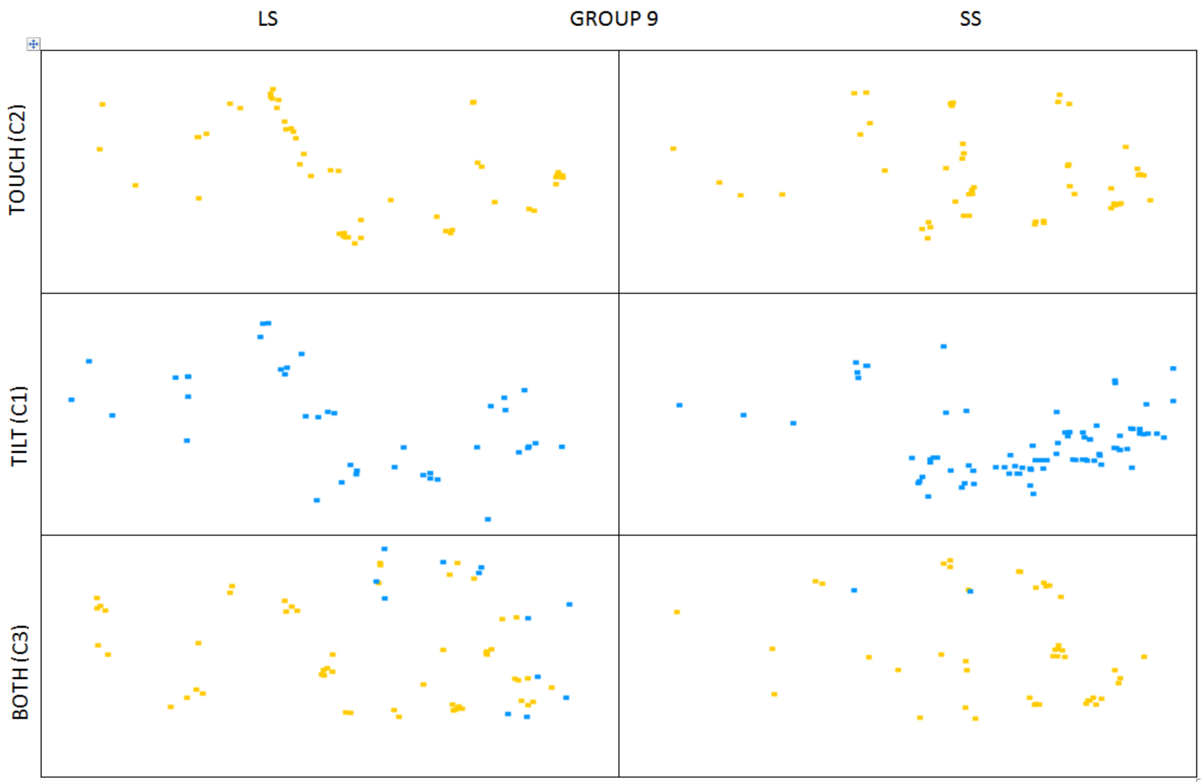
GROUP 8
SS
TOUCH (C2)
TILT (C1)
BOTH (C3)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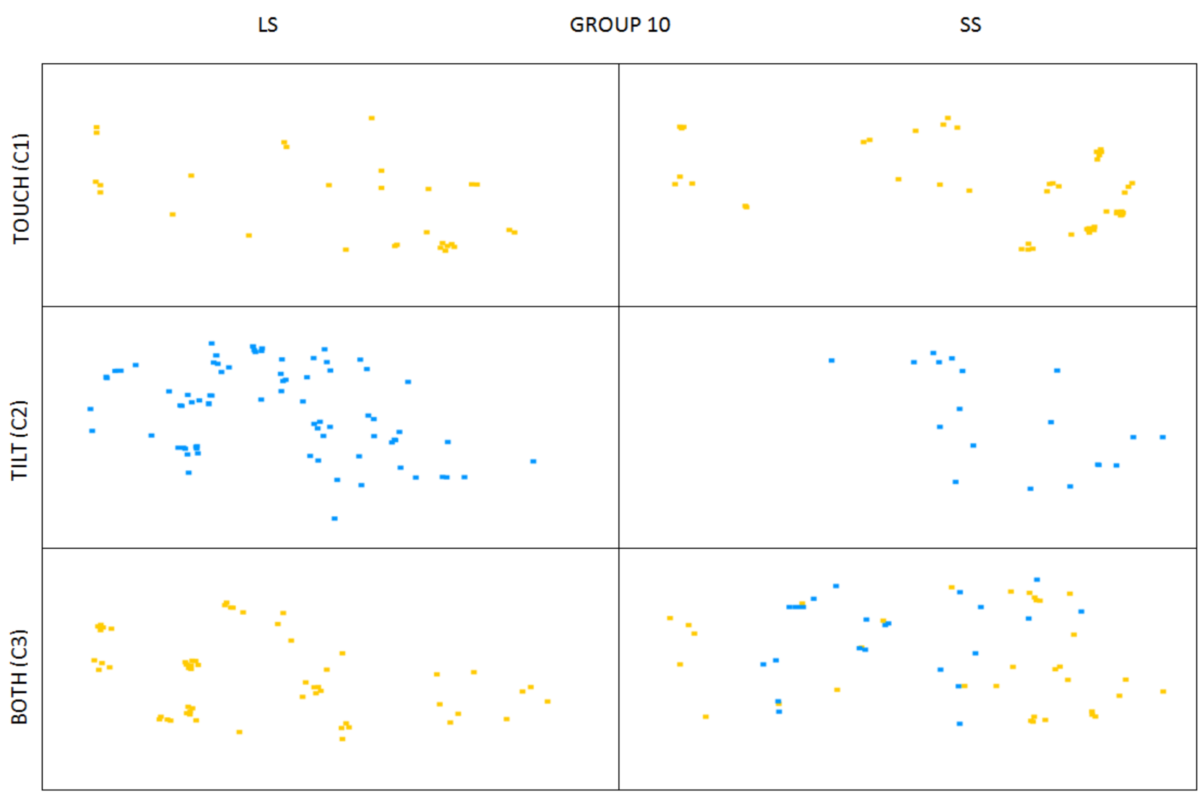
GROUP 9
SS
TOUCH (C2)
TILT (C1)
BOTH (C3)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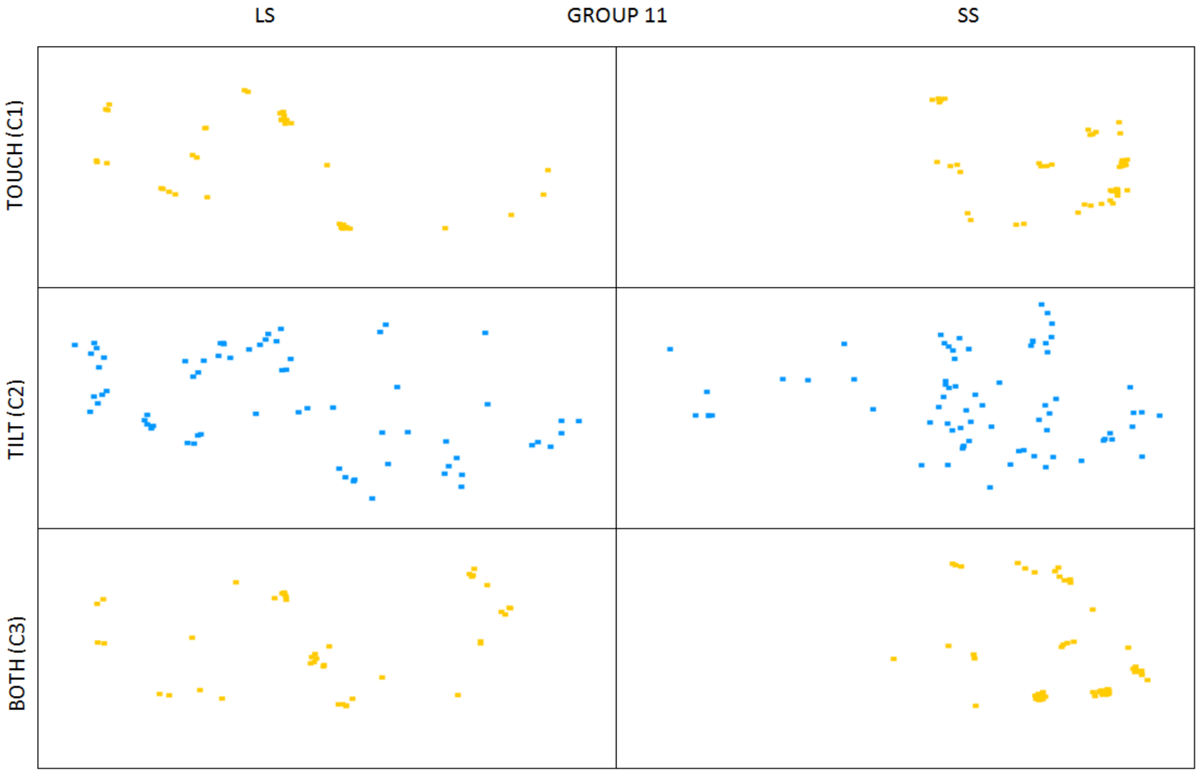
GROUP 10
SS
TOUCH (C1)
TILT (C2)
BOTH (C3)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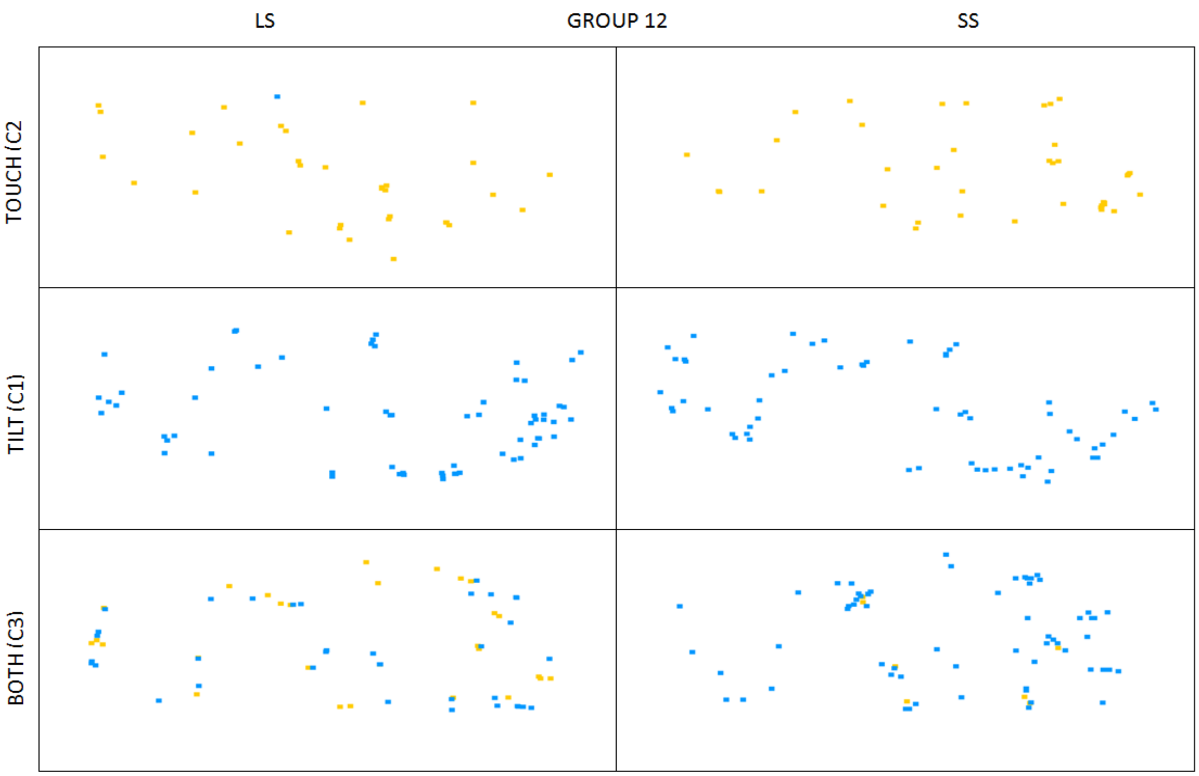
GROUP 11
SS
TOUCH (C1)
TILT (C2)
BOTH (C3)


LS
GROUP 12
SS
TOUCH (C2
TILT (C1)
BOTH (C3)