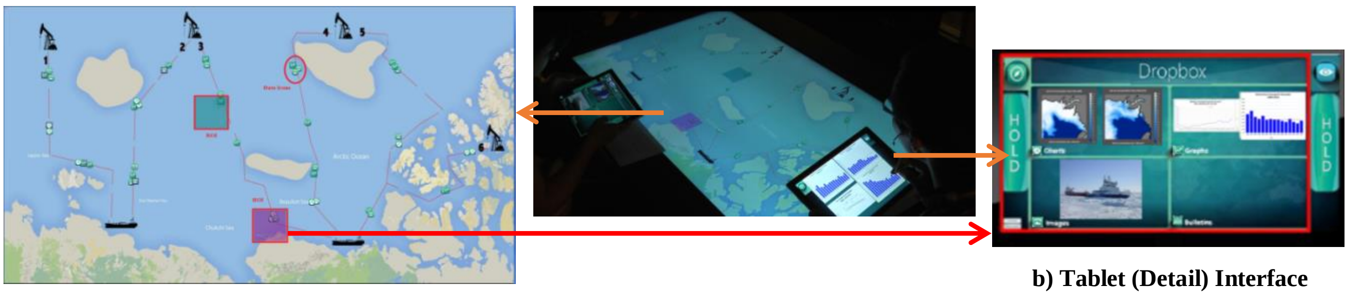
Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration

Leila Homaeian[1], Nippun Goyal[1], James R. Wallace[2], Stacey D. Scott[1,3]
[1]Systems Design Engineering
[2]School of Public Health and Health Systems
University of Waterloo, Waterloo, ON, Canada
{firstname.lastname}@uwaterloo.ca
[3]School of Computer Science
University of Guelph, Guelph, ON, Canada
stacey.scott@uoguelph.ca



b) Tablet (Detail) Interface

a) Tablet (Overview) Interface

Figure 1. Our cross-device Overview + Detail environment: (a) a tabletop interface containing an overview map of the analysis area, data icons depicting locations with associated geotagged data, and Region of Interest (ROIs) for each collaborator, and (b) a tablet interface that displayed a "detail" view for associated geotagged data within the bounds of the user's ROI.

ABSTRACT
Cross-device environments (XDEs) have been developed to support a multitude of collaborative activities. Yet, little is known about how different cross-device interaction techniques impact group collaboration; including their impact on independent and joint work that often occur during group work. In this work, we explore the impact of two XDE data browsing techniques: TOUCH and TILT. Through a mixed-methods study of a collaborative sensemaking task, we show that TOUCH and TILT have distinct impacts on how groups accomplish, and shift between, independent and joint work. Finally, we reflect on these findings and how they can more generally inform the design of XDEs.

Author Keywords
Cross-device, mixed-focus collaboration, touch, tilt

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
There is growing interest in using multi- or cross-device environments (XDEs) to support co-located group work, e.g., [6, 21, 37, 43]. The personal and shared devices offered in XDEs offer tremendous potential to support both the "taskwork" (actions needed to complete the task) and "teamwork" (communication, coordination, and group awareness) [15] that occur during group work. For example, Wallace et al. [38] found that a laptops-plus-wall XDE allowed individuals to concentrate on cognitively demanding aspects of an optimization task (on laptops) and supported group awareness and task coordination (on a wall display). Isenberg et al. [19] recommended XDEs for collaborative analytic tasks as they "allow the distribution of visualization tasks across individuals so that they can work independently when required" (p. 17).

Prior studies show that, procedurally, co-located groups often accomplish their taskwork and teamwork using a mix of independent and joint work, in a work style referred to as "mixed-focus" collaboration [14, 17, 34]. Providing both personal and shared workspaces in an XDE aims to facilitate these distinct work modes. However, a specific cross-device interaction design used in a given XDE is likely to impact the ability of group members to engage in, and shift between, these work modes. Yet, few studies have examined the impact of cross-device interaction techniques on mixed-focused collaboration. To address this gap, we conducted a user study to examine how different cross-device interaction techniques can impact independent and joint work processes during a representative collaborative task that involves mixed-focus collaboration.

In our study, we chose to use a collaborative sensemaking task given empirical evidence showing that sensemaking groups commonly employ mixed-focus collaboration [17, 34]. We also chose to use a tabletop-plus-tablets XDE as prior studies show that tabletops facilitate collaborative data analysis and sensemaking [23, 37]. Our study examined two cross-device data browsing techniques, among other possible types of XDE techniques, as they relate to several key XDE design challenges identified by Isenberg et al. [19], including managing information across displays, ownership and control of data, and mechanisms for data replication.

Our XDE modeled an Overview+Detail (O+D) [10] display environment, in which the tabletop (the "Overview" view; (Figure 1a) showed a geographic map with icons depicting locations that had associated geotagged data that could be viewed on a personal tablet (the "Detail" view; (Figure 1b). Consistent with other O+D displays, a "Region of Interest" (ROI) selection box was provided in the overview display (on the tabletop) to control which data were displayed in the detail view (on the tablet).

The two cross-device data browsing techniques examined in the study modeled existing techniques that conceptually offered different levels of support for independent and joint work. The first technique, TOUCH, utilized a direct-touch gesture on the tabletop to position the ROI, and consequently, update the detail view on the tablet. This approach provided familiar direct-touch interaction, and modeled a common approach in O+D interfaces to update the detail view through direct-touch gestures performed on the overview interface (e.g., [17, 36]). Direct manipulation of content in a shared workspace has also been shown to promote workspace awareness and group coordination [14, 15]. Yet, touch input on a large tabletop introduces challenges for accessing out-of-reach areas, especially for people seated at the short side of the tabletop.

The second technique, TILT, modeled existing techniques for controlling content on a large display "remotely" using a personal device (e.g. [11]). In TILT, the ROI position on the tabletop was controlled via tilt gestures, made with the tablet and enabled by the tablet's built-in motion sensors. Such "remote" cross-device interaction can facilitate individual work [11]; however, its impact on teamwork is unclear. Given these uncertainties and the potential reachability issues introduced by TOUCH, we performed an empirical study to explore the impact of TOUCH and TILT under different seating positions on collaborative processes. In particular, we sought to answer the following research questions:

RQ1: How does the choice of cross-device interaction technique (TOUCH or TILT) impact people's ability to work independently during collaboration?

RQ2: How does the choice of cross-device interaction technique (TOUCH or TILT) impact people's ability to work jointly during collaboration?

We show that, despite the benefits that TILT had for accessing out-of-reach data (and thus facilitating independent data exploration), most participants preferred TOUCH. A qualitative data analysis revealed that, when TOUCH was available, people exploited the ability to assume control of their partner's ROIs. This behaviour facilitated tightly synchronized work and sharing critical data with one's partner. Our findings also revealed limitations with both techniques for supporting transitions between independent and joint work. Our results also apply to the design of XDEs with different types of shared displays, such as a wall display [38] or shared tablet displays [40], as discussed later in the paper.

RELATED WORK

In this section, we present previous work on mixed-focus collaboration to set the context for our investigation. Next, we overview prior work on co-located collaborative sensemaking to describe the task and the collaborative behaviour context for our study. Finally, we review prior work on Overview+Detail (O+D) interfaces to set the design context for our XDE system which models an O+D display.

Mixed-Focus Collaboration

In their seminal work, Gutwin and Greenberg [14] describe a fundamental tension faced by designers seeking to support groups working around technology: one can support powerful interactions by the individual, or provide awareness of those actions to their peers, but not both. In the years since that work was published, work at CHI has addressed how technology can support mixed-focus collaboration, in which users will transition between individual and group work. Research has sought to identify [34] and support various styles of collaboration [29], and show how designing for these tensions can improve the outcomes of group work [7].

But technology has also changed – what was once done on PCs can now be shared across many devices, such as tablets and large, shared displays, each with their own characteristics, benefits, and drawbacks [37]. This change was also anticipated by Gutwin and Greenberg [14], who explain that new technologies may arrive that enable designers to better serve groups. But they also assert that "*only some of the design tensions between individuals and groups are caused by the limits of groupware technology—others are caused by the freedom designers have to invent interaction techniques that are impossible in the real world*" (p. 215). In this work, we revisit the tension between individual and group work first described by Gutwin and Greenberg, in the new context of XDEs. To do so, we investigated the use of XDE techniques during a collaborative sensemaking task.

Co-located Collaborative Sensemaking

Sensemaking as defined by Russell et al. [30] is the iterative process of searching for, understanding, and organizing information to answer questions specific to a task. Several models have been developed to understand the sensemaking process, e.g., [26, 41]. For example Yi et al. [41] propose an insight-based evaluation model that consists of four activities performed during sensemaking, (1) overview, (2) adjust, (3) detect pattern, and (4) match mental model. Overview involves users surveying the available data to discover and cognitively model the information. They then make comparisons between data and form hypotheses during the adjust and detect pattern activities. Finally, they test and confirm hypotheses during the match mental model stage.

These activities are distributed across periods of collaborative and individual work, and hence embody mixed-focus collaboration [14]. Collaborative sensemaking commonly starts with group members working independently, or in a "loosely-coupled" manner, to build an individual perspective of the shared data set, and then working together, in a "tightly-coupled" manner, to find common ground [5]. Complex tasks often require iteration – individuals or groups may test and confirm hypotheses, then revisit undiscussed information. Thus, as an iterative process, collaborative sensemaking involves many shifts between tightly- and loosely- coupled collaboration [17, 34].

Previous research on co-located collaborative sensemaking indicates that having a shared workspace enhances group performance and awareness [23]. These findings have led to the use of tabletops and large displays to support sensemaking in complex, data-driven environments such as social network analysis [18], oil and gas exploration [32], and defence and security [3, 40]. Researchers have also studied behaviour in shared workspaces impacting people's use of space [35] and territoriality around tabletops [31], i.e., how people divide and share the space during collective work.

Despite the benefits of a shared workspace for supporting group work, studies have shown that personal displays can better facilitate independent work in a group setting — especially when the work is cognitively demanding [27, 39]. Consequently, recent research has explored the potential of XDEs for collaborative sensemaking [22, 37, 43]. For example, McGrath et al. [22] developed a tabletop-plus-tablet XDE designed to support mixed-focus collaboration. Their XDE allowed users to "branch" off from the group and independently "explore" a dataset through a search operation, and then to "merge" back with the group. During this merge process, changes made to the shared information on the tabletop required group approval via a voting tool. Their approach allowed users to overview and adjust data independently before reaching a group consensus. In our work, we examine how XDE data browsing techniques influence independent and joint work during collaborative sensemaking, e.g. how well do the studied techniques enable independent overview of data in a large shared workspace?

Cross-device Interaction Techniques: Overview+Detail

Our XDE is modeled on an O+D interface, which provides multiple views of a single, often shared, data set [10]. An O+D interface provides an "overview", typically via a large display, that enables users to explore relationships between discrete data points and identify high-level trends. It also provides a detail view, often via a smaller display, that enables independent exploration of data without disrupting the rest of the group. O+D interfaces have been shown to provide useful benefits for collaborative sensemaking, particularly sensemaking involving spatially-ordered data (maps, medical images, etc.). For example, Hornbaek et al. [16] reports a user preference for conducting map-based interaction tasks when both the overview and detail views were available, compared to the detailed view alone. The large and small displays in XDE environments lend themselves to providing a natural O+D interface, and thus they have been widely explored in the literature (e.g., [20, 36, 42]).

However, it remains unclear how best to link the O+D views that sit across devices in a collaborative XDE [19]. In this work, we investigate two possible cross-device interaction approaches for linking these views, and study the impact they have on the overall collaborative process. In particular, we compare TOUCH and TILT techniques for selecting which areas of a shared, overview display are presented in detail on a user's personal tablet. Our results shed light on how different tools can shape collaboration, and identify a need to support transitions between collaborative and independent work in XDEs. Based on our findings, we also provide guidance for designing future cross-device techniques.

DESIGN OF A XDE FOR SENSEMAKING

Our O+D XDE was designed to support collaborative sensemaking around a geospatial dataset focused on the Canadian Arctic region (Figure 1). In designing the environment, we considered Gutwin and Greenberg's guidance [14] for designing mixed-focus environments: workspace navigation, artifact manipulation, and view representation.

To support workspace navigation, the XDE has a central shared tabletop that displays a geospatial overview map (Figure 1a). Previous research has shown that shared digital tabletops enhance group performance and aid awareness among group members [23, 28, 37]. Additionally, digital tabletops have been widely used by researchers to provide support in map-based collaborative environments, e.g., [2, 9, 12]. In addition to general geographic information such as land and sea boundaries, the map contains task-specific information such as the location of land-based ports, oil rigs at sea, and potential shipping routes between the ports and oil rigs. The map also depicts icons that represent locations with associated geotagged data, e.g., sea ice conditions, historic sea ice coverage, satellite images.

Tablets are used to view the available geotagged data (Figure 1b). Collaborative view representation is provided by representing each user's tablet view on the tabletop map via a Region of Interest (ROI) box. Each ROI is displayed as a unique, user-specific colour and contains an arrow pointing to the user's seating position. Moving the ROI on the tabletop updates the tablet view to show geotagged data located within the geographic area covered by the ROI (i.e. any data icons located inside the ROI container boundary on the tabletop map). The visibility of the ROI on the tabletop supports workspace awareness (Figure 1b).

In addition to the "data browsing" tablet view described above, the tablet also provides a "dropbox" screen that allows a user to view bookmarked data. Data of interest can be bookmarked from the "data browsing" screen by dragging it to an area labeled "dropbox" at the top of the screen (Figure 1b). To view items in their dropbox, the user can select the dropbox tab. Notably, this feature allows users to examine specific data regardless of the ROI's location, and allows data from different geographic locations to be viewed together on the tablet. Bookmarked items are reflected on the tabletop by outlining the associated icon with a user-specific colour in the map (Figure 1b).

This environment was intentionally designed to be simplistic in terms of the data organization, filtering, and synthesis tools available to analysts. Modern collaborative sensemaking desktop tools provide much more sophisticated tools for supporting the sensemaking process. However, the impact of specific interaction designs on individual and group work processes are much better understood for desktop and distributed groupware environments based on decades of usability and CSCW research. Thus, our approach was to first investigate cross-device interfaces designed to support a specific and common sensemaking activity—data browsing—to better understand how to support it an XDE.

Cross-device Interaction Techniques: TOUCH and TILT

To explore how different cross-device interaction designs might influence the collaborative sensemaking process, two data browsing techniques were developed: TOUCH and TILT. Other cross-device techniques were considered for linking the data between the tabletop and tablet views in early stages of the research, but were eliminated when considered against the project goals and task context. For instance, we considered techniques that allowed users to select the tablet "view" directly from the tablet interface, but rejected them due to their potential to encourage users to focus solely on their personal devices, as observed in prior O+D [2] and XDE [43] studies. Such focus on personal displays can hinder group awareness and other collaborative benefits of a shared display [39].

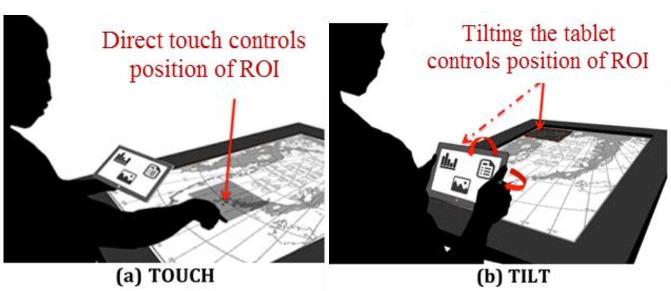


Figure 2. (a) Using a direct TOUCH gesture on the table to control the ROI movement, (b) Using a TILT gesture on the tablet to control the ROI movement on the table.

Building on the concept of magic lenses [1], both TOUCH and TILT techniques provide a see-through interface. However, they differ from previous techniques as the "detail" interface provides a semantically related view rather than a zoomed-in version of the information provided in the "overview". With TOUCH, users control the position of the ROI box through direct manipulation on the tabletop (Figure 2a), reflecting touch-based techniques from the literature (e.g., [6]), with expected benefits to workspace awareness since they take place on the shared display [15]. However, constraints such as arm reach or multiple people accessing the same location may make it socially awkward or physically impossible to interact with parts of the table, requiring coordination between collaborators.

Similar to cross-device techniques that use tilt gestures on a personal device to remotely control content on a distant display (e.g., [11]), TILT allows for remote movement of a user's ROI using a tablet's built-in gyroscope (Figure 2b), Users initiate movement using a 'hold' button on the edge of the tablet interface, after which ROI movement is mapped to the 3-dimentional tilt of the tablet. While pressing the hold button, users can 'scroll' across the map by titling the tablet and stop movement by levelling the tablet. Tilting the tablet upward or downward moves the ROI along the Y-axis, and tilting to the left or right side, moves the ROI along the X-axis. Directional movements were adjusted for tabletop seating position. Non-orthogonal movement was also possible by tilting along non-orthogonal axes.

TILT's gestural interactions were refined through iterative pilot testing to enable smooth and intuitive ROI control. The ability to scroll the ROI across the map was an intentional design choice to enable rapid serial visual presentation [33] of available geotagged data on the tablet, which in turn enables rapid overview of the data. As with TOUCH, awareness of a peer's activities within the workspace was a design consideration—in this case, the physical tilting of the tablet and the associated visual movement of the ROI across the tabletop provides awareness of the user's activities to their peers.

It was anecdotally observed that learning to control the ROI location using the tilting motion was easier for people with console gaming experience. Yet, after sufficient pre-condition training, all study participants learned to competently use both TILT and TOUCH to position the ROI.

USER STUDY

To understand the impact of the TOUCH and TILT cross-device interaction techniques on individual and group behaviour during collaborative sensemaking (**RQ1** and **RQ2**), we conducted a mixed-methods laboratory study. Pairs of participants completed a series of collaborative sensemaking scenarios in the experimental XDE described above. For full details about the user study see [13].

Experimental Design

We conducted a within-subjects study with two independent variables: TECHNIQUE and SEATING POSITION. TECHNIQUE had three levels: TOUCH, TILT, and BOTH. In the latter condition, both TOUCH and TILT interfaces were provided to be used as desired. The order of the first two conditions was counterbalanced, with all pairs completing the task using the BOTH interface in their final session.

Note, the primary goal of the study was to compare the impact of TOUCH and TILT independently to answer our two research questions; BOTH was included to provide qualitative insights on how the two techniques might be used when participants could use either of them as desired. Thus, BOTH was not included in the quantitative data analysis, nor in the counterbalanced condition ordering.

SEATING POSITION was a between-subjects factor, where one participant was seated on the LONG SIDE (LS) of the table, and their partner was seated on the adjacent SHORT SIDE (SS), always to the right of the LS position. Participants chose their own seating positions, and were instructed to remain in their self-assigned sides for the duration of the study. Given the large rectangular shape of the tabletop, the LS participant had a significant advantage over the SS participant for physically interacting with the tabletop in the TOUCH condition. SS represents the non-ideal seating position in terms of reachability (most participants were able to reach only half way across the table). TILT was expected to provide more equitable access to the tabletop. These two positions allowed us to study the impact of the two techniques under "ideal" and "non-ideal" reachability positions.

Experimental Task

Three task scenarios were developed for the study using Arctic sea ice data available from the Canadian Sea Ice Service [8] and National Snow and Ice Data Center [24] websites. In each scenario, the tabletop displayed a map of the Canadian Arctic that was overlaid with icons representing geotagged data (e.g., sea ice conditions, historic sea ice coverage, satellite images) associated with the icon locations viewable on the personal tablet (Figure 1b).

Participant pairs were tasked with collaboratively exploring the map and available data to discover the most effective navigation route from one of six land-based ports to one of two sea-based oil rigs. Within the Arctic context, an effective route would be one that is most likely to have open water (or thin ice) most of the year. The sensemaking process entailed becoming familiar with the different geographic regions of the map, understanding trends in historical ice flow data, and arriving at a consensus on which route would be most likely to be open throughout the year. This process required accessing data on their tablets using the TOUCH and TILT interaction techniques.

For each pair of participants, two task scenarios were randomized between the TOUCH and TILT conditions, and a third scenario was always used for the BOTH condition.

Participants and Apparatus

We recruited 24 participants (12 male) for the study. To ensure participant pairs were comfortable working together to solve a collaborative task; each pair was recruited together (i.e. friends, family, classmates). Participants were 18-45 years old, and were either students or employed at local technology companies. All participants were self-reported frequent users of touch-based computing devices.

The experimental XDE comprised a custom-built multi-touch tabletop and two Microsoft Surface Pro3 tablets. The tabletop incorporated a 4K (3840×2160 pixels, 121×67 cm screen size) flat-panel LED display fitted with a PQLabs infrared cross-touch frame. The LED display and touch input frame were surrounded by a solid metal frame that provided a ledge to rest paper, tablets and other artefacts along the tabletop's edge, increasing its size to 148×95 cm.

Procedure

The study began by participants completing a consent form and background questionnaire collecting demographic information. The group then completed a training session that introduced and allowed practice with the experimental XDE and the first interaction technique, TOUCH or TILT. The group was then asked to complete the first task scenario with the given interaction technique. Once finished, participants completed a post-condition questionnaire (described in the next section).

The group then completed a second training session and task scenario with the remaining interaction technique, TOUCH or TILT, followed by the post-condition questionnaire. Next, the group completed a task scenario in the BOTH condition, followed by the post-condition questionnaire and a post-study questionnaire. Finally, groups took part in a brief post-study group interview, and then were thanked and paid $20 CAD for their participation. For each task scenario, groups were given 12 minutes to conduct their sensemaking activities and report their selected "best" route given the available data to the experimenter. Each study session lasted about 90 minutes in total. The study protocol was approved by our university ethics office.

Data Collection and Analysis

Data collected during the study consisted of observational notes, computer logs of participants' interactions with the tabletop and tablets, and audio and video data. The post-condition questionnaire contained 7-point Likert-scale questions on perceived awareness, interference, and ease of use, as well as open-ended questions on collaborative behavior, task completion strategy. The post-study questionnaire collected preference rankings for TOUCH and TILT, as well as open-ended feedback about the perceived utility and limitations of the techniques. The group interview further probed participants on their opinions on how the cross-device techniques influenced their collaboration.

A 2×2 mixed-design ANOVA was used to examine difference in Likert scale ratings [25]. An alpha value of 0.05 was used to determine significance. These results were further validated through Thematic analysis of the video data and participant free-form feedback.

RESULTS

We first examined user preferences for cross-device technique, based on the rankings provided in the post-study questionnaire. A preference was found for TOUCH across the majority of participants (17/24), with SEATING POSITION, as expected, influencing this preference: 11/12 of Long-Side (LS) participants preferred TOUCH over TILT compared to only 6/12 of Short-Side (SS) participants.

One important aspect of any cross-device interaction is the ability for the user to understand the relationship between the information being shown on each device. TOUCH (M = 5.8, SD = 1.3) was found to provide higher reported levels of awareness of the relationship between a user's ROI and the data displayed on their tablet than TILT (M = 4.9, SD = 2.1); $F_{1,22} = 5.85$, $p = 0.024$, $\eta^2 = 0.21$). No effect was found for SEATING POSITION ($F_{1,22} = 0.29$, $p = 0.59$, *n.s.*) nor was there a significant interaction effect.

We also examined the disruption caused by XD interactions, and found differences in both how much participants felt disrupted and how much they felt they caused disruption. Participants reported being more disrupted by their partners in TOUCH (M = 2.5, SD = 1.7) than in TILT (M = 1.3, SD = 0.7), ($F_{1,22} = 13.48$, $p = 0.001$, $\eta^2 = 0.38$). SEATING POSITION also had an effect, LS participants (M = 2.4, SD = 1.4) reported being disrupted more than SSs participants (M = 1.4, SD = 0.7), ($F_{1,22} = 5.92$, $p = 0.024$, $\eta^2 = 0.21$). No interaction effect was found. Similarly, participants reported causing more interference with partners' actions in TOUCH (M = 2.5 SD = 1.7) than in TILT (M = 1.7 SD = 1.04), ($F_{1,22} = 7.77$, $p = 0.011$, $\eta^2 = 0.26$). A significant effect was also found for SEATING POSITION; LS participants reported interfering more with their partner (M = 2.7, SD = 1.6) than SS participants (M = 1.5, SD = 0.9), ($F_{1,22} = 5.88$, $p = 0.024$, $\eta^2 = 0.21$). No interaction effect was found.

These quantitative findings suggested differences in how the two techniques supported individual and joint work during collaboration (**RQ1** and **RQ2**). While 75% of participants preferred TOUCH, and it appeared to be more effective at helping them connect the data being shown on both the tabletop and tablets, they also reported being disrupted more by their partner. To better understand these differences we performed a Thematic video analysis [4].

Qualitative Analysis

The Thematic video analysis revealed that groups used two main strategies for tackling the sensemaking task: a two-phase approach, and a single-phase approach. In the two-phase approach, groups would first "divide-and-conquer" their initial data explorations so that each group member investigated roughly half of the available data set, and then would later work together to arrive at a consensus. For convenience, we refer to these two phases as the D&C Phase and the Unified Phase, respectively. Groups who employed a single-phase approach, instead, chose to work together in a tightly-coupled manner throughout the entire session.

The observed two-phase strategy involved periods of both independent (or loosely-coupled) and joint (or tightly-coupled) data exploration and is consistent with observations from previous collaborative sensemaking studies [17, 22]. In the D&C Phase, most groups independently viewed and filtered the data. The Unified Phase was dominated by tight interactions with brief loosely coupled interaction for verification before reaching a mutual decision. During this phase, groups continued to adjust data and engaged in pattern detection and matching their mental model to the data.

Nine of twelve groups adopted the two-phase strategy in both TILT and TOUCH. Another two groups used the two-phase strategy in only one condition: one in TOUCH and the other in TILT. The remaining group employed a tightly-coupled approach the whole time in both TILT and TOUCH. Groups who utilized the two-phase strategy spent, on average, 62% of their time in the Unified Phase.

Territoriality Facilitated Independent Data Exploration

Our video analysis revealed that most participants were able to use both TOUCH and TILT effectively to explore data independently in the D&C Phase. The geospatial nature of the task and the equitable distribution of routes in the map leant itself to a divide-and-conquer strategy. The six potential shipping routes on the map were easily divided into three routes for each participant to explore, and were spatially distributed such that three routes were within reach of each participant. This conceptual and spatial division of the dataset corresponded to a natural spatial division of the tabletop into two territories, one per group member.

To better understand how the study factors impacted collaborative process, heatmap visualizations were generated from log data to show participants' ROI movements during different task phases. Figure 3 shows the heatmaps for the D&C Phase, with data segregated by TECHNIQUE and territorial behaviour (as explained below). We characterized groups whose members focused their data exploration efforts on their respective territories as exhibiting *strong territoriality (ST)*, and observed that these groups experienced few issues with either TILT or TOUCH during the D&C Phase. All data within their respective routes were within reach of each member, thus they could easily navigate their own ROIs independently using both TILT and TOUCH to view the desired data on their tablets. Of the groups who used a two-phase approach, 7/10 groups exhibited strong territoriality in TILT in the D&C Phase, and 6/10 groups exhibited strong territoriality in TOUCH.

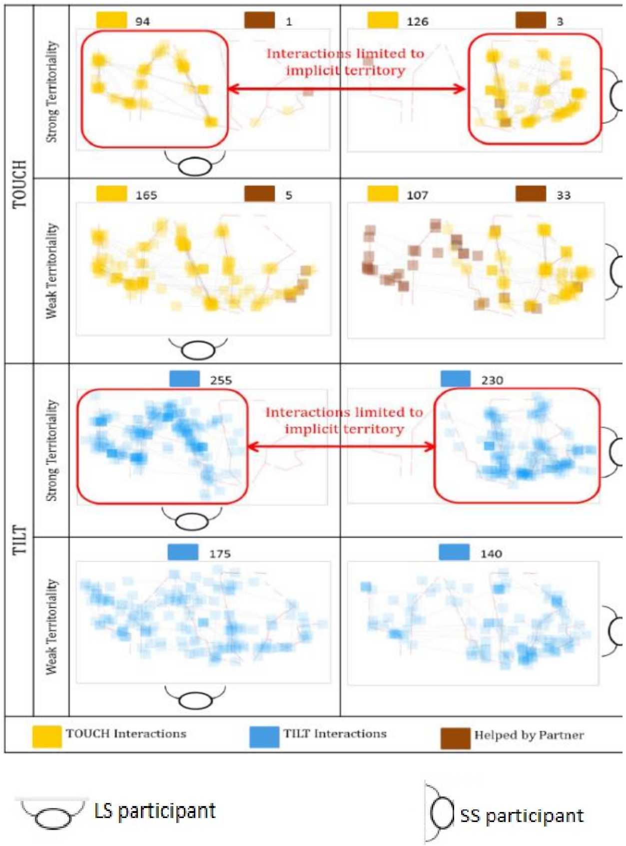


Figure 3. ROI Interaction heatmap visualizing group interactions in TOUCH and TILT during D&C Phase. ST interactions primarily occurred within the implicit territory.

In the remaining groups, one or both participants also explored data outside their respective territories, and thus exhibited *weak territoriality (WT)*. After these participants finished exploring their assigned data, they would then start exploring data in their partner's territory. The video data revealed several reasons for this behaviour, including boredom or impatience waiting for their partner, or lack of trust in their partner's analysis abilities. Three of ten groups exhibited weak territoriality in both TOUCH and TILT, while another group exhibited weak territoriality in only TOUCH.

The heatmaps also show which ROI movements in TOUCH were facilitated by a participant's partner. There were relatively few instances of partner-assisted ROI movements in ST groups (1 for all LS, and 3 for all SS participants). In contrast, WT groups required more assistance from their partner (5 for LS, 33 for SS participants). These data illustrate that for ST groups, the lack of access to out-of-reach data on the tabletop in TOUCH had little impact on participants' independent data explorations. In contrast, WT groups in the D&C Phase were more impacted by the the physical constraints, of the TOUCH technique.

As expected, these constraints hindered SS participants, as they were forced to rely on their partners for help accessing out-of-reach data. This dependence on partners in WT groups is illustrated by the partner-assisted ROI interactions (Figure 3, TOUCH). The heatmaps also show that LS's partner-assisted ROI interactions were limited to the area directly in front of the SS participant (Figure 3, TOUCH).

The video data also revealed that when a participant wished to move their ROI near their partner, it sometimes led to physical and virtual interaction conflicts. For example, awkward arm crossing sometimes occurred when both participants tried to move their respective ROIs past each other. When participants decided to explore the same data, their ROIs would necessarily overlap. Then, when one participant decided to explore other data, they sometimes mistakenly moved their partner's ROI, or had to intentionally move their partner's ROI to access their own. Either action would disrupt their partner's detail view, typically in a very abrupt and unexpected manner.

In contrast, participants in TILT could easily move their ROIs to out-of-reach tabletop locations without disrupting their partner. This ability allowed all participants to explore data anywhere on the tabletop, providing more flexibility for independent data exploration. This observation is consistent with the previously reported questionnaire data, which showed that both SS and LS participants reported less partner interference with TILT than with TOUCH.

Collaborative Data Exploration Strategies

In the Unified Phase, group members worked together to discuss emerging patterns, verify hypotheses through arranging and comparing key data, and develop consensus. Recall, a small number of groups worked in a tightly-coupled manner throughout one or more of their task scenarios. Thus, these groups also conducted their data overview activities during the Unified Phase.

The video analysis revealed that cross-device TECHNIQUES impacted three types of collaborative behaviours during this phase: synchronized viewing of the same data to support collaborative analysis and discussion, comparing and contrasting certain data to highlight specific evidence, and spatially arranging data in "tableaux" to support comparison of key data. These behaviours are discussed in detail below.

The analysis also revealed that groups spent much of their time during the Unified Phase collaboratively revisiting data items that were deemed important during group members' initial overview of the data. Through this process, groups would narrow the focus of their analyses and discussions down to a few potential routes that seemed most relevant for satisfying the given task requirements. They would continue this collaborative filtering process until they mutually agreed on a single candidate solution.

Synchronized Data Viewing

The Unified Phase was characterized by long periods of synchronized data viewing, during which group members jointly viewed the same data items. When doing so, their ROIs were located at the same tabletop location and their respective tablets displayed the same information. Together, they analyzed and discussed the displayed data, and then moved on together to analyze different data, as needed to foster mutual understanding of the data.

However, TOUCH and TILT supported synchronized data viewing in different ways. When using TILT, each person had to independently manipulate their tablets to move their respective ROIs to the same tabletop location. As a group, this required considerable coordination; each time the group wished to explore data at a different location, both partners had to use their respective tablets to relocate the ROIs. Synchronized data viewing was often initiated by one group member suggesting certain data for the group to examine together. This required additional cognitive effort to orient the "following" group member to understand where to relocate their ROI; this process was often accompanied by pointing gestures from the initiating group member. While individually these physical and mental efforts were relatively minor, they were repeated many times during the study.

In contrast, analysis of the TOUCH condition revealed that seven groups adopted a different approach to synchronized data viewing. These groups exploited a "feature" of TOUCH that let anyone move any ROI, not just one's own. This "design feature" — or useful capability as it turned out — was necessary as the tabletop used in the study did not distinguish between users. In these groups, one person was delegated responsibility for moving both ROIs to facilitate a mirrored data view on both partners' tablets. These groups exhibited strong coordination and cooperation.

ROI control might naturally be delegated to the LS participant since they could reach the entire tabletop. However, video and log data revealed that for 5/7 groups who delegated responsibility, the ROI was moved by the respective "owner" of the tabletop territory in which the data resided. When team members were viewing different data on their tablets, this navigation style appeared to encourage the group to begin synchronized data viewing, which resulted in better coordination between the partners. This behaviour was further evidenced by comments to the question "What aspect of technology helped in the completion of the task?": "*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*" (G7, LS TOUCH).

Comparing and Contrasting Evidence

An important aspect of the Unified Phase was the merging, comparing, and contrasting of individual findings and hypotheses. When discussing or debating different opinions about the data, one group member would often try to convince the other of their viewpoint by showing them relevant evidence. With both TECHNIQUES, a participant would sometimes simply turn their tablet toward their partner to show them the data of interest. However, in many cases, participants preferred their partner to view and more closely examine the data on their own tablet. This necessitated the partner's respective ROI to be moved to the associated geographic area on the tabletop. TILT and TOUCH offered different levels of support for such evidence highlighting.

In TILT, if a participant (P_A) wished their partner (P_B) to view a certain data item, P_A would physically or verbally point out the data icon(s) on the tabletop, and then wait for P_B to navigate their respective ROI to the correct location using their tablet (Figure 5(top)). This process was commonly accompanied by P_A providing verbal or gestural clarifications to ensure P_B moved their ROI to the correct location. P_B would then view the data on their own tablet.

In contrast, in TOUCH this process was facilitated by the aforementioned "flexible" ROI ownership that allowed any participant to move any ROI. Thus, in the example above, P_A could simply move P_B's ROI to the desired tabletop location, which correspondingly would show the associated data on P_B's tablet (Figure 4, bottom). Many participants appreciated this capability in TOUCH, as evidenced by participant comments from the study questionnaire, *"The touch controls allowed my partner to control if she wanted to show me a particular data point (or vice versa)."* (G3 SS) and *"The ability to move my partner's box and show him what I was viewing assisted me in presenting my ideas as well as giving him confirmation of my hypotheses."* (G10 LS). Moreover, participants reported missing this capability in TILT, as evidenced by the following participant comment "*... could not show my partner quickly what I was seeing since I could not move his box.*" (G10, LS).

This approach to directing one's partner's to view specific data was effective in well-coordinated groups, but caused frustration in other groups. For example, some participants did not communicate their intention to show their partner new data, or they did not wait for implicit or explicit permission to do so. In situations where the "receiving" participant (P_B) was working independently or if they were still examining data that the group had previously been exploring together, the sudden change in view on their tablet caused by the “sending” participant’s (P_A) movement of P_B’s ROI could be quite disruptive.

Formation of Tableaux

Video analysis revealed that groups commonly arranged data items side-by-side or in a grid (or *tableaux*) format (whether using the tablet user interface or placing tablets next to each other) to create common ground and facilitate hypothesis testing. Tableaux formation is an important cognitive aiding technique that allows analysts to do rapid visual comparison of key aspects of different data, which in turn assists with pattern detection and matching analysts’ mental model of the problem to discover key insights [37].

Two main strategies were used to form tableaux. The simplest approach was to use the grid-style interface that was offered by either of the two screens on the tablet: 1) the data browsing screen that displayed data items within the ROI in a grid layout, or 2) the “dropbox” screen that displayed a grid of previously bookmarked data. The dropbox screen was used, on average, 16% of the time in the TILT sessions compared to 9% of the time in the TOUCH sessions.

Another way to form tableaux was for participants to position both tablets side-by-side, either in their hands or resting on the tabletop (Figure 5). As TOUCH enabled the ROI to be positioned without moving the tablet, participants typically left their tablets in tableaux, even when relocating a ROI. In contrast, maintaining a continuous tablet-based tableaux in TILT was more complex as participants had to pick up their tablets to move the ROIs. Thus, participants often formed temporary tableaux by holding the tablets side-by-side in their hands, or used the dropbox screen to form tableaux.

INSIGHTS GAINED FROM THE BOTH CONDITION

Given the uncovered benefits and limitations of TOUCH and TILT, we were curious to learn how groups would use these techniques when both were available. Most groups (8/12) used a two-phase strategy in BOTH, while the remaining groups used a one-phase, tightly-coupled strategy.

Despite its limitations when accessing out-of-reach areas and the interference participants experienced, TOUCH was frequently used by all participants, regardless of SEATING POSITION, in BOTH. Across all groups, 71% (1086/1532) of all ROI moves were made with TOUCH. Of these, 20% (215/1086) were partner-assisted ROI moves (107 by SS, 108 by LS). Analysis of heatmaps and videos showed that much of these partner-assisted ROI moves occurred during synchronous data viewing involving delegated ROI control in each partner’s respective territory. Thus, the benefits of TOUCH for joint data exploration were appreciated and exploited during the BOTH condition, even by SS participants.

Of the remaining 29% of TOUCH ROI moves, many were used in combination with TILT to work around its limitations. For instance, SS participants would use TILT to bring their out-of-reach ROI closer, and then use TOUCH to complete the ROI move. This strategy was also used to address the ROI overlap and partner disruption problems reported above. In general, participants appreciated the flexibility of having both TECHNIQUES available, as evidenced by the participant comment, *“using the hold button [for TILT] helped when viewing distant objects, but I prefer touch and drag when the [ROI] box is within reach”* (G4, SS, BOTH).

In summary, providing both techniques improved independent data access, while still supporting joint work. It also offered some support for transitions between these working styles, e.g. using TILT to retrieve an out-of-reach

Figure 4. (top) In TILT, SS points at a location where he needs LS to move his ROI, (bottom) In TOUCH, SS uses “flexible ownership” feature to drive LS’s ROI to desired location.

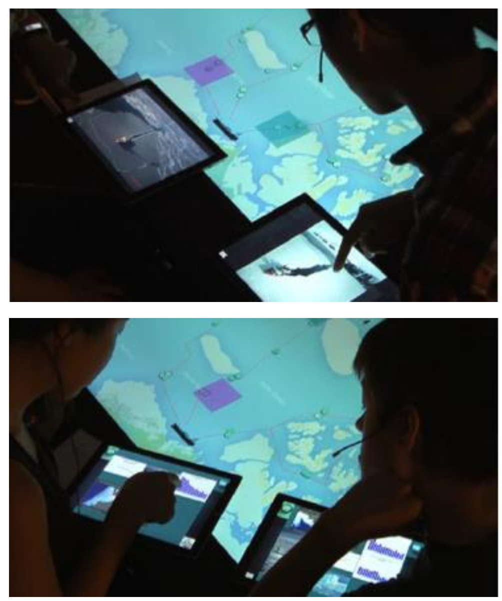


Figure 5. Groups 11 (top) and 10 (bottom) forming tableaux

ROI when transitioning from synchronized data viewing to independent hypothesis validation. Yet, BOTH did not resolve all transition issues, as discussed below.

DESIGNING FOR MIXED-FOCUS COLLABORATION

In their seminal paper, Gutwin and Greenberg [14] discuss a tradeoff between individual "power" and group functioning in a shared environment. Our study shows that the cross-device techniques fell into the same trap: TOUCH better supported group work, while TILT better supported independent work. Providing both techniques together helped alleviate some of their respective limitations, but did not address the entire collaborative work flow, including transitions between joint and collaborative work. Here we discuss findings related to our two research questions and design considerations for mixed-focus collaboration in XDEs.

Supporting Independent Work (RQ1)

A key challenge study participants faced when working independently was accessing data in the shared workspace without disrupting their partner. Social norms, such as territoriality, both support and hinder this activity [31]. Indeed, groups who exhibited strong territoriality during periods of independent work in TOUCH experienced few issues even among SS participants. Yet, as a social construct influenced by individual personality and culture, territorial behaviour cannot be relied on alone by designers. Some participants attempted to explore data in their partner's territory during periods of independent work. Also, some participants were territorial about their "own" ROI, and preferred to move it themselves even during joint work. In both cases, TOUCH imposed severe restrictions on their ability to access out-of-reach data, limiting their individual "power" in the XDE.

The "remote" control of the ROI provided by TILT helped to address this problem, providing more equitable access to the entire data set. However, individual "power" within a group environment also relates to users being able to individually accomplish collaborative goals within the system. For example, TILT did not allow group members to directly "share" data with their partners, whereas this goal could be easily accomplished in TOUCH by moving one's partner's ROI. Yet, this type of data "sharing" approach could also be disruptive when the receiving person was engaged in independent work, as their current view would be immediately replaced with new data. Providing lightweight mechanisms that allow the "receiver" to buffer incoming information may resolve this issue, but care should be taken to maintain simplicity in the primary interaction tasks, such as the rapid data browsing supported by TOUCH and TILT.

Supporting Joint Work (RQ2)

The study uncovered two key features of TOUCH that facilitated joint work. First, the user-agnostic property of the ROI makes it *shareable*. Many groups appropriated this feature to delegate movement of both ROIs to one person during synchronized data viewing. Yet, using the ROIs in this manner introduced challenges for a single user, as they were not intentionally designed to be moved together. There was no mechanism to "snap" the ROIs together, thus moving them from one place to another required more effort than simply moving one ROI. Participants reported this to be tedious. Introducing a mechanism to group multiple ROIs together would better support synchronized data viewing. However, care should be taken to provide lightweight mechanisms to group and ungroup the ROIs to support transitioning to and from joint data explorations.

A second feature of the ROI that supported joint work was the ability to independently position and share tablets in the environment. This feature enabled groups to form tableaux to facilitate joint comparison and discussion of selected data items. However, as Wallace et al. [37] found, using tablets for tableaux formation can be restrictive. It offers less physical space than the tabletop does to spread out data between collaborators. Thus, one could also consider enabling users to open selected data directly on the tabletop, or to enable selected data to be moved from the tablets to the tabletop to facilitate joint examination of the "detailed" data. This design direction should be explored carefully, however, as it may negate the collaborative benefits provided by the shared reference "overview" map on the tabletop.

Our study findings indicate that compared to TOUCH, TILT required more effort to perform joint data exploration, as discussed in the Results section. A feature of TILT that caused this phenomenon was the inability of partners to directly assist each other in moving ROIs. In theory, one could grab their partner's tablet and re-locate their ROI. However, this was cumbersome and it was never observed. Thus, a cross-device interaction technique should let partners to aid each other in viewing data on their personal devices to facilitate conversation and reduce the group's collective effort, as TOUCH allowed. Another characteristic of TILT that hindered joint work was the need to hold the tablet to update the tablet's view. This especially manifested itself during tableaux formation. Thus, cross-device interaction techniques should allow personal devices to be freely placed anywhere to foster easy side-to-side data viewing.

Supporting Transitions between Working Styles

A common observation was that our XDE provided little support for transitioning between independent and joint work, often disrupting the work flow and frustrating users. A solution offered by the BOTH condition allowed users to simply switch between the TOUCH and TILT interfaces when encountering problems with one or the other. This approach helped, but did not completely solve the interaction issues users experienced during transitions between working styles. Some of the design considerations in the previous sections targeted at facilitating transitions into a specific working style, e.g. enabling ROIs to be easily grouped and ungrouped may assist with transitions between periods of independent and joint data browsing. Also, allowing users to buffer content shared to their tablet by a collaborator may ease the transition between independent and joint work.

In general, however, the "personal" nature of tablets introduces complexities for supporting transitions between joint and independent work, as users working independently on their tablets can more easily cognitively disconnect from the group than when working at a shared display. Using the shared display to coordinate independent work done in a group context may provide transitional benefits as it provides a shared reference point to the overall group activity.

Our insights into how TOUCH facilitated tightly-coupled work extend to other shared display types, such as a wall or a collection of tablets. Our participants assisted each other with moving ROIs even when the ROI was within reach of its owner, which shows that TOUCH can be beneficial to group work regardless of the size of the shared display.

CONCLUSION

We presented results from an exploratory, laboratory-based study in which pairs of participants performed a series of collaborative sensemaking tasks using two cross-device data browsing techniques: TOUCH and TILT. Our qualitative analyses show that cross-device interaction techniques can profoundly influence collaborative process. While TILT facilitated access to out-of-reach data, especially during independent data browsing, TOUCH better supported tightly synchronized discussion of data. Further investigation is warranted to determine how best to balance these competing group needs in XDEs. In particular, they point to a need to better understand how techniques support individual and joint work, but also *transitions* between the two modes.

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