# Interaction Design for Mixed-Focus Collaboration

# in Cross-Device Environments

by

Leila Homaeian

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Systems Design Engineering

Waterloo, Ontario, Canada, 2022

# Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

| | |
|---|---|
| Supervisor: | **Stacey D. Scott, Ph.D.**<br>Professor, School of Computer Science<br>University of Guelph<br>Adjunct Professor, Systems Design Engineering<br>Faculty of Engineering<br>University of Waterloo |
| | **James R. Wallace, Ph.D.**<br>Associate Professor, School of Public Health Sciences<br>Faculty of Health<br>University of Waterloo |
| Internal: | **Carolyn MacGregor, Ph.D.**<br>Associate Professor, Systems Design Engineering<br>Faculty of Engineering<br>University of Waterloo |
| | **Jennifer Boger, Ph.D.**<br>Adjunct Assistant Professor, Systems Design Engineering<br>Faculty of Engineering<br>University of Waterloo |
| Internal-External: | **Rob Duimering, Ph.D.**<br>Associate Professor, Management Sciences<br>Faculty of Engineering<br>University of Waterloo |
| External: | **Nicolai Marquardt, Ph.D.**<br>Associate Professor, Computer Science<br>Faculty of Engineering<br>University College London |

# Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the 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.

# Statement of Contributions

## Association for Computing Machinery (ACM) Publications

This dissertation includes first-authored peer-reviewed material that has appeared in conference and journal proceedings published by the Association for Computing Machinery (ACM). The ACM's policy on reuse of published materials in a dissertation is as follows[1]:

*"Authors can include partial or complete papers of their own (and no fee is expected) in a dissertation as long as citations and DOI pointers to the Versions of Record in the ACM Digital Library are included."*

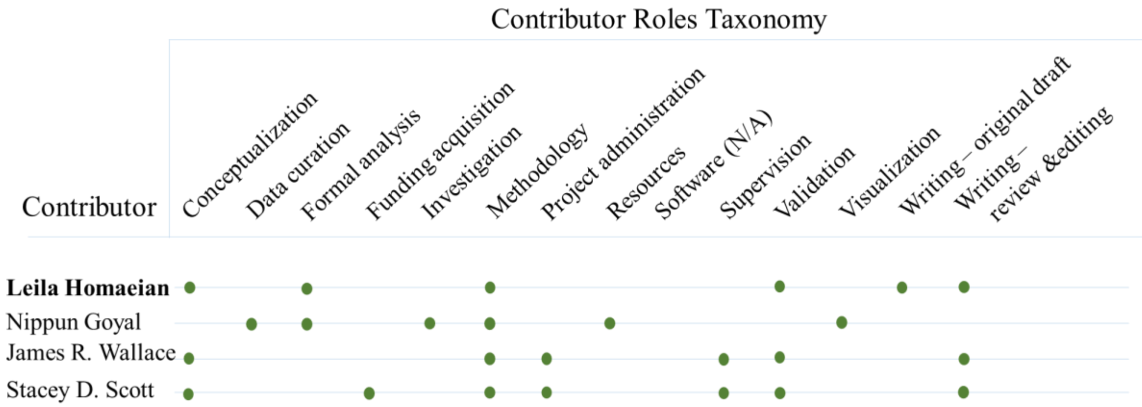
In listing the type(s) of contribution made by the authors and other contributors, I use CRediT (Contributors Roles Taxonomy)[2]. CRediT *"was introduced with the intention of recognizing individual author contributions, reducing authorship disputes and facilitating collaboration. The idea came about following a 2012 collaborative workshop led by Harvard University and the Wellcome Trust, with input from researchers, the International Committee of Medical Journal Editors (ICMJE) and publishers, including Elsevier, represented by Cell Press."*[2]

The following list serves as a declaration of the Versions of Record for works included in this dissertation:

**Chapter 3: Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration**

Homaeian, Leila, Nippun Goyal, James R. Wallace, and Stacey D. Scott. (2018). Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)* (p. 73). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3173574.3173647

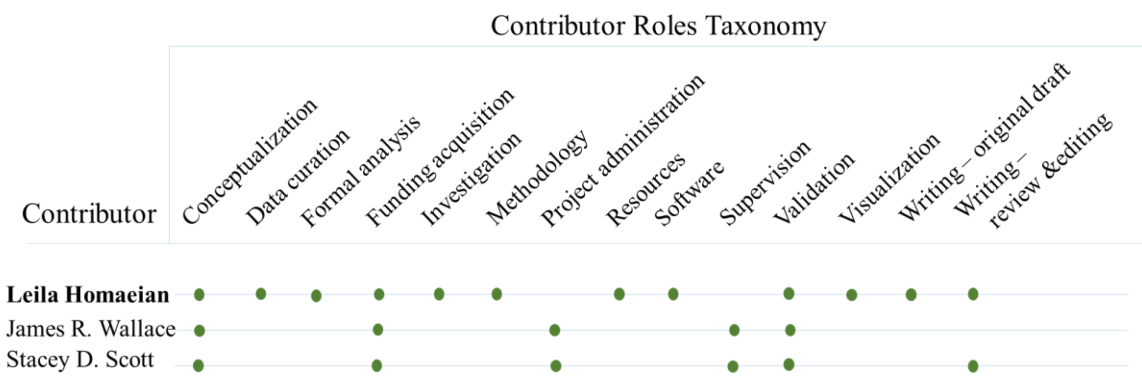
[1] https://authors.acm.org/author-resources/author-rights
[2] https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement




**CRediT author statement 1. Contributors of the project presented in Chapter 3**

**Chapter 5: Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration**

Homaeian, Leila, James R. Wallace, and Stacey D. Scott. (2022). Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration. *To Appear in Proceedings of the ACM on Human-Computer Interaction (CSCW).*




**CRediT author statement 2. Contributors of the project presented in Chapter 5**

**Chapter 6: Joint Action Storyboards: A Framework for Visualizing Communication Grounding Costs**

Homaeian, Leila, James R. Wallace, and Stacey D. Scott. (2021). Joint Action Storyboards: A Framework for Visualizing Communication Grounding Costs. *Proceedings of the ACM on Human-Computer Interaction, 5(CSCW1)*, 1–27. DOI: https://doi.org/10.1145/3449102

Contributor Roles Taxonomy

| Contributor | Conceptualization | Data curation | Formal analysis | Funding acquisition | Investigation | Methodology | Project administration | Resources | Software (N/A) | Supervision | Validation | Visualization | Writing – original draft | Writing – review &editing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Leila Homaeian** | ● | ● | ● | ● | ● | ● | | ● | | | ● | ● | ● | ● |
| James R. Wallace | ● | | | ● | | | ● | | | ● | ● | | | |
| Stacey D. Scott | ● | | | ● | | | ● | | | ● | ● | | | ● |

**CRediT author statement 3. Contributors of the project presented in Chapter 6**

## Abstract

The proliferation of interactive technologies has resulted in a multitude of form factors for computer devices, such as tablets and phones, and large tabletop and wall displays. Investigating how these devices may be used together as Cross-Device Environments (XDEs) to facilitate collaboration is an active area of research in Human Computer Interaction (HCI) and Computer-Supported Cooperative Work (CSCW). The research community has explored the role of personal and shared devices in supporting group work and has introduced a number of cross-device interaction techniques to enable interaction among devices in an XDE. However, there is little understanding of how the interface design of those techniques may change the way people conduct collaboration, which, in turn, could influence the outcome of the activity. This thesis studies the impact of cross-device interaction techniques on collaborative processes. In particular, I investigated how interface design of cross-device interaction techniques may impact communication and coordination during group work.

First, I studied the impact of two specific cross-device interaction techniques on collaboration in an XDE comprised of tablets and a tabletop. The findings confirmed that the choice of interaction techniques mattered when it came to facilitating both independent and joint work periods during group work. The study contributes knowledge towards problematizing the impact of cross-device interaction techniques on collaboration in HCI research. This early work gave rise to deeper questions regarding coordination in cross-device transfer and leveraging that to support the flexibility of work periods in collaborative activities. Consequently, I explored a range of interface design choices that varied the degree of synchronicity in coordinating data transfer across two devices. Additionally, I studied the impact of those interface designs on collaborative processes. My findings resulted in design considerations as well as adapting a synchronicity framework to articulate the impact of cross-device transfer techniques on collaboration. While performing the two research projects, I identified a need for a tool to articulate the impact of specific user interface elements on collaboration. Through a series of case studies, I developed a visual framework that researchers can use as a formative and summative method to understand if a given interaction technique hinders or supports collaboration in the specific task context. I discuss the contributions of my work to the field of HCI, design implications beyond the environments studied, and future research directions to build on and extend my findings.

# Acknowledgements

## Land

With gratitude, I would like to acknowledge that the land on which I live and work today and during my degree is situated on the traditional territory of the Attawandaron (Neutral), Anishinaabeg, and Haudenosaunee peoples. The University of Waterloo, was built on the Haldimand Tract, the land granted in 1784 to the Six Nations that includes 10 kilometers on each side of the Grand River from its source in Dundalk to its mouth at Lake Erie.

## Funding

Thank you to the funding bodies who supported my work: National Science and Engineering Research Council of Canada (NSERC), Ontario Graduate Scholarship (OGS) program, the Office of Graduate Studies and Postdoctoral Affairs, and the University of Waterloo.

## Sincere Thanks

I have been so fortunate to have the support of many professors, colleagues, friends, and family during my Ph.D. journey. I know there are more people that have been there that I can possibly thank in this section.

I am grateful for the tremendous support of my Ph.D. advisors, Stacey and Jim. Thank you for your mentorship and guidance. Your insightful vision always helped me think deeper and appreciate the challenges of doing research in our multi-disciplinary field and turn them into opportunities. I am grateful for the chance to have attended multiple CHI, ISS, CSCW, and DIS conferences to present my work, learn from other researchers, and grow my professional network.

Thank you members and alumni of the EngHCI team, the Games Institute, and the HCI + Health lab at the University of Waterloo, including professors Mark Hancock, Oliver Schneider, Cayley MacArthur, Daniel Harley, Lennart Nacke, Leah Zhang-Kennedy, Rina Wehbe, and Ville Mäkelä, and colleagues Robert Gauthier, Marcela Bomfim, Tina Chan, Katja Rogers, Veen Wong, and Rachel Woo for providing invaluable feedback on my research and presentations. Our weekly meetings and discussions were a great opportunity towards professional and academic development. A special thanks to Betty Chang, Victor Cheung, and Diane Watson for their friendship and helping with my transition to the Ph.D. program. Thanks to the Games Institute staff for always being resourceful and providing an organized and friendly environment to perform research. Thank you Nathan Chan for developing the software for Project 2 and for helping with running the user observations.

Thank you to all my committee members Stacey D. Scott, James R. Wallace, Carolyn MacGregor, Jennifer Boger, Rob Duimering, and Nicolai Marquardt for reading my dissertation and providing guidance as I work toward my Ph.D. degree.

A sincere thanks to my family for their support and love. Thank you to my husband Reza, and my sons Arman and Nikan for your understanding, patience, and encouragement. Thank you to my parents, Marzieh and Asadollah for believing in me and your unconditional love. Thanks to my siblings Parisa, Faranak, and Amin, and my lovely in-laws including Farideh, Shahrokh, and Shirin for being there for me.

# Table of Contents

# List of Figures

# List of Tables

# Chapter 1: Introduction

There is growing interest in Human Computer Interaction (HCI) to design multi-device or *cross device environments* (XDEs) to foster collaborative activities (e.g. (Brudy et al., 2020; Marquardt, Hinckley, et al., 2012; Zagermann et al., 2016)). XDEs often comprise personal devices, for instance tablet computers, and shared devices, such as digital tabletops and walls (e.g. (Homaeian et al., 2018; W. McGrath et al., 2012; Wallace et al., 2013)), or one or more tablet-size displays (e.g. (Rädle et al., 2014; Zagermann et al., 2016)). By providing personal and shared workspaces, XDEs facilitate parallel individual work as well as joint work styles (Isenberg et al., 2013; Wallace et al., 2013; Zagermann et al., 2016). Moreover, the increased screen real estate is beneficial for data manipulation and organization (Hamilton & Wigdor, 2014; Homaeian et al., 2018; Zagermann et al., 2016). Although collaborative XDEs have been the subject of academic research for many years (Brudy et al., 2019), the emerging commercial XDEs are often designed for single users (Houben et al., 2017). Transferring data across devices is in particular often clunky and gets in the way of collaborative flow (Houben et al., 2017).

Designing collaborative XDEs requires careful consideration of a number of factors related to how people conduct group work. *Communication* and *coordination*, which are the pillars of group work, must be supported. In their seminal paper, Pinelle et al. (2003) introduced the theory of mechanics of collaboration: low level activities that people perform to communicate with each other and coordinate their actions in shared workspaces. Mechanics of communication include spoken and written messages, deictic references, and overhearing. Moreover collaborators must maintain awareness of other's activities in the environment to coordinate their actions. Mechanics of coordination include obtaining and protecting shared resources, and transferring objects. The mechanics of collaboration can be used to model group work and thus are useful in designing and evaluating collaborative XDEs.

Moreover, research shows that collaboration often occurs in independent work periods as well as joint work periods and transitions between the two work periods, in a style referred to as *mixed-focus collaboration* (Gutwin & Greenberg, 1998; Isenberg et al., 2012; Tang et al., 2006). For example, collaborators often individually browse and analyze data and then come together to share their findings and find patterns (e.g. (Isenberg et al., 2012; W. McGrath et al., 2012; Zagermann et al., 2016)). Therefore, the user interface of collaborative XDEs should support communication and coordination needed in mixed-focus collaboration.

Even subtle changes to the user interface design of a system can impact collaborative processes (Convertino et al., 2009; Gutwin & Greenberg, 1998; Jamil et al., 2011; Marquardt, Ballendat, et al., 2012), which can in turn, influence the effort required to make progress in the task (Clark & Brennan, 1991; Gergle, 2017) and the outcome of the activity (Bachl et al., 2011; Mahyar & Tory, 2014; Nacenta et al., 2007).

However, there is shortage in HCI literature on the effect of XDEs on collaborative processes, making it difficult for designers to make appropriate design choices when building XDEs. Given the proliferation of interactive technologies, a multitude of XDEs and cross-device interaction techniques continue to be introduced in the literature (see (Brudy et al., 2019) for a recent review). Yet, more research in HCI is needed to help us understand how the user interface could support or get in the way of mixed-focus collaboration (Convertino et al., 2008, 2009). Existing literature has studied the role of individual devices, e.g. interactive tabletops (Bachl et al., 2011; Isenberg et al., 2012; Morris et al., 2010; Shadiev et al., 2015) and walls (Jakobsen & HornbÆk, 2014), and a combination of shared and personal devices, e.g. tablet computers and tabletops or walls (Bachl et al., 2011; Tokunaga et al., 2018; Wallace et al., 2013; Zagermann et al., 2016), in collaboration. Brudy et al. (2018) explored the role of an overview device in supporting a collaborative trip-planning task. The impact of input techniques, e.g. direct touch versus a mouse, in single display tabletop environments on awareness (Pinelle et al., 2008; Shadiev et al., 2015), communication (Jamil et al., 2011), and coordination (Nacenta et al., 2007) has also been studied.

The above work is valuable in providing high level insight into designing XDEs, for example, by describing collaborative behaviour given the form factor and affordances of the devices and the interaction techniques. I contribute to this body of research by focusing on cross-device interaction techniques and how communication and coordination requirements of the techniques can affect the different phases of mixed-focus collaboration.

## 1.1 Thesis Statement

When we create XDEs for mixed-focus collaboration, we are faced with a number of design choices to engineer a system that facilitates communication and coordination among collaborators. This design problem is complex as there are a number of factors to be considered, e.g. the needs of individuals and groups, and how to best utilize the screen space of multiple devices. Designers can control every aspect about where one can interact with and how to represent data. However, that freedom must be exercised carefully since even subtle changes to the user interface design can impact collaborative processes, for instance how closely they work together. That can ultimately influence performance and the outcome of the collaborative activity.

The research that I conducted during my PhD program supports the following thesis statement:

*Allowing collaborators to choose a cross-device interaction technique can support the flow of mixed-focus collaboration. We can indeed design coordination in such techniques in a way that facilitates the flexibility of work styles. Also, designers of collaborative XDEs would benefit from means of understanding and articulating the impact of user interface elements on collaborative processes.*

The scope of my research is a group of two collaborators using an XDE to conduct collaborative sensemaking. I used sensemaking as my experimental task context since research shows that collaborative sensemaking is often performed in a mix-focus style (Isenberg et al., 2012; Tang et al., 2006). I focus on designing cross-device interaction techniques for sending data across devices, and how the user interface elements may facilitate or impede different phases of mixed-focus collaboration, i.e. individual and joint work periods, and shifts between them. My findings have implications for designing interactions between personal devices, between personal and shared devices, for shared devices in single device environments, and for remote systems.

## 1.2 Contributions

The focus of this thesis is to understand the impact of user interface elements of cross-device interaction on collaborative processes. Figure 1-1 summarizes thesis research questions (RQs) and contributions.

| Overarching RQ | Specific RQs | Research projects | Answers to RQs | Thesis contributions |
|---|---|---|---|---|
| **RQ-T:** How does the user interface design of cross-device interaction techniques impact mixed-focus collaboration? | **RQ1:** How does the choice of TOUCH and TILT cross-device interaction techniques impact mixed-focus collaboration? | **Project 1:** Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration *(Homaeian et al. CHI'18)* | TILT supported independent work, whereas TOUCH facilitated joint work. Providing both techniques gave collaborators flexibility. Yet, it did not alleviate all limitations of individual techniques. | 1. Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration<br>2. Design considerations for cross-device interaction techniques to support mixed-focus collaboration |
| | **RQ2:** What are some possible ways to design coordination in cross-device transfer to support flexibility of work styles in mixed-focus collaboration? | **Project 2:** Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration *(Homaeian et al. PACMHCI '22)* | There are design criteria that impact synchronicity between the sender and receiver. The synchronicity framework provides a conceptual model to articulate temporal coordination in cross-device transfer and consequential impact on mixed-focus collaboration. | |
| | **RQ3:** How can we articulate the (sometimes subtle) impact of specific user interface designs on communication grounding? | **Project 3:** Joint Action Storyboards: A Framework for Visualizing Communication Grounding Cost *(Homaeian et al. PACMHCI '21)* | The concept of joint actions can be used to show collaborators' mental actions, and interactions with each other and the system in collaborative instances. JASs visualizes joint actions and the corresponding grounding costs. | 3. A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes |

**Figure 1-1. Thesis and project contributions**

My thesis contributions are listed below:

1. Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration (Projects 1 and 2)
2. Design considerations for cross-device interaction techniques to support mixed-focus collaboration (Projects 1 and 2)
3. A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes (Project 3)

My overarching research question is:

**[RQ-T]:** How does the user interface design of cross-device interaction impact mixed-focus collaboration?

Houben et al. (2017, p. 59) define cross-device interaction as "seamless use of multiple devices to achieve the same goal". In the context of mixed-focus collaboration, collaborators should be able to shift between independent and joint work periods with minimal disruption to their task flow. For instance, a transfer technique should give one the choice to finish an ongoing work and then attend to the transferred data. In that case, the goal of both parties is to use the data to perform the given task.

The transfer technique should allow them to coordinate that 'same goal' while respecting the receiver's work state. Also, during active discussions, the user interface should facilitate effortless data access and sharing instead of getting in the way of the flow of the discussion. Collaborators have the 'same goal' of using data to facilitate discussions and thus the user interface should not require unnecessary interactions, for example, having to retrieve the received data first and show data to a partner, in the middle of an ongoing conversation.

While my primary research question asks about the impact of design choices on collaborative processes, it is broad. Therefore, in my thesis I focus on the deeper exploration of the impact of specific cross-device interaction techniques on mixed-focus collaboration, and on developing a framework to help designers understand and communicate the impact of user interface elements on collaborative processes.

I began my investigation in Project 1 by re-analyzing existing data gathered in a prior user study (Goyal, 2016). The study provided an XDE comprised of a shared digital tabletop and personal devices for a collaborative sensemaking task. I re-analyzed the video data using Thematic analysis to understand the impact of two cross-device interaction techniques, TOUCH and TILT, on people's strategies to tackle the experimental task. I had the following research question in this project:

**RQ1:** How does the choice of TOUCH and TILT cross-device interaction techniques mixed-focus collaboration?

The results showed that while TILT was beneficial for accessing data on the large tabletop independently, TOUCH supported joint work periods more effectively by allowing partners to assist each other in viewing data on their personal tablets. Offering both techniques relieved some limitations experienced with each individual technique but not all, including transitions between work styles. Project 1 presents design considerations to facilitate mixed-focus collaboration in XDEs (Thesis Contribution 2).

The findings of Project 1 confirmed that the choice of cross-device interaction technique mattered when it came to fostering mixed-focus collaboration (Thesis Contribution 1). Given the multitude of cross-device interaction techniques introduced in HCI literature (Brudy et al., 2019), I then became interested in exploring alternative designs for cross-device transfer that would support the freedom of individuals within XDEs while allowing collaborators to communicate and coordinate with each other during transfer. In particular, I pursued the following research question in Project 2:

**RQ2:** What are some possible ways to design coordination in cross-device transfer to support flexibility of work styles in mixed-focus collaboration, i.e., independent and joint work styles and transitions between them?

The mechanics of collaboration (Pinelle et al., 2003) was my guiding theory in this project. The theory asserts that people use two forms of transfer in shared workspaces: Handoff and Deposit. Handoff is used to immediately grab a collaborator's attention and give them an item. Deposit, however, allows one to leave an item somewhere within the workspace for later retrieval by a colleague. I followed a Research through Design (Gaver, 2012; Zimmerman et al., 2007) approach in this project. This approach enabled me to investigate a design research problem in which the conflicting needs of individuals and groups likely prevent an optimal solution. Individuals seek freedom of actions in an environment while groups require awareness of others' actions (Gutwin & Greenberg, 1998). For example, a transfer technique that gives control to one party to initiate and complete transfer (for instance, by automatically updating the target screen with a full-screen version of the item) is likely to sometimes interrupt the flow of collaboration.

By following a Research through Design approach, I was able to explore several design options for Handoff and Deposit and learn how one might operationalize the theory of mechanics of collaboration in digital shared workspaces. I learned some limitations of the theory and identified a framework (Harris, 2019) that helped me articulate the impact of temporal coordination in cross-device transfer on mixed-focus collaboration (Thesis Contribution 1). The outcome of this project was a set of 5 design considerations for cross-device transfer (Thesis Contribution 2).

While conducting Projects 1 and 2, I identified a need for a tool to articulate the impact of specific user interface designs on collaborative processes. There was a gap in HCI literature with respect to available tools for focused analysis at the user interface level. Existing methods had their own advantages but were primarily designed for single user interfaces, did not include non-verbal interactions with technology, or had a broad unit of analysis. Here is my research question in Project 3:

**RQ3**: How can we articulate the (sometimes subtle) impact of specific user interface designs on communication grounding?

As Clark says (Clark & Brennan, 1991), communication grounding is the process of building and maintaining a shared understanding about the task at hand, and it is essential for conducting mixed-focus collaboration around technology (Isenberg et al., 2012). Given the affordances (or lack thereof) of a collaborative environment, e.g. visibility, audibility, etc., people incur grounding costs – a way of measuring the effort required to maintain common ground. Particularly, in XDEs people's attentions may be distributed across devices at different times and therefore it is crucial for collaborators to keep up-to-date knowledge about others' actions in the environment. They then decide what to say or do based on what they believe their collaborators are aware of (Clark & Brennan, 1991). The Joint Action Storyboards (JASs) developed in Project 3 allows HCI researchers to analyze and articulate the impact of user interface designs on collaboration through the lens of communication grounding (Thesis Contribution 3).

The grounding theory asserts that in a conversation, people perform momentary joint actions to increment their common ground (Clark, 1996). JASs visualizes those joint actions during collaborative instances in XDEs. I extended the concept of joint actions to include interactions with the XDE. The framework uses grounding costs as a way of measuring the effort in each joint action, which ultimately impact collaborative processes

## 1.3 Thesis Organization

The remainder of this document presents background information, my three research papers (corresponding to Projects 1-3), and a separate chapter on Research through Design (RtD) to position my research methodology in Project 2. I end this thesis by discussing the contributions, limitations, and research directions to extend my findings.

Chapter 2 provides background information and reviews related literature to situate the contributions of my dissertation. It talks about mixed-focus collaboration in general, and group work around XDEs and coordination in cross-device interaction in particular. Then, I argue for a need to understand the impact of interface design of cross-device interaction on mixed-focus collaboration. Finally, I review how the impact is currently measured and what my contributions add to the literatures. Chapter 3 presents Project 1 (Homaeian et al., 2018), which addresses RQ1 by investigating the impact of two cross-device interaction techniques on collaborative processes. It provides knowledge towards the first two thesis contributions.

Chapter 4 presents RtD as a method of inquiry in HCI research. I discuss RtD as a qualitative approach to tackle under-studied research problems in HCI, the nature of outcomes, how they are evaluated, and their reliability. The chapter ends by providing an overview of the RtD process in Project 2 with regards to the points discussed in the chapter. In Chapter 5, I present Project 2 (Homaeian et al., 2022). It is currently pending acceptance of minor revisions. Project 2 addresses RQ2 by providing a set of design considerations for temporal coordination in cross-device transfer. Chapter 5 provides further knowledge towards the first two contributions of my dissertation.

Project 3 appears in Chapter 6 (Homaeian et al., 2021). It addresses RQ3 by presenting the development of joint action storyboards (JASs) as a design and analysis framework for HCI research. JASs are the third contribution of my dissertation.

Chapter 7 concludes my thesis by discussing the thesis contributions and linking the three project's roles in making those contributions. I then discuss my findings that point to benefits of providing flexible cross-device interaction techniques to support mixed-focus collaboration. Design implications beyond the collaborative environments that I studied are also presented. As my research was impacted by the COVID-19 pandemic, I reflect on my pivot to Project 2. Finally, the chapter discusses limitations of my PhD research and provides directions for future research.

# Chapter 2: Background

Communication and coordination are fundamental aspects of collaboration (Gutwin & Greenberg, 2002). Collaborators communicate with each other to build and maintain common ground, which is a shared set of knowledge, assumptions, and beliefs about the task at hand (Clark & Brennan, 1991). Even when there is no direct communication, collaborators keep peripheral awareness of what happens in the environment (Pinelle et al., 2003), which increments their common ground. Collaborators also use the knowledge they believe is already shared by others to coordinate their verbal and non-verbal actions (Clark, 1996). In other words, communication builds awareness of others' activities in the environment and the context, which in turn leads to more efficient communication and coordination of actions (Clark & Brennan, 1991; Pinelle et al., 2003). For example, in a shared visual space, people can use deictic references (pointing or gesturing to simplify referring to objects in the space (Pinelle et al., 2003)) instead of detailed descriptions for less effortful communication (Gergle et al., 2013).

A collaborative software application must facilitate communication and coordination (Pinelle et al., 2003). The affordances and constraints of the application shape the way collaborators conduct group work or their *collaborative process* (Clark & Brennan, 1991; Gutwin & Greenberg, 1998), *which includes communication and coordination to maintain common ground* (Wallace et al., 2009). The collaborative process, in turn, can impact user experience and the outcome of the activity (e.g. (Brudy et al., 2018; Homaeian et al., 2018; Mahyar & Tory, 2014; Wallace et al., 2011)). For instance, revealing content that can be shared or devices that are available for connection may encourage data sharing (Marquardt, Ballendat, et al., 2012; Ramos et al., 2009). Therefore, it is important for technology designers and researchers to have tools and methods to inform their early decisions as well as aid in evaluation of high fidelity prototypes and existing designs (Gutwin & Greenberg, 1998; Pinelle et al., 2003).

This dissertation primarily focuses on the impact of cross-device interaction techniques on collaborative processes. Project 1 explored how the design of two cross-device interaction techniques influence independent and joint work periods that can both occur during collaboration (Homaeian et al., 2018). Its findings inspired me to explore designs for interaction techniques that are flexible in supporting mixed-focus collaboration, i.e., individual freedom as well as group coordination in XDEs. In Project 2, I proposed a set of design considerations for temporal coordination in cross-device transfer (Homaeian et al., 2022). Through my experience in conducting Projects 1 and 2, I identified the need for a tool for researchers to articulate the impact of interaction design on collaborative processes. Therefore, in Project 3, I developed a visual framework to analyze and communicate the impact of specific user interface elements on communication grounding (Homaeian et al., 2021).

## 2.1 Mixed-Focus Collaboration

Many collaborative activities, such as sensemaking, planning, and brainstorming take place in a *mixed-focus* fashion, where collaborators fluidly shift between independent (loosely coupled) and joint (tightly coupled) work periods (Gutwin & Greenberg, 1998). Often, people individually explore and filter data and then come together to merge findings and find patterns (e.g. (Isenberg et al., 2012; W. McGrath et al., 2012; Wallace et al., 2013)). Tang et al. (2006) studied how people transition between the two work periods and identified six coupling styles describing the degree to which collaborators are occupied with each other's work. For instance, collaborators could be working on the same problem but focusing on different areas, or one could be working while the other one is observing. Isenberg et al. (2012) extended Tang et al.'s research by identifying three more work styles between the two extreme ends of joint and independent work periods. These findings assert that collaborative XDEs should facilitate parallel independent work as well as tightly coupled work in order to be effective (e.g. (Isenberg et al., 2010; Jetter et al., 2011; Tang et al., 2006; Vogt et al., 2011)).

However, addressing the needs of individuals as well as groups is a complex design problem: individuals seek freedom in the environment whereas groups need awareness of others' activities (Gutwin & Greenberg, 1998). Designers often face a tradeoff when facilitating both independent and joint work styles. For example, one could give users the freedom to manipulate the environment fast and efficiently, e.g. using short-cut keys. In this case, lack of timely feedback reduces group's ability to maintain awareness. Yet, balancing the amount and type of feedback with potential interruptions to the ongoing work style of other collaborators is not trivial. Adding to the complexity of this design problem is that even subtle changes to the user interface of collaborative systems can impact collaborative processes (Gutwin & Greenberg, 1998).

## 2.2 Collaboration around XDEs

Recent proliferations in touch and virtual-reality technologies have provided new device form factors and novel ways of interaction. Consequently, there has been growing interest among HCI researchers in designing collaborative XDEs to enable new and potentially more effective forms of communication and coordination. Indeed, research shows that XDEs can support mixed-focus collaboration by providing distinct spaces for parallel and joint work styles (e.g. (W. McGrath et al., 2012; Wallace et al., 2011; Zagermann et al., 2016)) and thus supporting individuals as well as groups (Gutwin & Greenberg, 1998; Tang et al., 2006). For example, Wallace et al. (2013) studied collaborative sensemaking in an XDE comprised of a shared digital tabletop and personal tablet computers. They found that the tabletop acted as a shared reference point and fostered communication and coordination for the group. The personal devices facilitated independent work. BEMViewer (W. McGrath et al., 2012) is another XDE fostering a collaborative search application. It has a shared tabletop display and personal tablets. Team members can branch off to explore data independently on their tablets, and then come together to vote and combine their findings on the shared display. Zagermann et al. (2016) studied the impact of tabletop size in a collaborative sensemaking context. They found that a large shared tabletop was more suitable for focusing collaborators' attention on the screen, compared to a small shared tabletop which better supported eye contact.

HCI researchers have also designed and studied many techniques for cross-device interaction (e.g. (Marquardt, Hinckley, et al., 2012; Nacenta et al., 2005; Rädle et al., 2014))(see (Brudy et al., 2019) for a complete review). Such techniques facilitate interacting with content by:

1) linking the screen space of connected devices to zoom in and pan an image (e.g. (Hinckley et al., 2004; Marquardt, Hinckley, et al., 2012)),

2) transferring content (for instance by swiping (e.g. (Paay et al., 2017; Wozniak et al., 2016)) and coordinated gestures (Nacenta et al., 2005; Shibata et al., 2016)), and

3) exploring content (for instance by sending information to a target device to be handled by the corresponding application (Hamilton & Wigdor, 2014; Homaeian et al., 2018)).

I focus on cross-device interaction techniques that transfer content across devices.

Even though cross-device interaction techniques in collaborative systems should facilitate independent and joint work periods (Pinelle et al., 2003), the research community tends to introduce novel cross-device interaction techniques more often than investigate how existing techniques may impact collaborative processes. My Ph.D. research contributes knowledge to help fill this research gap.

## 2.3 Coordination in Cross-device Interaction Techniques

In Projects 1 and 2 of this dissertation, the focus is on cross-device interaction techniques that facilitate data sharing between devices, for instance, to show or send an image to a collaborator. In such techniques, a high degree of *spatial* and *temporal* coordination is necessary to facilitate the interaction (Pinelle et al., 2003).

Spatial coordination concerns the use of physical and digital spaces and has been studied widely following the theory of tabletop territoriality by Scott et al. (2004). In that seminal work, they reported that when working around a traditional tabletop, people use three types of territories: personal, group, and storage territories. This partitioning of shared spaces has been found to apply in many different digital collaborative settings (e.g. (Morris et al., 2010; Ryall et al., 2004; Tse et al., 2004)). Therefore, several design concepts for spatial coordination in cross-device transfer have been explored in the literature (Scott et al., 2014). Some techniques transfer a shared item to an area along the bezel of the receiving screen (e.g. (Marquardt, Ballendat, et al., 2012; Rädle et al., 2015; Ramos et al., 2009)), whereas others allow it to appear in other parts of the screen (e.g. (Marquardt, Hinckley, et al., 2012; Seyed et al., 2013; Shibata et al., 2016)).

For instance, in the contiguous virtual workspace techniques, a static or ad-hoc adjacency map of the displays in the environment is maintained by the system (Scott et al., 2014). Users can then transfer objects to neighboring devices, for instance, by drawing a 'stitch' gesture with a pen across displays and to the desired location (Hinckley et al., 2004) or by tilting a device towards the target display to share a partial view across the display's edge or a full screen view (Marquardt, Hinckley, et al., 2012).

Another technique for spatial coordination is called virtual portals or bridges, which refer to a dedicated area along the edge of a display that is used for sending and receiving items. Thus, such techniques facilitate creating personal, group, or storage territories. Dragging an item to the portal causes it to appear on the target display's portal (e.g. (Marquardt, Ballendat, et al., 2012; Rädle et al., 2015; Scott et al., 2014)) by showing a thumbnail (Marquardt, Ballendat, et al., 2012), notification (Biehl et al., 2008; Hamilton & Wigdor, 2014), or partial view of the item (Marquardt, Hinckley, et al., 2012; Ramos et al., 2009). Physical proxies is yet another design concept for cross-device transfer that is similar to the physical act of moving objects in a workspace. In such techniques, a digital object is bound to a physical one called a proxy, e.g. a system-recognized pen (Haller et al., 2010). Touching the proxy on the target location then moves the object. An example is the Pick-and-Drop technique (Rekimoto, 1997).

In contrast, temporal coordination, defined as the sequence of actions executed by the sender and receiver to complete the transfer, is less understood in terms of design considerations. Some existing design frameworks mention the sequence of actions in cross-device transfer (e.g. (Nacenta et al., 2005; Ramos et al., 2009)) though they do not provide insight on the potential impact on collaboration.. Many cross-device transfer techniques automatically interrupt the receiver (e.g. (Hinckley et al., 2004; Marquardt, Hinckley, et al., 2012; Rekimoto, 1997)), which may or may not be desirable given the ongoing work style of the group. For instance, if the receiver is independently exploring data, the transfer is likely to disrupt them. However, if the group is engaged in an active discussion, showing relevant data to a partner in a readily-usable format (e.g. full screen) supports the flow of the joint work.

In Project 2, I adapted a framework (Harris, 2019) to articulate the degree of synchronicity between the sender and receiver and thus temporal coordination in cross-device transfer. The resulting design considerations help researchers understand the impact of temporal coordination in cross-device transfer on mixed-focus collaboration.

## 2.4 Impact of User Interface Design of XDEs on Collaborative Processes

Research shows that the user interface of software can impact collaborative processes and ultimately the outcome of the activity (e.g. (Gutwin & Greenberg, 1998; Isenberg et al., 2012; Mahyar & Tory, 2014; Vogt et al., 2011)). However, the research community has focused less on studying the impact and more on introducing novel interfaces and systems for group work. For instance, designers could give individuals the power to change the displayed representation of data with a hierarchical structure to 'outline' or 'tree' on different interfaces within an XDE system. However, the type of representation displayed in each interface could hinder a group's ability to talk about and point to the same items in the structure if individuals do not share the same view. Therefore, in this case the individual power comes at the expense of group awareness and common ground (Gutwin & Greenberg, 1998).

In a study comparing different physical and virtual interaction methods, Jamil et al. (2011) found that interaction design can impact communication patterns during a collaborative learning task around a large interactive tabletop. One studied technique, called Pantograph, allowed each individual group member to access all areas of a tabletop display independently via a small area directly in front of each person on the tabletop interface. Compared to direct touch interaction, Pantograph resulted in more off-task discussions, which could be disadvantageous to learning. Some researchers have reported a touch interaction technique that was potentially disruptive to individuals led to more discussions and tightly coupled work, providing potential collaborative benefits (Fleck et al., 2009). In a collaborative learning environment around a tabletop, unauthorized undo actions caused confusion at first but facilitated discussions to explain decision making (Fleck et al., 2009)

Various studies have found that closeness of collaborative styles can impact outcomes (e.g. (Isenberg et al., 2012; Mahyar & Tory, 2014; Vogt et al., 2011; Wallace et al., 2013)). Isenberg et al. (2012) and Vogt et al. (2011) reported that groups working in a tightly coupled manner were more successful at solving sensemaking tasks. In an environment comprised of personal desktop computers, awareness notifications on the collaborators' screens led to more task-focused discussions and coordination of findings compared to when notifications were absent and coordination occurred only through verbal communication (Mahyar & Tory, 2014). Moreover, the awareness notifications resulted in better analytic outcomes. Wallace et al. (2013) found that groups working closely identified more key facts and insights in a sensemaking task.

Despite ample evidence that the user interface design of collaborative systems influences the way people work together and potentially the outcome of the activity, the impact of cross-device interaction techniques on collaborative processes is an understudied area (Convertino et al., 2008, 2009). Meanwhile a number of novel cross-device interaction techniques continue be introduced by HCI researchers (Brudy et al., 2019). My dissertation is a step towards filling this research gap by contributing a user study on the impact of two cross-device interaction techniques on different phases of mixed-focus collaboration, and a visual framework and design considerations to aid researchers and technology designers in understanding and articulating how an interaction technique may support or hinder group work.

### 2.4.1 How is Impact Evaluated?

Evaluating the impact of user interface design on collaborative processes is a complex subject as there are a number of factors at play in collaborative behaviour, including group structure and dynamics, the type and requirements of the task, and so on (Gutwin & Greenberg, 1998; Janis, 1982; Pinelle et al., 2003; Wallace et al., 2009). Nonetheless, researchers have employed a number of quantitative and qualitative measures to evaluate the efficiency and effectiveness of collaborative systems. Taskwork measures focus on activities required to complete the task (Pinelle et al., 2003). Completion time, solution quality, error rate, and subjective measures indicate whether the system facilitates the intended task. Qualitative data such as interview and observations may also be collected and analyzed to understand if the system design supports or hinders the task (Wallace et al., 2009).

In contrast, teamwork measures focus on the communication, coordination, and awareness processes needed to complete a collaborative task (Pinelle et al., 2003). My dissertation focuses on these teamwork aspects of collaborative work. Video, interview, observational notes, and subjective questionnaire analysis are methods commonly used to understand how affordances and constraints of a collaborative environment influence collaborative processes (e.g. (Biehl et al., 2008; Brudy et al., 2018; Ramos et al., 2009; Zagermann et al., 2016)). However, the above methods have a broad unit of analysis and therefore may not identify subtle design improvement opportunities in the interface. In contrast, the visual framework developed in Project 3 focuses on specific user interface elements and how they may support or get in the way of interaction minutiae (Homaeian et al., 2021).

Conversational analysis is another method often used to analyze communication grounding, the process of building and maintaining common ground (Clark & Brennan, 1991), to understand the impact of technology on collaboration. Communication grounding is an essential part of working around technology (Clark & Brennan, 1991; Convertino et al., 2008; Homaeian et al., 2021; Isenberg et al., 2012) and entails maintaining awareness and coordination of actions accordingly (Clark & Brennan, 1991). As a group's common ground increases, their communication becomes more efficient and effective (Convertino et al., 2008). Communication efficiency is measured, for instance, by counting the number of utterances, deictic references, the number and length of conversational turns (Convertino et al., 2008, 2009; Wallace et al., 2009, 2011). Communication effectiveness and coordination is measured by using a coding scheme to examine the content of conversations. Examples of codes are checks for understanding, seeking awareness, referring to the interface, etc. (Convertino et al., 2009; Jamil et al., 2011; Mahyar & Tory, 2014).

However, conversational analysis ignores interactions with technology, especially if they occur in the absence of verbal communication. Thus, it may limit researchers' understanding of the impact of user interface elements, and therefore restrict opportunities to improve an interaction design. The visual framework developed in Project 3 (Homaeian et al., 2021) includes interactions among collaborators as well as with the system. The framework may be used alongside of conversational analysis and other methods for evaluating collaborative environments to provide a holistic view for researchers.

# Chapter 3: Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration

## 3.1 Preface

This chapter presents the paper that was published at the 2018 ACM CHI Conference on Human Factors in Computing Systems (Homaeian et al., 2018), in which I was the primary author. I made minor edits to the paper content to suit the purpose and formatting of the dissertation.

The work presented in this chapter addresses RQ1 and led to Contribution 1: Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration, and Contribution 2: Design considerations for cross-device interaction techniques to support mixed-focus collaboration.

This project was based on a prior study conducted by Nippun Goyal from our research group at the University of Waterloo for his Master's thesis. To investigate additional questions unexplored in Nippun's thesis, I re-analyzed video data gathered in the original study. Details of the study methodology, including the user study materials, can be found in Nippun's Master's thesis (Goyal, 2016). The video analysis I conducted followed the *inductive thematic analysis* approach (Boyatzis, 1998). My analysis led to identifying three main collaborative behaviour exhibited by the participants in the user study: 'synchronized data viewing', 'comparing and contrasting evidence', and 'formation of tableaux'.

The coding of the data took place over multiple meetings with my advisors (second and third authors of the paper) who were knowledgeable about the data. We discussed our interpretations of the codes that I had identified, refined the codes, and finally merged the codes to form the three themes describing collaborative behaviour of the participants in tightly coupled work periods. The thematic analysis done by Nippun mainly focused on territoriality around the digital tabletop in the study and spatial coordination of the task. In contrast, the themes that emerged from my analysis mainly concerned how the two cross-device interaction techniques impacted temporal coordination of data sharing and viewing. My analysis also led to four design considerations for cross-device interaction design to support mixed-focus collaboration in XDEs. Limitations experienced with cross-device interactions in the study inspired me to think about how to design interaction techniques that support the flexibility of work styles in mixed focus collaboration. This reflection led to the formulation of RQ2 (Chapter 5).

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. This chapter presents Project 1, which addresses RQ1 by exploring the impact of two XDE data browsing techniques: TOUCH and TILT on phases of mixed-focus collaboration. It has two more specific research questions, RQ1-1 and RQ1-2, which ask how TOUCH and TILT influenced independent and joint work periods, respectively. 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.

## 3.2 Introduction

There is growing interest in using multi- or cross-device environments (XDEs) to support co-located group work, e.g. (Brudy et al., 2016; Mahyar & Tory, 2014; Wallace et al., 2013; Zagermann et al., 2016). 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) (Gutwin & Greenberg, 2002) that occur during group work. For example, Wallace et al. (2011) 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. (2013) 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 (Gutwin & Greenberg, 1998; Isenberg et al., 2012; Tang et al., 2006). 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 collabo-ration (Isenberg et al., 2012; Tang et al., 2006). We also chose to use a tabletop-plus-tablets XDE as prior studies show that tabletops facilitate collaborative data analysis and sensemaking (Morris et al., 2010; Wallace et al., 2013). 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. (2013), including managing information across displays, ownership and control of data, and mechanisms for data replication.

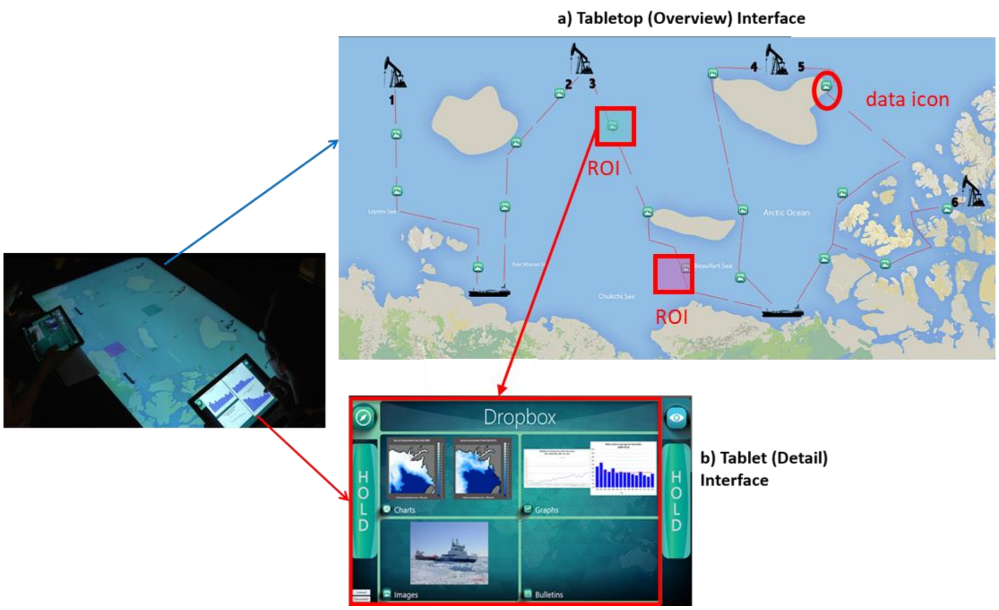



**Figure 3-1. Project 1. Our cross-device Overview + Detail environment: (a) a tabletop interface containing an overview map of the analysis area, data icons depicting locations with associated geotagged data, and Region of Interest (ROIs) for each collaborator, and (b) a tablet interface that displayed a "detail" view for associated geotagged data within the bounds of the user's ROI**

Our XDE modeled an Overview + Detail (O+D) (Cockburn et al., 2009) display environment, in which the tabletop (the "Overview" view; Figure 3-1a) 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 3-1b)). 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. (Isenberg et al., 2012; Voida et al., 2009)). Direct manipulation of content in a shared work-space has also been shown to promote workspace awareness and group coordination (Gutwin & Greenberg, 2002, 1998). 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. (Dachselt & Buchholz, 2009)). 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 (Dachselt & Buchholz, 2009); 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:

RQ1-1: How does the choice of cross-device interaction technique (TOUCH or TILT) impact people's ability to work independently during collaboration?

RQ1-2: 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 (Wallace et al., 2011) or shared tablet displays (Wu & Zhang, 2009), as discussed later in the chapter.

## 3.3 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.

### 3.3.1 Mixed-Focus Collaboration

In their seminal work, Gutwin and Greenberg (1998) 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 (Tang et al., 2006) and support various styles of collaboration (Lissermann et al., 2014), and show how designing for these tensions can improve the outcomes of group work (Liu et al., 2016).

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 (Wallace et al., 2013). This change was also anticipated by Gutwin and Greenberg (Gutwin & Greenberg, 1998), 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.

### 3.3.2 Co-located Collaborative Sensemaking

Sensemaking as defined by Russell et al. (1993) 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. (Pirolli & Card, 2005; Yi et al., 2008). For example Yi et al. (2008) 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 (Gutwin & Greenberg, 1998). 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 (Brennan et al., 2006). 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 (Isenberg et al., 2012; Tang et al., 2006).

Previous research on co-located collaborative sensemaking indicates that having a shared workspace enhances group performance and awareness (Morris et al., 2010). These findings have led to the use of tabletops and large dis-plays to support sensemaking in complex, data-driven environments such as social network analysis (Isenberg et al., 2009), oil and gas exploration (Seyed et al., 2013), and defence and security (Christopher Bortolaso et al., 2013; Wu & Zhang, 2009). Researchers have also studied behaviour in shared workspaces impacting people's use of space (Tse et al., 2004) and territoriality around tabletops (Scott & Carpendale, 2010), 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 (Plaue & Stasko, 2009; Wallace et al., 2009). Consequently, recent research has explored the potential of XDEs for collaborative sensemaking (W. McGrath et al., 2012; Wallace et al., 2013; Zagermann et al., 2016). For example, McGrath et al. (2012) developed a tabletop-plus-tablet XDE designed to sup-port 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?

### 3.3.3 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 (Cockburn et al., 2009). 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. (2002) report 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. (Javed et al., 2012; Voida et al., 2009; Zadow et al., 2014)).

However, it remains unclear how best to link the O+D views that sit across devices in a collaborative XDE (Isenberg et al., 2013). 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, over-view 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.

## 3.4 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 3-1). In designing the environment, we considered Gutwin and Greenberg's guidance (Gutwin & Greenberg, 1998) 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 3-1a). Previous research has shown that shared digital tabletops enhance group performance and aid awareness among group members (Morris et al., 2010; Rogers & Lindley, 2004; Wallace et al., 2013). Additionally, digital tabletops have been widely used by researchers to provide support in map-based collaborative environments, e.g. (Christophe Bortolaso et al., 2014; Chokshi et al., 2014; Doeweling et al., 2013). In addition to general geo-graphic 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 3-1b). 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 3-1).

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 3-1b). 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 3-1b).

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 Computer Supported Cooperative Work (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.

### 3.4.1 Cross-Device Interaction Techniques: TOUCH and TILT

To explore how different cross-device interaction de-signs 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 (Christophe Bortolaso et al., 2014) and XDE (Zagermann et al., 2016) studies. Such focus on personal displays can hinder group awareness and other collaborative benefits of a shared display (Wallace et al., 2009).

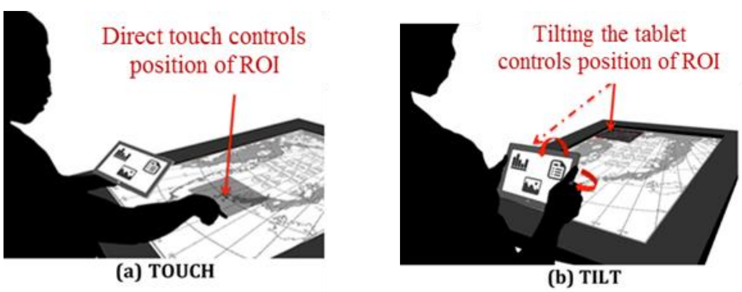



**Figure 3-2. Project 1. TOUCH and TILT techniques. (a) Using a direct TOUCH gesture on the table to control the ROI movement, (b) Using a TILT gesture on the tablet to control the ROI movement on the table**

Building on the concept of magic lenses (Bier et al., 1993), 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 3-2a), reflecting touch-based techniques from the literature (e.g. (Brudy et al., 2016)), with expected benefits to workspace awareness since they take place on the shared display (Gutwin & Greenberg, 2002). 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. (Dachselt & Buchholz, 2009)), TILT allows for remote movement of a user's ROI using a tablet's built-in gyroscope (Figure 3-2b), 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 (Spence & Witkowski, 2013) 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.

## 3.5 User Study

To understand the impact of the TOUCH and TILT cross-device interaction techniques on individual and group behaviour during collaborative sensemaking (RQ1-1 and RQ1-2), 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 (Goyal, 2016).

## 3.6 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 ad-vantage 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.

### 3.6.1 Experimental Task

Three task scenarios were developed for the study using Arctic sea ice data available from the Canadian Sea Ice Service (“Canadian Sea Ice Service. Latest ice conditions,” 2015) and National Snow and Ice Data Center (“National Snow and Ice Data Center,” 2015) 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 3-1b).

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.

### 3.6.2 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.

### 3.6.3 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.

### 3.6.4 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 (Norman, 2010). 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.

## 3.7 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 cross-device 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 (RQ1-1 and RQ1-2). 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 (Boyatzis, 1998).

### 3.7.1 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 (Isenberg et al., 2012; W. McGrath et al., 2012). 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.

#### 3.7.1.1 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 3-3 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.

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 physical constraints, of the TOUCH technique.

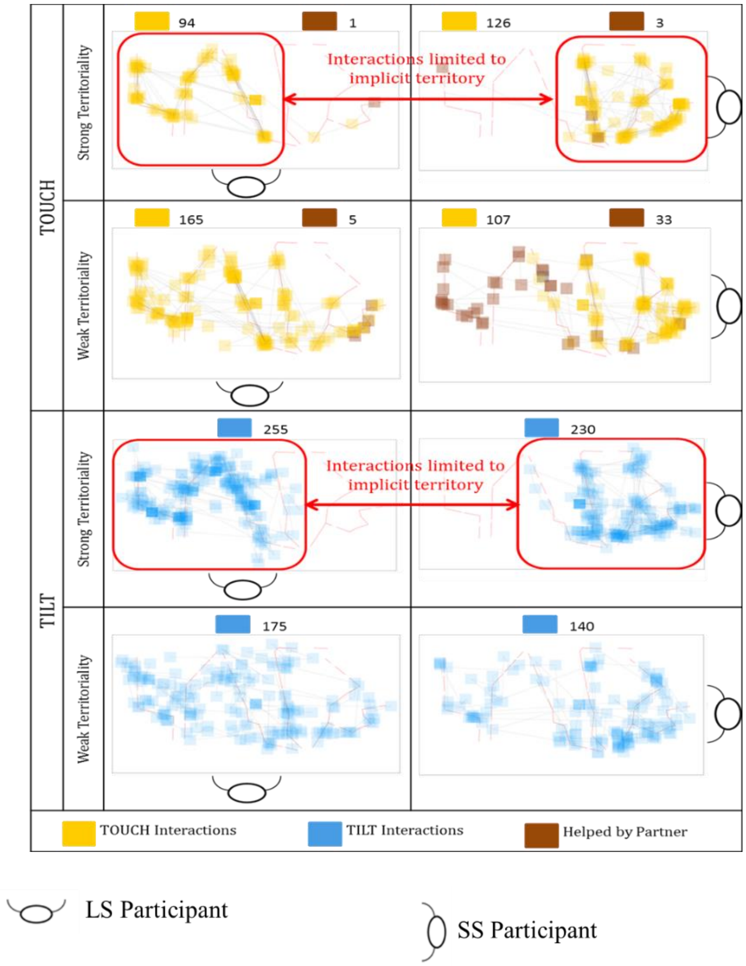



**Figure 3-3. Project 1. ROI Interaction heatmap visualizing group interactions in TOUCH and TILT during D&C Phase. ST interactions primarily occurred within the implicit territory**

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 3-3, 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 3-3, 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.

#### 3.7.1.2 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 re-visiting 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.

#### 3.7.1.3 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).

#### 3.7.1.4 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 3-4 Left). 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.

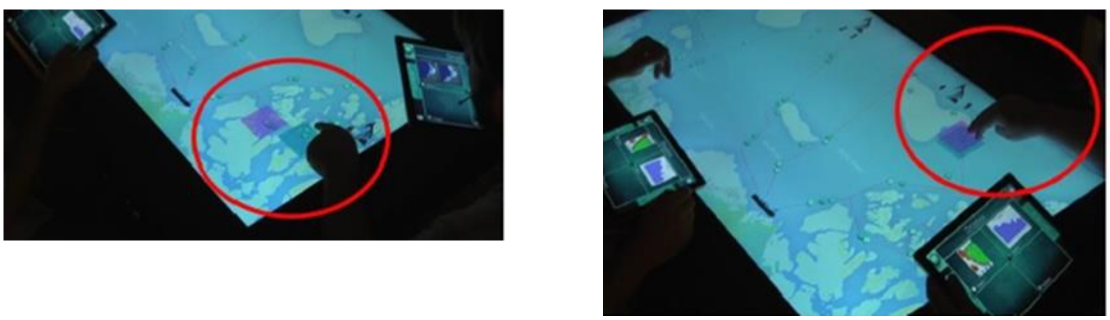


**Figure 3-4. Project 1. Showing data to a partner in TOUCH versus TILT : (Left) In TILT, SS points at a location where he needs LS to move his ROI, (Right) In TOUCH, SS uses "flexible ownership" feature to drive LS's ROI to desired location**

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 3-4 Right). 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).

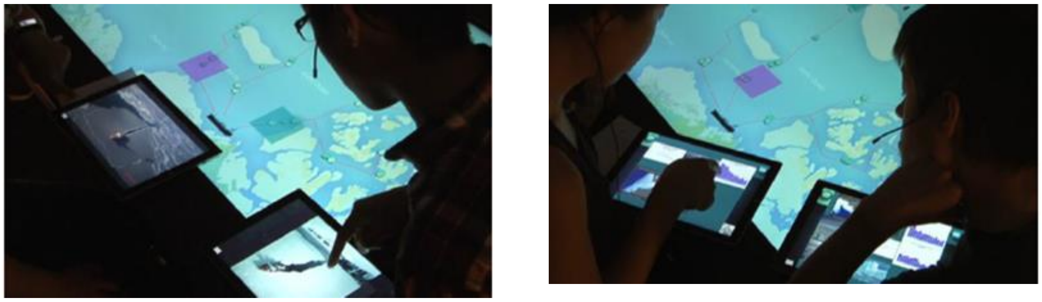


**Figure 3-5. Project 1. Groups 11 (Left) and 10 (Right) forming tableaux**

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.

#### 3.7.1.5 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 (Wallace et al., 2013).

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 3-5). 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.

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

## 3.9 Designing for Mixed-Focus Collaboration

In their seminal paper, Gutwin and Greenberg (1998) 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.

### 3.9.1 Supporting Independent Work (RQ1-1)

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 (Scott & Carpendale, 2010). 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.

### 3.9.2 Supporting Joint Work (RQ1-2)

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. (2013) 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 relocate 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 de vices 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.

### 3.9.3 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.

## 3.10 Conclusion

This chapter addressed RQ1 by presenting 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. Project 2 and Project 3 contribute knowledge that is toward filling this gap in HCI literature.

# Chapter 4: Research through Design

In this chapter, I talk about Research through Design (RtD) (Gaver, 2012; Zimmerman et al., 2007) as a research method for interaction design in HCI. In RtD, performing design activities are the means of conducting research and generating knowledge. In my thesis, I refer to 'design activities' as iterative research activities (Zimmerman & Forlizzi, 2014) to understand a complex problem from multiple perspectives, to formulate and reformulate the problem, and to develop several possible solutions or prototypes that address it (Stappers & Giaccardi, 2017). HCI research problems that are under-constrained with agendas driven by various stakeholders are often difficult to address with traditional scientific and engineering methods (Zimmerman et al., 2007). In other words they are better addressed by first understanding their various aspects and their relationship rather than by directly reducing the problem to a few factors (e.g. for a controlled user study). Such research problems lend themselves to an RtD approach (Zimmerman & Forlizzi, 2014).

The prototype has an important role in knowledge production in RtD (Gaver, 2012; Stappers & Giaccardi, 2017). For instance, it combines aspects that did not exist previously, and thus allows people to engage in interactions with technology that were not possible before. In doing so, it makes those interactions and people's behaviour observable, and thus creates an opportunity to uncover knowledge that could not be discovered otherwise. Moreover, in the iterative and generative process of idea and prototype development and evaluation, the researcher faces constraints and opportunities, and implications of theories given the realities of the context under study (Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014). This process brings insights to the researcher and lets them learn about, among others, the prototype, the people who interacted with it and the interactions, and about the research process itself (Stappers & Giaccardi, 2017). If the insights can be articulated in a way that are applicable to situations beyond the prototype that was created, then they can be shared with other researchers to advance knowledge in HCI (Gaver, 2012; Zimmerman et al., 2007).

## 4.1 RtD Process is Primarily Qualitative

RtD is a suitable approach for research problems that are messy, under constrained, and complicated and thus do not have a single optimal solution. For example, the stakeholders could have competing needs in the context. Therefore, RtD is primarily a qualitative approach to inquiry and has an interpretivist view (Creswell, 2014; McDonald et al., 2019) in knowledge discovery; the focus is not to objectively study a small set of factors to determine causal relationships, at least at the beginning when the important factors are not even clearly defined. Instead, RtD researchers engage in a reflective and iterative design and evaluation process that allows important aspects of the problem to be identified and the type of questions that should be asked to emerge (Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014). Moreover, the researcher is the main instrument in conducting the research (Creswell, 2014) and their expertise and knowledge (which could be tacit) impact their decisions throughout the process (Krogh & Koskinen, 2020; Stappers & Giaccardi, 2017).

This style of research resonates with the approach to tackling understudied HCI problems in general. In dealing with such research problems, it is often helpful to start with research methods that can be used in an exploratory manner, e.g. observations, surveys, and interviews, to understand the aspects of the problem, e.g. target population, current solutions, etc. (Lazar et al., 2017). The knowledge gained can then guide the researchers to formulate a hypothesis for an experimental design (Shneiderman, 2016). In RtD, the knowledge about the problem is gained through designing and creating a thing or a prototype. The prototype allows, for instance, experimenting with implications of abstract theories, demonstrating the possibility of a new solution, and sparking discussions around the problem (Stappers & Giaccardi, 2017).

RtD crosses multiple disciplines, such as art, engineering, and human computer interaction (Stappers & Giaccardi, 2017). Thus, there is a variety of methods employed by researchers depending on the research team's disciplinary backgrounds and areas of expertise (Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014). They range from those with theoretical grounds to those that are primarily based on imagination and experimentation (Gaver, 2012; Zimmerman et al., 2007). In any case, RtD researchers use a variety of tools and techniques, such as sketching, plans, models, visuals, and prototypes to explore a wide range of possible designs (Forlizzi et al., 2009; Gaver, 2012; Stappers & Giaccardi, 2017). Depending on the stage of the project, how satisfied the researchers are with their design, and their expertise, design evaluation includes discussions and critiques among the research team or their peers, and also qualitative or mixed methods involving prototypes (Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014).

A characteristic of RtD is that RtD researchers seek to envision the future and thus ask 'what if questions' (Gaver, 2012; Zimmerman et al., 2007). A lab or field study in RtD could look similar to other user studies in HCI. However, the distinction is in the nature of research questions addressed by

RtD: questions that speculate about the future and possibilities given the proposed design. Thus, RtD researchers may combine factors in the study that did not exist before to make interactions in the presence of those factors observable (Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014). In contrast, researchers holding the postpositivist world view often try to understand the existing reality. Nonetheless, they could also be interested in the future. However, they favour one possible future and try to objectively predict it (Creswell, 2014).

The above characteristics of RtD have implications for evaluating knowledge generated by RtD. That topic is discussed in the following section.

## 4.2 Evaluating RtD Contributions

RtD contributions are evaluated based on four criteria: process, invention, relevance, and extensibility (Zimmerman et al., 2007).

The process of RtD must be documented with enough details that it could be reproduced by other researchers. However, given the qualitative nature of RtD, there is no expectation that two researchers following the same procedure will produce the same designs (Gaver, 2012). Instead, rationale behind design decisions and choosing specific methods must be reported. Documenting details of the process in a transparent manner allows for examining the reliability and rigour of the process and thus the quality of the contribution (Creswell, 2014; Gaver, 2012; Zimmerman & Forlizzi, 2014).

RtD researchers must also demonstrate that the produced prototype is novel and that it addresses the context of the study. Therefore, a comprehensive literature review must be conducted to situate the work and articulate how the contributions increment the knowledge in the research community. Moreover, the outcome or the features of the prototype must be articulated in a way that points to opportunities that others can pursue (Zimmerman et al., 2007).

The benchmark for assessing validity of RtD outcomes is relevance (Zimmerman et al., 2007). The researchers cannot claim that the prototype they have created is the ‘correct’ solution for the situation that it addresses. However, they need to articulate the benefits that their prototype creates in the context under study. In other words, the community needs to know why the novel thing that was produced matters and how it can create a better situation or solution over the existing one.

Extensibility means that the RtD process should be described in enough details that allows the research community to build on the resulting outcomes, by either using the process in future work or by leveraging the knowledge that was generated (Gaver, 2012; Zimmerman et al., 2007).

## 4.3 Reliability in RtD Research

Since RtD is primarily a qualitative form of research, it is useful to discuss reliability in qualitative inquiries, which is also true for RtD contributions in HCI research.

The dominant view in RtD inquiries is interpretivist. The researcher is interested in learning how participants make meaning of the designed prototype. The subjective and varied views of the participants are valued in understanding how the prototype may address or impact the situation that is being studied (Creswell, 2014; Stappers & Giaccardi, 2017). The researcher is the instrument in performing the inquiry; they gather and analyze the data. Therefore, they recognize that their own expertise and background play a role in shaping their interpretation (Creswell, 2014; Gaver, 2012; Löwgren, 2013). There are a number of strategies that RtD researchers can follow to ensure the reliability of their findings for HCI (Creswell, 2014; Zimmerman et al., 2007).

One strategy is describing the research process *in detail* to communicate rigour and allow for reproducibility of the process. The documentation, which is one of the primary outcomes of RtD (Zimmerman et al., 2007), provides other benefits for the community, too. It shows the constraints and consequences of design choices (Dove et al., 2016; Stappers & Giaccardi, 2017), design directions that were considered but not pursued or pursued but did not work (Zimmerman & Forlizzi, 2014). Therefore, the researcher documents how the design space was filtered, which may provide future research opportunities (Dove et al., 2016).

A second strategy is communicating the positionality of the researcher, i.e. their background, area of research, expertise, to clarify the bias that the researcher brings with them (Creswell, 2014; McDonald et al., 2019).

The researchers continually reflect and evaluate the problem formulation (Zimmerman & Forlizzi, 2014). In the iterative design process, they discuss what they learned and how that ties to the aspects of the problem that were investigated. The discussions can happen among the research team or with peers outside of the team (referred to as ‘peer debriefing’) (Creswell, 2014). Feedback provided by the impartial peers can make the researchers more aware of their own views and perspectives in performing the inquiry. They should continue to challenge their framing of the problem and, where appropriate, reframe the problem according to the knowledge that they gain.

Finally, an external auditor can review the entire project and ask questions about the process and findings. This strategy is different than peer debriefing in that the external auditor is not familiar with the project or the researchers and can therefore conduct an objective evaluation of the study (Creswell, 2014). The independent investigator assesses the research methods, data and its relationship to the research questions, and conclusions of the project. Thus, this procedure enhances the overall quality and validity of the project (Creswell, 2014) and is similar to the anonymous peer review process in HCI publication venues.

## 4.4 Intermediate-Level Knowledge: Abstraction of RtD Outcomes

The goal of RtD is producing knowledge that is applicable beyond the prototype or the thing that was created; knowledge that is extensible and can be used by others (Gaver, 2012; Zimmerman et al., 2007). Over the years, many researchers (e.g. (Forlizzi et al., 2009; Gaver, 2012; Hoök & Lowgren, 2012; Löwgren, 2013)) have investigated the role of RtD in theory creation for HCI by identifying the types of contributions that RtD makes and articulating the abstraction level (or their ‘scope of applicability’ (Löwgren, 2013)) of those contributions.

Hook et al. (2012) argue that RtD creates opportunities for generating knowledge that is more abstract than particular instances yet it is not general like a well-established theory (Zimmerman & Forlizzi, 2008) (Figure 4-1., adapted from (Löwgren, 2013, p. 3)).

Indeed the territory between specific instances and general theory is not empty. Knowledge created by RtD resides in that territory and it is called intermediate-level knowledge (Hoök & Lowgren, 2012; Löwgren, 2013). Zimmermann et al. (2008) state that such knowledge lays the foundation for spawning theory to guide future research and design practitioners.

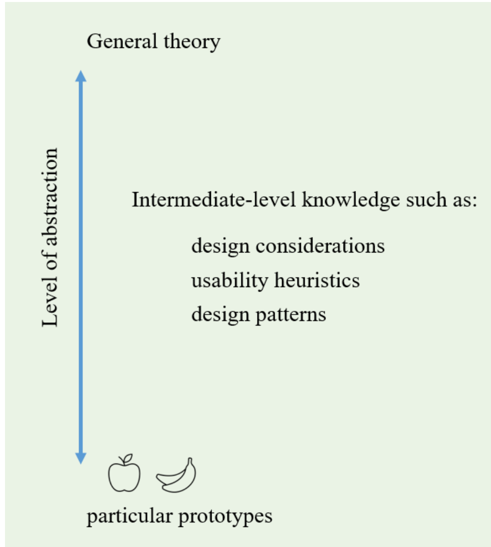



**Figure 4-1. Level of abstraction in knowledge produced by RtD : Intermediate level knowledge produced by RtD is more general than particular instances yet has a smaller scope of applicability compared to general theory**

Many examples of intermediate-level knowledge have been proposed in HCI literature (Hoök & Lowgren, 2012; Löwgren, 2013; Zimmerman & Forlizzi, 2008), such as the following:

*Design methods and tools* can emerge from RtD as researchers learn about the process of RtD itself, e.g. how to measure a construct and how to document the research process. Such methods and tools range from those specialized for particular contexts to those that are more universal. For example, Dalsgaard et al. (2012) developed a blog-like tool to document an RtD process that can be accessed and edited by researchers and participants.

*Design considerations* (also referred to as design guidelines) originated in the early days of HCI and continue to be proposed in the literature. They can be generative, inspiring and guiding new designs, or evaluative, used to assess an existing design. Well-known examples are Universal Principles of Design (Lidwell et al., 2010), and Neilson's usability heuristics (Nielsen & Molich, 1990).

*Design patterns* represent key ideas in a design or family of designs, and are useful in creating a language for designers and researchers to talk about best practices in their fields. An example from the software engineering field are design patterns in object-oriented design (Gamma et al., 1994), which allow software developers to create reusable pieces of code for particular use cases.

*Design concepts* are another instance of intermediate-level knowledge. They embody a design idea that demonstrates the potential to inspire other design ideas. The well-known Alan Kay's Dynabook was a vision that described a personal computer for children. It laid out the requirements and functionalities of a potable education device, similar to those of today's laptop and tablet computers. The design concept initiated much HCI research for many subsequent years.

### 4.4.1 Outcomes of RtD for HCI Research

Zimmermann et al. (2007) proposed a model for RtD in HCI that shows the types of knowledge from various disciplines feeding into RtD and the types of knowledge generated by RtD that feed back into the disciplines:

1. ***engineering*** provides knowledge about technical possibilities and how an interaction technique might be implemented. In return, RtD could result in technical opportunities for engineers to pursue.
2. ***behavioural sciences*** provides a wealth of theories and models of human behaviour that could be generative in interaction design. RtD could reveal gaps in those theories when it comes to applying them to interaction in digital environments.
3. ***anthropology*** provides descriptions of contexts and how humans operate within them. Prototypes created in RtD, make new forms of interaction possible and thus give anthropologists the opportunity to observe and investigate human behaviour around the new creations.

## 4.5 Overview of RtD Process in Project 2

In my RtD project (Chapter 5), I brought my own software engineering background, as well as my human-computer interaction knowledge and training to collaborate with a software engineer to implement a software application that supported data exchange across tablet computers over a Wi-Fi network. My findings include design considerations for cross-device transfer in collaborative sensemaking that are useful for technology designers. I based my initial designs on the theory of mechanics of collaboration (Pinelle et al., 2003). The knowledge I gained while conducting the RtD process revealed nuances in transfer using tablet computers, which were not described in the theory that is based on transfer in physical environments.

I began by iteratively designing and reflecting on several cross-device transfer techniques based on the mechanics of transfer in physical shared spaces (Pinelle et al., 2003). My initial instruments were paper and digital sketches for quick exploration and critique of potential user interfaces (Gaver, 2012; Stappers & Giaccardi, 2017). When I was satisfied with the techniques' designs (with respect to their support for collaborative sensemaking), I moved to a series of user observations, in which participants interacted with a high-fidelity porotype that implemented my cross-device transfer techniques. My goal was to observe and understand how the participants made use of the techniques and the impact on collaborative processes, which resulted in further refinement of the cross-device interaction techniques. Finally, I corroborated my findings with HCI literature to find any potential inconsistency and gap in my design considerations Throughout the RtD process, my understanding of how I could operationalize the theory of mechanics of collaboration developed. Based on the knowledge that I was gaining, I learned that there was a broader set of design criteria, beyond those implied by the theory.

As presented in Chapter 5, I followed a number of strategies to ensure the reliability in Project 2. I documented the RtD process in detail and provided reasoning for my research methods design choices. I held peer debriefing sessions to discuss and receive feedback not only about the cross-device interaction techniques, but also about the research process and its significance. Moreover, the resulting research paper was anonymously reviewed at CSCW 2022 and received an acceptance decision (Homaeian et al., 2022).

One of the contributions of my RtD project (Chapter 5) is a set of design considerations for cross-device transfer in collaborative sensemaking contexts. They identify aspects of cross-device transfer that should be taken into account as they impact the independent and joint work styles in collaboration. Design considerations that resulted from Project 2 are a theoretical contribution to HCI literature (Wobbrock & Kientz, 2016). They have generative and evaluative potential and their current scope of applicability is the context that I studied, i.e. collaborative sensemaking in an XDE comprised of a large tabletop and personal tablets. As other researchers build on and apply them in other contexts and settings, more knowledge about their generalizability will emerge (Lazar et al., 2017; Wobbrock & Kientz, 2016).

# Chapter 5: Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration

## 5.1 Preface

This chapter presents the accepted paper that is to appear in the Proceedings of the ACM on Human-Computer Interaction (Homaeian et al., 2022), in which I was the primary author. I made minor edits to the paper content to suit the purpose and formatting of this dissertation.

The work presented in this chapter addresses RQ2 and led to Contribution 1: Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration, and Contribution 2: Design considerations for cross-device interaction techniques to support mixed-focus collaboration.

The findings of Project 1 (Chapter 3) inspired me to study how cross-device interaction techniques may be designed to facilitate the flexibility of workstyles in mixed-focus collaboration. I found the mechanics of collaboration (Pinelle et al., 2003) a useful theory to guide the design of such techniques. The theory describes two low-level actions that people use to transfer objects in physical shared workspaces. It has implications for designing transfer techniques for digital shared workspaces. I started by designing cross-device transfer techniques based on my understanding of those design implications. As I engaged in the Research through Design (RtD) (Gaver, 2012; Zimmerman et al., 2007) process, my understanding of the problem, its important aspects, and the problem framing evolved. I conducted the iterative design activities in the RtD process, e.g., brainstorming sessions, user observations with high-fidelity prototypes, and corroboration with HCI literature. The project resulted in five design considerations for cross-device transfer to support mixed focus collaboration, and also a synchronicity framework (adapted from Harris (2019)) to articulate the temporal coordination of transfer in collaborative XDEs.

The development of Joint Action Storyboards (JASs) ((Homaeian et al., 2021), Chapter 6) overlapped with this project. I used JASs to help me understand the impact of the interaction techniques I was designing on collaborative processes, specifically on the grounding process.

When working together, people frequently share information with each other to create a shared understanding and to enable division of labour, assistance, and delegation of responsibility. Sharing of digital information and content is commonly referred to as transfer in the HCI literature and user interfaces and interactions processes that enable such digital sharing are called transfer techniques (Brudy et al., 2019). The literature has explored both synchronous and asynchronous transfer techniques, known as Handoff and Deposit, respectively. However, current cross-device environments tend to only provide a single mechanism. Moreover, we have little understanding of the impact of different techniques on collaborative process. To understand how Handoff and Deposit may be designed to support complex sensemaking tasks, we followed a Research through Design process to iteratively design techniques using paper and digital sketches and high-fidelity prototypes. We consulted the HCI literature to corroborate our findings with studies and descriptions of existing cross-device transfer designs and to understand the potential impact of those designs on mixed-focus collaboration. We learned that as we move away from a restricted physical workspace and leverage the flexibility of digital personal devices, there is a large design space for realizing cross-device transfer. To inform these designs, we provide five design considerations for cross-device transfer techniques: Transfer Acceptance, Action Dependencies, Immediate Usability[3], Interruption Potential, and Connection Actions.

## 5.2 Introduction

Pinelle et al.'s (2003) seminal research introducing the mechanics of collaboration describes two fundamental "mechanics" that collaborators use to transfer task materials, resources, and tools when working together: Handoff and Deposit. Handoff is a synchronous transfer act, like the physical act of handing a piece of paper to a partner. Deposit is an asynchronous act, like leaving the paper on a table for the partner to pick up later at their convenience. These mechanics serve distinct purposes in collaborative activities, like getting a partner's immediate attention versus asking them to review a document later on (Pinelle et al., 2003). They are used to coordinate a transfer temporally, such as through a sequence of actions, as well as spatially, such as when placing an object near to a collaborator (Sutcliffe et al., 2013). Providing different transfer mechanisms in a shared workspace gives collaborators freedom to use contextual factors, such as their current activity, task requirements, or the

[3] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

group's collaboration style to decide how to share task materials with one another in the moment (Liu Jun et al., 2008; Pinelle et al., 2003).

Yet, prior research in Human Computer Interaction (HCI) has largely focused on providing a single transfer technique in a given multi-display environment (e.g. (Biehl et al., 2008; Paay et al., 2017; Wozniak et al., 2016)). So, there is a lack of knowledge about how different transfer techniques impact collaborative processes. For example, if a system only supports Handoff, collaborators may experience frequent interruptions when transfer occurs, or they may hesitate to share data to avoid interfering with a collaborator's individual work. Whereas, if only Deposit is supported, transfer interactions may be more effortful than necessary during times when collaborators are engaged in ongoing discussions around shared content. Similarly, implementation details like how a transfer is initiated — such as when using a physical gesture (Marquardt, Hinckley, et al., 2012; Seyed et al., 2013) or picking and dropping content using a pen (Rekimoto, 1997) — have also been shown to impact a group's ability to work together (Biehl et al., 2008; Gutwin & Greenberg, 1998; Homaeian et al., 2018). Such details are crucial in facilitating coordination in cross-device transfer. In particular, the impacts of design choices, like who is interrupted and to what degree, on collaborative processes are less understood by the HCI community, whereas spatial coordination has been widely studied following the theory of tabletop territoriality (Scott et al., 2004).

To investigate how the design and availability of different cross-device transfer techniques impact collaborative processes, we engaged in a series of design activities following a Research through Design process (Gaver, 2012; Zimmerman et al., 2007; Zimmerman & Forlizzi, 2014). In particular, we designed cross-device transfer techniques within the context of a collaborative sensemaking task. Previous research shows that groups often perform sensemaking tasks in a mixed-focus fashion, comprising joint (tightly coupled) and independent (loosely coupled) work periods and transitions between them (e.g. (Homaeian et al., 2018; Morris et al., 2010; Wallace et al., 2013)). We explored how temporal coordination of Handoff and Deposit can be designed to support mixed-focus collaboration through iterative design activities, observations of user sessions with design prototypes, and corroborating our findings with studies and descriptions of existing cross-device transfer designs and understand the potential impact of those designs on mixed-focus collaboration.

Five design considerations emerged through our research process that highlight key design choices that can impact mixed-focused collaboration during cross-device transfer: C1) Transfer Acceptance, C2) Action Dependencies, C3) Immediate Usability[4], C4) Interruption Potential, and C5) Connection Actions. In this paper, we document our Research through Design process, discuss the often nuanced implications of subtle changes to the design of transfer techniques, and report on how others can use this research to inform the design of cross-device transfer techniques in collaborative environments. The cross-device designs explored in this research were largely based on existing techniques; our emphasis was on understanding the impact of these designs on group work, especially involving mixed-focus collaboration.

In summary, our contributions are:

1. We problematize the impact of cross-device transfer techniques on collaborative process, and the need for more HCI research to explore flexible transfer techniques,

2. We present our Research through Design activities and design reflections on temporal coordination for a co-located collaborative sensemaking task, and

3. We identify five design considerations that can help researchers understand how temporal coordination supports or impedes joint and independent work periods and transitions between them.

## 5.3 Background

In Pinelle et al.'s (Pinelle et al., 2003) description of the mechanics of collaboration transfer is defined as "the movement of objects and tools between people" (Pinelle et al., 2003, p. 292). They identified two distinct mechanics people use to transfer objects and tools in shared workspaces; Handoff and Deposit. Handoff occurs when one person transfers an item to another as a coordinated, synchronized action. In contrast, Deposit is an asynchronous action where one person leaves the item in the shared workspace where it can be retrieved later. In physical workspaces, an object's attributes are fixed and people can maintain awareness of others' interactions with the environment. Therefore, coordinating transfer requires little negotiation and often does not interfere with the task flow (Sutcliffe et al., 2013). However, in computer-based workspaces, designers can control every aspect of where and what one can interact with and how data may be represented. Thus, cross-device transfer techniques have been widely explored by HCI researchers as they have developed more powerful and complex collaborative

[4] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

environments involving multiple displays (e.g. (Marquardt, Hinckley, et al., 2012; Rädle et al., 2014)). This freedom and flexibility can lead to novel techniques that enable new forms of interaction. However, research has shown that even subtle design decisions can impact collaborative processes (Clark & Brennan, 1991; Gutwin & Greenberg, 1998).

Indeed, transfer techniques are deeply connected to the complex processes of communication and coordination, and when developing such techniques, designers navigate a myriad of trade-offs (Homaeian et al., 2018; Wallace et al., 2013). One such trade-off is the well-known tension between the needs of the individual and the needs of the group (Gutwin & Greenberg, 1998); where individuals require independence and groups need awareness, coordination, and communication. A related design concern is how to best utilize the various displays available in cross-device environments during mixed-focus collaboration. Large-screen displays can act as shared reference points in collaborative activities and thus may be a suitable space to show shared data (Wallace et al., 2013). Personal devices, on the other hand, facilitate independent data exploration (Homaeian et al., 2018; W. McGrath et al., 2012). However, as people focus on personal devices for detailed data manipulation they may lose awareness of others' activities in the multi-display workspace (Homaeian et al., 2018; Wallace et al., 2009). It may also be disruptive to have one's partner pause their ongoing activity and attend to shared information.

Yet, we have little understanding of how the design and availability of cross-device transfer techniques ultimately impact collaborative processes. A multitude of transfer techniques have been introduced in the HCI literature (e.g. (Marquardt, Hinckley, et al., 2012; Seifert et al., 2012; Wozniak et al., 2016); see (Brudy et al., 2019) for a review) However, the literature has largely explored the use of transfer mechanics in isolation to each other — That is, either Handoff (e.g. (Paay et al., 2017; Simeone et al., 2013)) or Deposit (e.g. (Hamilton & Wigdor, 2014; Marquardt, Ballendat, et al., 2012)) is available, but rarely the two techniques at once. Notably, Marquardt et al. (2012; 2012) and Ramos et al. (2009) provided both Handoff and Deposit mechanisms in collaborative environments. However, neither research group studied how people employed the transfer techniques during anything beyond simplistic collaborative interactions.

In this work, we elucidate the connections between transfer techniques and collaborative processes. Through the iterative process of design, reflection, and observed user interactions of cross-device transfer techniques, we identify design considerations that help us understand how the user interface design of transfer techniques can facilitate temporal coordination of cross-device transfer and how various design choices may impact collaborative processes.

### 5.3.1 Coordination in Transfer Techniques

The mechanics of collaboration (Pinelle et al., 2003) highlight the high degree of both spatial and temporal coordination to facilitate object transfer in a shared workspace. Collaborators must agree on the timing of transfer and the location where it occurs. Spatial coordination concerns the use of physical and digital workspaces, and has been widely explored in work surrounding territoriality (Scott et al., 2004). For instance, group members may use a distinct, “group” territory when sharing materials on a digital tabletop (Scott et al., 2004) or when working on a large wall display (Wallace et al., 2016). This use of space has been found to apply in many collaborative settings (e.g. (Morris et al., 2010; Ryall et al., 2004; Tang et al., 2006)). Thus, mechanisms for spatial coordination have been widely explored in the literature, for both Handoff and Deposit techniques, such as portals (Hinckley et al., 2004; Marquardt, Ballendat, et al., 2012; Scott et al., 2014), or partial or full views (Hamilton & Wigdor, 2014; Marquardt, Hinckley, et al., 2012; Zagermann et al., 2016).

However, temporal coordination — the sequence of actions executed by the parties to complete the transfer or the degree of synchronicity between the sender and the receiver — is less understood. Many transfer techniques adopt a design pattern where a sender interrupts the person receiving shared information by requiring them to pause their ongoing work. For example, in Pick-and-Drop (Hinckley et al., 2004) the sender initiates the technique on their own device but must interact with the receiver’s screen to finish the transfer. Other techniques automatically update the target display in a potentially disruptive manner. For instance, Face-to-Mirror (Marquardt, Hinckley, et al., 2012), swiping (Paay et al., 2017; Wozniak et al., 2016), flicking (Rädle et al., 2014; Seyed et al., 2013), and pouring techniques (Jin et al., 2015) transfer a full screen or original-sized copy of the item. They do not require a receiver to confirm they are willing to accept shared information, but they do interrupt the receiver by pausing their individual work. These techniques explicitly synchronize collaborators which may be beneficial during tight collaboration. On the other hand, they may hinder independent work periods and transitions to joint work by forcing the receiver to pause ongoing work.

Conversely, other techniques need a lower degree of temporal coordination, by, for example, not requiring the receiver to attend to a shared item immediately. For instance, a portal on the target screen that receives a thumbnail of the shared item (Biehl et al., 2008; Marquardt, Ballendat, et al., 2012) or a partial view of the item that appears on the side of the receiving display (Marquardt, Hinckley, et al., 2012). Such designs give the receiver control over when to reposition and view the full item. Therefore, these techniques implicitly synchronize collaborators, promoting a stronger sense of freedom for the individuals but potentially at the expense of group awareness (Gutwin & Greenberg, 1998).

Existing frameworks for cross-device transfer cover interactions by the sender and receiver to execute transfer (e.g. (Nacenta et al., 2005; Ramos et al., 2009)), though they do not provide guidance on how the specific degrees of synchronicity (described below) of a transfer technique may support or hinder collaborative processes. Nacenta et al. (2005)'s framework categorizes cross-device transfer techniques based on various characteristics, such as: topology of the interaction space, reach range, and implicit privacy concerns. Other frameworks focus on the infrastructure for connecting devices together, for instance by using proxemics of people and devices, (e.g. (Hinckley et al., 2004; Marquardt, Hinckley, et al., 2012; Rädle et al., 2014, 2015)). Radle et al. (2015) classified cross-device transfer techniques into three main categories: techniques that require both parties to perform synchronous gestures on their respective devices (this relates to our design consideration C2 (Action Dependencies)), techniques that leverage spatial positioning of devices in the environment, and techniques that do not rely on such information.

Our design considerations complement those frameworks by capturing the degree of synchronicity between the sender and receiver, and thus how a given cross-device transfer may foster or hinder tightly and loosely coupled work styles and transitions between them, whether or not the underlying environment is spatially aware or spatially agnostic. Moreover, the degrees of synchronicity provide (1) a way to categorize cross-device transfer techniques based on their impact on mixed-focus collaboration, and (2) a language for researchers to articulate and understand the design space of cross-device transfer design.

### 5.3.2 Degrees of Synchronicity

We adapted a framework developed by Harris (2019) to understand and articulate temporal coordination in multi-device environments. The original framework articulates the timing and duration of interaction between players in cooperative games. They define degrees of synchronicity that describe how in-game actions can be coordinated between players. We adapt the definition as "the sequence of actions by the sender and receiver until the receiver can use the item without any further interaction with the interface”. Below are degrees of synchronicity for cross-device transfer, as adapted from Harris’s original framework (Harris, 2019):

1. Instant coordination occurs when the sender can both initiate and complete the transfer through their action(s) and the receiver does not have to interact with the interface before using the item. For instance, Face-to-Mirror (Marquardt, Hinckley, et al., 2012) and Slam-to-Share (Grønbæk et al., 2020) automatically update the target screen by displaying a shared picture in full-screen and original size, respectively.
2. Expectant coordination occurs when the sender initiates transfer, and are then held up until the receiver completes the transfer. For example, in Rhythmic tapping (Shibata et al., 2016), two collaborators perform a sequence of actions to execute transfer.
3. Sequential coordination requires the sender to initiate transfer. The receiver then has a fixed amount of time to complete the transfer. For example, in Collaborative Handoff (Marquardt, Ballendat, et al., 2012) and Stitch+Lift (Ramos et al., 2009), the item is transferred to a portal on the target display and the sender must accept the item by repositioning it.
4. Asynchronous coordination occurs when the sender initiates transfer and sometime later the receiver can attend to the transferred item to use it. For example, with Impromptu (Biehl et al., 2008), a thumbnail of a shared window appears on a portal on the target device. It is then up to the receiver when to open the window and view the document.

We omit the Coincident and Concurrent degrees of Harris’ original framework, as our research did not uncover any transfer techniques that used those degrees of synchronicity (i.e., sender and receiver performing actions at exactly the same time, either instantaneously or for some duration of time, respectively). Note, our degrees of synchronicity apply to the process of content transfer only. Actions required to connect devices to enable content transfer may require coincident or concurrent interactions, for instance, holding two devices together to enable content transfer between them (e.g. Bumping (Hinckley, 2003a)) or Tilt-to-Preview (Marquardt, Hinckley, et al., 2012)). We also added the Instant degree of synchronicity to account for transfer techniques that require no actions from the receiver to access or use transferred content.

In this work, we articulate how degree of synchronicity can inform the design of cross-device transfer techniques. In particular, we identify five design considerations that emerged as a part of our Research through Design process. These design considerations highlight the potential impact of a given temporal coordination design on collaborative processes. Our design considerations complement work by Ramos et al. (2009) by offering insight on how any of the four choices of synchronicity in temporal coordination of transfer may impact the phases of mixed-focus collaboration.

## 5.4 Methodology

There is a lack of knowledge in HCI literature regarding the impact of cross-device transfer techniques on collaborative processes (Homaeian et al., 2018, 2021). Even though Handoff and Deposit provide unique functions in supporting collaborators (Pinelle et al., 2003; Sutcliffe et al., 2013), existing work tends to provide only one mechanic of transfer in cross-device environments. Meanwhile, even subtle changes in the interface design could impact how people use technology to conduct group work (Gutwin & Greenberg, 1998). Moreover, various factors impact group work around technology, like task settings and group dynamics (Janis, 1982). We therefore decided on a Research through Design approach (Gaver, 2012; Zimmerman et al., 2007) to study this underexplored area, since it would enable us to:

- consider the conflicting needs of individuals and groups (Gutwin & Greenberg, 1998) that likely prevent an optimal solution for cross-device transfer,
- iteratively design, reflect, and reframe the problem as we develop an understanding of the design space, and
- identify questions that should be asked during the design process (Zimmerman & Forlizzi, 2014).

A key outcome of Research through Design is the documentation of our process (Dove et al., 2016; Zimmerman & Forlizzi, 2014). This documentation increases our awareness (Dove et al., 2016) of how constraints shaped the design of our Handoff and Deposit techniques and impacted our design choices. For instance, we paid particular attention to how Handoff and Deposit actions may be temporally and spatially coordinated (Sutcliffe et al., 2013) in the system, and aimed to design transfer techniques to provide a reasonable balance between the needs of individual collaborators (i.e., freedom and power within the system) and the needs of the group (i.e., awareness of others' activities in the environment) (Gutwin & Greenberg, 1998). Our designs were also inspired by the mechanics of collaboration (Pinelle et al., 2003) which describe how transfer takes place in physical shared workspaces. The documentation also provides information about discarded options given our research design context and, thus, could encourage exploratory research and reconsidering the opportunities that were filtered away in other contexts (Dove et al., 2016).

### 5.4.1 Design and Technology Contexts

We adapted our existing experimental cross-device platform designed to support a mixed-focus sensemaking task for two people (Homaeian et al., 2018). The experimental task involved joint analysis and decision-making around provided geospatial data. We re-architected the task to include a larger variety of information sources, and to encourage information sharing between two expert roles through a hidden profile task (Stasser & Titus, 2003). In this section, we only describe the configuration of the system and the features of the experimental task that are relevant to the research reported in this paper. Additional details about the system are provided in the supplementary materials.

The platform, which comprised a large interactive tabletop and two personal tablets, was designed to support a pair of collaborators seated at adjacent sides of the tabletop. The two tablets and the tabletop were configured to be automatically and by default connected through Wi-Fi. In this context, collaborators were trusted peers and had permission and authority to transfer data to each other's devices without any authentication actions. Our investigation focused on cross-device transfer between the tablet displays; transfer between the tabletop and tablets was left for future study.

## 5.5 Research through Design Activities

Our Research through Design process comprised three phases (Table 5-1). First, we developed low fidelity paper and digital prototypes with a focus on how they impede or support collaboration (Gaver, 2012; Zimmerman & Forlizzi, 2014). These prototypes allowed us to rapidly reflect on and critique our designs and consider their potential advantages and disadvantages, through discussion and feedback sessions with HCI experts and HCI trainees. Second, we developed high-fidelity prototypes that we used to explore the impact of our Handoff and Deposit techniques on mixed-focus collaboration. Third, we corroborated our findings with transfer techniques from the HCI literature to obtain a broader understanding of temporal coordination issues in cross-device transfer and the potential impact of degrees of synchronicity on collaborative processes.

**Table 5-1. Project 2. Our Research through Design comprised 6 iterative design activities grouped into three phases based on instruments used. In each activity, we gained insights about designing Handoff and/or Deposit techniques to support mixed-focus collaboration. The outcome of each activity informed the next design activity. In each phase, our insights and outcomes led to design considerations for designing Handoff and Deposit**

| Instruments | Design activity | Insights | Outcomes | Design Considerations |
|---|---|---|---|---|
| Paper and digital sketches | 1. Handoff Design | Sender is held up in transfer to grab Receiver's attention | Designed Handoff with partial view | C1: Transfer Acceptance |
| | 2. Deposit Design | Portals support spatial coordination of transfer | Re-designed the tablet interface and a Deposit technique | C2: Action Dependencies |
| | 3. Handoff Alternative | The interface can grab Receiver's attention. So, Sender does not have to be held up | Designed Freeze-Handoff and refined the tablet interface | |
| High-fidelity prototypes | 4. User observations with Deposit and Freeze-Handoff | Freeze-Handoff was perceived as intrusive and thus was avoided | Designed Fullscreen-Handoff | C3: Immediate Usability[5] |
| | 5. User observations with Deposit and Fullscreen-Handoff | Showing data immediately to Receiver reduces collaborative effort | Found Deposit and Fullscreen-Handoff were both used, in different situations | C4: Interruption Potential |
| HCI literature | 6. Corroboration | Our design considerations impact the degree of synchronicity between Sender and Receiver | Created design considerations | C5: Connection Actions |

We started designing Handoff and Deposit techniques based on the mechanics of collaboration (Pinelle et al., 2003). Throughout our Research through Design process, we gained and developed an understanding of the theory's limitations when it comes to facilitating temporal coordination of Handoff and Deposit in our digital environment. Adapting Harris's framework (2019) was helpful for us to better understand and articulate the constraints in our design research problem.

[5] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

The cross-device transfer designs we created during the process of this research are based heavily on existing techniques from the literature in terms of their degrees of synchronicity. The user interface of our techniques, however, was different. The focus of our research was to better understand how the design features of these techniques support or hinder mixed-focus collaboration, and thus, we consider their impact on individual interactions, joint group interactions, and transitions from loosely coupled to tightly-coupled work periods.

### 5.5.1 Paper and Digital Sketches

We began by iteratively generating numerous designs for Handoff and Deposit using digital and paper sketches (Figure 5-1). The sketches facilitated communicating our designs to others and rapid design revisions at early stages of the research. Insights gained in this phase about who might be held up (sender and/or receiver) during transfer in mixed-focus collaboration led to the development of C1 (Transfer Acceptance) and C2 (Action Dependencies). These design considerations draw attention to interactions needed by the sender and/or receiver with the interface to perform a transfer.

**During our Initial Handoff Design** (Figure 5-1, Design Activity 1), we discussed the roles of the sender and receiver in Handoff and Deposit in a physical environment. We determined that temporal coordination in Deposit follows an Asynchronous pattern. It can also require fewer interactions compared to Handoff as the sender leaves the item somewhere in the environment for later retrieval by the receiver. However, Handoff has an Expectant degree of synchronicity; the sender is held up in Handoff as they hold an item and wait for the receiver to accept or reject it. This situation creates social pressure on the receiver for a timely response. Thus, our initial design idea for Handoff (Figure 5-1) was a technique that paused the ongoing work of the receiver and updated the display to show the transferred item. Design alternatives considered included showing a full screen or partial view of the item. We decided the latter was a more reasonable design choice as it did not invade the receiver's personal territory, similar to physical Handoff, which often occurs in a shared space rather than in personal territories (Sutcliffe et al., 2013). This design is similar to Tilt-to-Preview (Marquardt, Hinckley, et al., 2012), which requires the sender to tilt and touch an image so that a partial view is sent to the target screen. However, our technique did not rely on collaborators' devices being in close proximity nor being tilted to enable content transfer.

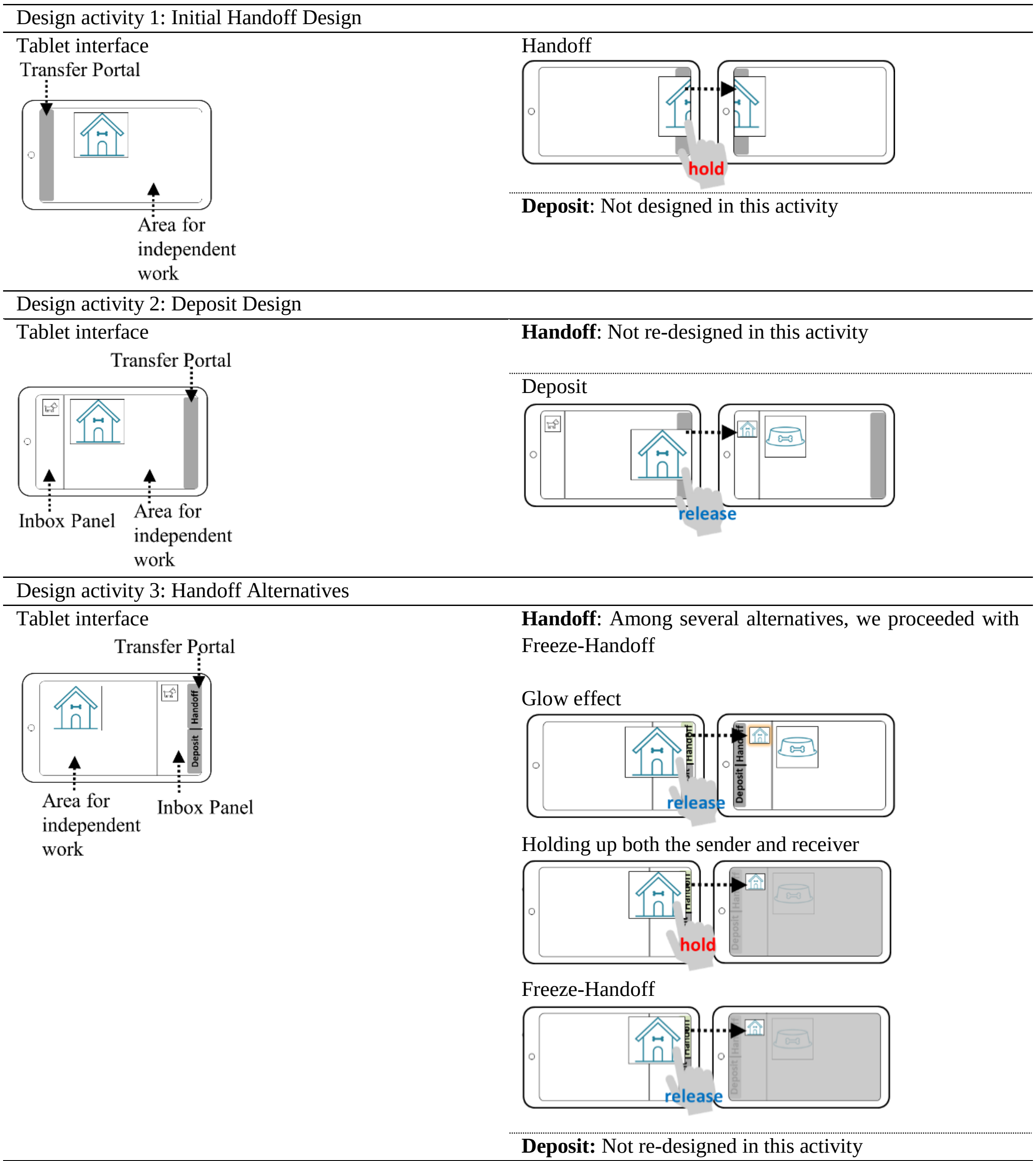



**Figure 5-1. Project 2. Our iterative design activities in Phase 1 using paper and digital sketches. The design of our tablet interface, and Handoff or Deposit techniques in each activity evolved as our framing of the design problem developed. For each activity, the resulting designs are illustrated. Note that in some activities, the design of Handoff or Deposit techniques did not change**

We felt this design provided a reasonable balance between the needs of the individual (the receiver) and the group (both sender and receiver). The partial view keeps the sender aware that part of the item is visible on the target screen, and it makes the receiver aware of the data transfer while not substantially changing their current view (reducing interference). Thus, the design had the potential to support loosely coupled work periods and shifts to tightly coupled work. However, our initial design discussions identified several factors related to temporal and spatial coordination of both Handoff and Deposit. Forexample, there were open questions related to the location of transferred items, the distinction between transfer techniques on home and target screens, and so on. Thus, we proceeded with a brainstorming session with people outside of our group to hear more diverse perspectives on designing a Deposit technique given the above factors impacting collaboration and given our initial Handoff design.

**For a Deposit Design** (Figure 5-1), we held a brainstorming session with three HCI trainees to gather ideas on how we could incorporate a Deposit technique into our tablet interface. The small group size allowed us to lead a focused discussion and hear from all participants. Our participants identified previous research that showed when people work around a table, they usually hesitate to take items from or put them in a partner's personal work space (Ryall et al., 2004; Scott & Carpendale, 2010). Also, people naturally avoid interfering with each other in shared spaces by spatially separating their work (Tse et al., 2004). Therefore, we redesigned the tablet interface to have three distinct areas to support content sharing and independent work.

An inbox panel and a portal (Figure 5-1, Design Activity 2, Tablet interface) facilitated spatial coordination of cross-device transfer (Sutcliffe et al., 2013) similar to the idea of virtual portals (Fei et al., 2013; Scott et al., 2017); a thumbnail of a shared item would appear on the panel in Deposit (Figure 5-1, Deposit Design). Other techniques such as Collaborative Handoff (Marquardt, Ballendat, et al., 2012) and some Cooperative Stitching Gestures (Ramos et al., 2009) also send a thumbnail or notification to a portal on the target screen upon transfer. However, our Deposit technique did not impose a time limit nor require acceptance by the receiver. The technique synchronized the sender and receiver in an Asynchronous manner, as the receiver could retrieve the thumbnail at their convenience. We felt the Deposit design would foster independent work as it did not interfere with any ongoing interactions in the tablet's main workspace. The sender could also release the touch gesture and continue their ongoing work.

**To create Handoff Alternatives** (Figure 5-1), we first integrated our Initial Handoff design into the redesigned tablet interface and then presented it to another, larger group of two HCI experts and twenty HCI trainees for feedback on our design and to help generate ideas for potential Handoff design alternatives. An insight we gained through this activity was that in physical Handoff, the receiver could be held up as well as the sender. The receiver is aware their partner is waiting for a response. Social protocols could create pressure for them to react promptly. Therefore, it is important to consider whether the receiver may also be held up as they pause their ongoing work to accept or reject the shared item.

This insight led to the development of design considerations C1 (Transfer Acceptance) and C2 (Action Dependencies). Transfer Acceptance (C1) draws attention to whether transfer should be permitted by default or if the receiver must accept or reject the transfer. The latter design approach may be selected, for instance, if security and privacy are matters of concern in the expected usage context. Action Dependencies (C2) refers to whether the user interface holds up any party by requiring one or both to perform a series of actions to initiate and/or complete the transfer. A relevant context for C2 is where asymmetric roles exist, for instance a teacher-student relationship, and the sender wants to ensure the shared item is attended to immediately.

Following the insights that led to C1 and C2, we considered alternative Handoff designs that hold up the sender, receiver, or both. We drew inspiration from existing transfer techniques in terms of their degrees of synchronicity and considered them through the lens of the theory of mechanics of collaboration. For example, the Stitch+Hold (Ramos et al., 2009) technique holds up the sender until the recipients accept the connection. Rhythmic Tapping (Shibata et al., 2016) holds up both parties as they perform a series of gestures to establish a connection between devices. Similar to our Freeze-Handoff, AirDrop holds up the receiver and asks them to accept or reject the transfer when sending content to an iPhone with a different Apple ID. Our technique transfers a thumbnail of the item and then halts the screen until the receiver drags the item off their inbox panel. AirDrop, however, shows a pop-up window notifying the receiver of a pending transfer.

Careful reflection on those options revealed new insights on operationalizing the mechanics of collaboration in our digital workspace. The digital context enables us to get the receiver's attention and, thus, alleviate some effort on the sender's side. That is, it may not be necessary to hold up the sender. Although techniques that hold up the sender may be more consistent with people's mental model of how they transfer physical objects, we believed that in our peer collaboration context holding up the sender would be unnecessary and potentially effortful.

Given these trade-offs, we decided to proceed with a Handoff design that only holds up the receiver by potentially interrupting them (Figure 5-1, Freeze-Handoff). Freeze-Handoff adopts the Sequential degree of synchronicity; after the sender initiates the Handoff by placing an item on their "Handoff" portal, the receiver must move the thumbnail off their inbox panel into their main workspace to complete the transfer, and before they can either continue with any ongoing work in their main workspace or enlarge the transferred image to view it full-size. Thus, the receiver would be interrupted during independent work or transitions to joint work. However, we did not anticipate interruptions during joint work periods since the receiver would be expecting the transfer and the associated update to their screen.

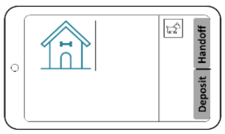
At this point, we felt that our Handoff and Deposit transfer designs would provide flexible means for groups to share data in a mixed-focus collaboration context. Our design activities with our sketch-based prototypes indicated that our Deposit design would support loosely coupled work periods as it showed a thumbnail of the item but did not hold up the receiver—they could use the transferred item at their convenience. The Freeze-Handoff design would support tightly coupled work and transitions to tightly coupled work as it grabbed the attention of the receiver without covering their independent work area. Thus, we proceeded to develop high-fidelity prototypes to enable observation of user interactions with our techniques to help better understand how they supported or hindered collaboration and to facilitate further design refinement.

### 5.5.2 High-Fidelity Prototypes

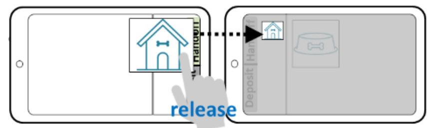
We conducted two rounds of user observations (Figure 5-2) involving four different pairs of collaborators (two per round) (5 male). The participants were between the ages of 20-45. Seven were graduate students; six in Engineering or HCI, one in Applied Health Sciences. One participant was a software engineer. Each pair used our high-fidelity prototypes to complete a collaborative sensemaking task in approximately 45 minutes. The pairs in the first round used Freeze-Handoff and Deposit techniques (Figure 5-2, Design activity 4). The pairs in the second round used Fullscreen-Handoff and Deposit techniques (Figure 5-2, Design activity 5). During each session, the first author and the software developer who implemented our prototypes observed the sessions and took notes. At the end of each session, the first author conducted an informal interview to further understand participant behaviour. In all four sessions, groups completed the experimental task using a mix of joint and independent work periods, dominated by long periods of joint work. We elaborate further on these activities below.

Design activity 4: User observations with Deposit and Freeze-Handoff

Tablet interface*




Freeze-Handoff*



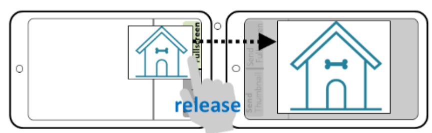

Deposit*


*These designs did not change in this activity. They are the same designs as in Activity 3 (Figure 5-1). The pictures are placed in this figure for easier readability.

Design activity 5: User observations with Deposit and Fullscreen-Handoff

Tablet interface

Fullscreen-Handoff




**Deposit**: Not redesigned for this activity (remained the same as Deposit in Activity 4)

**Figure 5-2. Project 2. Our iterative design activities in Phase 2 using high fidelity prototypes. The tablet interface, Handoff and Deposit techniques in each prototype are illustrated. Note that our Deposit technique remained the same for both activities**

**In our User observations with Deposit and Freeze-Handoff**, to our surprise, participants hesitated to use Freeze-Handoff, even during tightly coupled joint work periods, when we expected this technique to be used. The interviews revealed that participants perceived the technique as intrusive. They reported that they did not want to force the receiver to pause their ongoing work to attend to the transferred data. We carefully reflected on how Freeze-Handoff placed responsibility for temporal coordination on the sender: Freeze-Handoff automatically interrupts the receiver by halting their screen and highlighting the thumbnail in their inbox panel. While in a physical environment, Handoff is likely to be quickly received due to social pressure on the receiver, there is also some flexibility in the timing of when the receiver must accept it. In Freeze-Handoff, however, the interface did not allow such flexibility: as soon as the sender completed the interaction, the receiver's screen was interrupted, and the only possible action was dragging the thumbnail off the inbox panel to the independent work area of the screen.

Since Freeze-Handoff was avoided, our participants used Deposit to achieve the intended goal of "Handoff", that is, in situations when the receiver immediately attends to the transferred item. However, when Deposit was used during tightly coupled work, a group's conversation was often disrupted while the receiver moved the data item off the inbox panel to their independent work area and then enlarged it to view its details. This disruption made the Deposit technique effortful for the group during tightly coupled work periods.

The above observations led us to reconsider a design alternative disregarded in our Initial Handoff Design: transferring a full-screen version of the item in Handoff. In this design approach, the ongoing work of the receiver is still interrupted (like Freeze-Handoff). However, there is a benefit that potentially mitigates the interruption in transitions to joint work: the group can immediately start a discussion around the data without the receiver needing to move and/or enlarge a shared image to a legible size. Moreover, when transfer occurs as part of ongoing tightly coupled work, the receiver can immediately view the details of the shared data without having to first enlarge it. These insights led to the third design consideration C3 (Interruption Potential), which describes the potential benefits and drawbacks of automatically interrupting the receiver.

Therefore, we revised Freeze-Handoff to immediately show data full-size on the receiver's workspace. We called this design alternative Fullscreen-Handoff (Figure 5-2). Other techniques that transfer a full-size copy of the item include Face-to-Mirror (Marquardt, Hinckley, et al., 2012) and Slam-to-Share (Grønbæk et al., 2020). Our technique differed from those in that it grayed out the tablet screen and then showed the enlarged item. Based on participant use of Deposit in the first round of observations, we predicted that Fullscreen-Handoff would support the flow of an ongoing discussion and, thus, joint work periods in mixed-focus collaboration. Fullscreen-Handoff synchronizes the sender and receiver in an Instant manner; as soon as the sender completes transfer on their side, the system shows the item in full screen on the target device without the need for further interactions by the receiver.

**In our User observations with Deposit and Fullscreen-Handoff**, the system incorporated Fullscreen-Handoff (Figure 5-2, Design Activity 5). In the first user session, we labelled Handoff as "Quick Share" and Deposit as "Send thumbnail". We observed that the group used Fullscreen-Handoff more frequently than Deposit. We were concerned that the name "Quick share" might have biased people to use the technique more frequently. Thus, before the second session, we renamed Handoff to be "Send fullscreen" to more accurately describe its function (Figure 5-2, Design activity 5, Tablet interface). Even with this change, participants in the second session still used Handoff more often than Deposit, providing us more confidence that use of this feature was not likely biased by the label.

As we predicted, Fullscreen-Handoff was used during joint work periods, especially when groups discussed specific solutions and data. In such cases, the receiver would sometimes ask their partner to send data using the full screen option. The fact that the image was immediately usable, i.e., large enough for the image/graph details to be legible, afforded an effective conversational flow. In other words, the design supported tightly coupled work periods by displaying the content immediately and without further need to interact with the user interface. Conversely, Deposit allowed participants to respect the ongoing work of their partners by only sending a thumbnail of the item to avoid disrupting ongoing work. Thus, as we expected, people used Deposit primarily during independent work periods.

These observations led to the development of our fourth design consideration C4 (Immediate Usability[6]). This design consideration provides insights on how joint work periods may be facilitated by making a transferred item readily usable upon transfer and, thereby, reducing disruption —and potentially the collective effort—during the transfer process.

## 5.6 Discussion and Corroboration with the Literature

As the final activity in our Research through Design process, we reviewed prior studies and descriptions of existing cross-device transfer designs from the HCI literature to corroborate our design considerations and understand the potential impact of those designs on mixed-focus collaboration. This activity provided a broader perspective on how our design considerations might apply to transfer techniques beyond those we studied in the Research through Design activity. Our goal was to identify potential inconsistencies with design issues discussed in the literature and uncover any gaps in our

[6] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

design considerations that might be highlighted by design features of other transfer techniques. Through this process we mapped our design considerations to existing techniques from the literature (Table 5-2), and in doing so, discovered a need for an additional design consideration related to connectivity in multi-device environments.

This corroboration activity led us to adapt Harris's (2019) framework to understand and articulate the degree of synchronicity between collaborators in cross-device transfer, and to include a design consideration around the Connection Actions (C5) required to establish a multi-device environment. As Brudy et al. (2019) point out, cross-device interaction techniques could have a connection establishment phase to prepare and authorize devices for content transfer. Researchers have identified a broad array of such actions, including explicit interactions with the interface or both devices (Hinckley, 2003a; Nacenta et al., 2005; Tandler et al., 2001), implicit actions such as taking a device out of a pocket (Nacenta et al., 2005), explicit movement of devices in the environment (Marquardt, Ballendat, et al., 2012; Marquardt, Hinckley, et al., 2012; Nacenta et al., 2005; Rädle et al., 2015), and authorizing a technique to transfer content to the receiving device (Biehl et al., 2008; Ramos et al., 2009). This design consideration was not apparent in our Research through Design process, as devices in our high-fidelity prototype maintained a permanent, trusted connection upon application start-up. Synthesizing our work with the literature allowed us to explore a wider variety of device capabilities and task and user requirements. Connection actions are a useful consideration in designing transfer techniques where privacy concerns exist. Design details such as revealing content that can be shared or devices that are available for connection might encourage data sharing (Marquardt, Ballendat, et al., 2012; Ramos et al., 2009).

Our corroboration activity also enabled us to reflect on and refine our definitions for each design consideration, to consider how different techniques from the literature have implemented different design concepts within the design space, and how those design choices ultimately impact the degree of synchronicity of collaborative processes.

**Table 5-2. Project 2. Design considerations for temporal coordination in cross-device transfer techniques. Our corroboration with the HCI literature revealed a gap, which led to C5 and adaptation of a framework** (Harris, 2019) **for articulating the degree of synchronicity in cross-device transfer. Our Deposit and Handoff techniques and some representative techniques are shown with respect to how they address C1-C5, their degree of synchronicity and their likely impact on mixed-focus collaboration**

| | Design Considerations | | | | | | |
|---|---|---|---|---|---|---|---|
| Example Techniques | C1: Transfer Acceptance | C2: Action Dependencies | C3: Immediate usability[6] | C4: Interruption Potential | C5: Connection Actions | Degree of synchronicity | Likely to support |
| Fullscreen Handoff (Figure 5-2), Slam-to-Share (Grønbæk et al., 2020), Flicking (Rädle et al., 2014; Seyed et al., 2013), Superflick (Reetz et al., 2006) | | | • | • | | Instant | |
| Bumping (Hinckley, 2003a, 2003b), Smart-Its Friends (Holmquist et al., 2001), ConnecTable (Tandler et al., 2001), Pick-Drag-and-Drop (Rädle et al., 2014) | | | • | • | • | Instant | Tightly coupled work |
| Face-to-Mirror (Marquardt, Hinckley, et al., 2012) | optional | • | • | • | • | Instant | |
| Rhythmic tapping (Shibata et al., 2016) | • | • | | | | Expectant | |
| Tilt-to-preview (Marquardt, Hinckley, et al., 2012), | optional | • | | | • | Expectant | |
| Stitch+Hold (Ramos et al., 2009) | • | • | | | • | Expectant | Transitions |
| Stitch+Lift (Ramos et al., 2009), Broadcasting-cues (Hamilton & Wigdor, 2014), Corresponding gestures (Nacenta et al., 2005), PicknDrop, Menu (Zagermann et al., 2020) | • | | | | | Sequential | |
| AirDrop* (when sending content to iMac or MacBook with a different Apple ID), Collaborative Handoff (Marquardt, Ballendat, et al., 2012) | • | | | | • | Sequential | Loosely coupled work |
| Portals (Marquardt, Hinckley, et al., 2012), IMPROMPTU (Biehl et al., 2008), Our revised Deposit Figure 5-2, Portfolio (Brudy et al., 2020), Tray (Zagermann et al., 2020) | | | | | | Asynchronous | |
| Freeze-Handoff (Figure 5-2) | | | | • | | Sequential | Was found ineffective |
| AirDrop* (when sending content to an iPhone with a different Apple ID) | • | | | • | • | Sequential | Likely to be ineffective |

*: AirDrop sends a non-blocking notification to iMac and MacBook devices, whereas notifications sent to an iPhone block the receiver from interacting with other parts of screen.

This corroboration activity led us to adapt Harris's (2019) framework to understand and articulate the degree of synchronicity between collaborators in cross-device transfer, and to include a design consideration around the Connection Actions (C5) required to establish a multi-device environment. As Brudy et al. (2019) point out, cross-device interaction techniques could have a connection establishment phase to prepare and authorize devices for content transfer. Researchers have identified a broad array of such actions, including explicit interactions with the interface or both devices (Hinckley, 2003a; Nacenta et al., 2005; Tandler et al., 2001), implicit actions such as taking a device out of a pocket (Nacenta et al., 2005), explicit movement of devices in the environment (Marquardt, Ballendat, et al., 2012; Marquardt, Hinckley, et al., 2012; Nacenta et al., 2005; Rädle et al., 2015), and authorizing a technique to transfer content to the receiving device (Biehl et al., 2008; Ramos et al., 2009). This design consideration was not apparent in our Research through Design process, as devices in our high-fidelity prototype maintained a permanent, trusted connection upon application start-up. Synthesizing our work with the literature allowed us to explore a wider variety of device capabilities and task and user requirements. Connection actions are a useful consideration in designing transfer techniques where privacy concerns exist. Design details such as revealing content that can be shared or devices that are available for connection might encourage data sharing (Marquardt, Ballendat, et al., 2012; Ramos et al., 2009).

Our corroboration activity also enabled us to reflect on and refine our definitions for each design consideration, to consider how different techniques from the literature have implemented different design concepts within the design space, and how those design choices ultimately impact the degree of synchronicity of collaborative processes.

### 5.6.1 Design Considerations for Temporal Coordination in Cross-Device Transfer

We identified five design considerations that articulate how one may support temporal coordination when designing a cross-device transfer technique (Table 5-2). The design considerations draw attention to how specific design choices in the interface design of a transfer technique may impact the way people use technology during mixed-focus collaboration. The way a given transfer technique addresses each design consideration creates a certain degree of synchronicity, which can help HCI researchers and practitioners predict how a cross-device transfer technique may affect collaborative processes.

**C1: Transfer Acceptance**

It is important to consider whether a transfer technique requires the receiver to explicitly accept an item before it is transferred to their device. Designers should use the expected collaborative context to guide this decision. For example, if trust and privacy are of key concern, the receiver could be required to explicitly permit the transfer to occur (Doeweling et al., 2013; Nacenta et al., 2005; Ramos et al., 2009). In this case, the target device could temporarily receive the item and notify the receiver (e.g. (Marquardt, Ballendat, et al., 2012)). In our peer collaboration context, we assumed that parties are permitted to transfer content to each other's devices (Ramos et al., 2009). Therefore, our Freeze-Handoff, Deposit, and Fullscreen-Handoff designs all allowed the system to automatically accept the transfer. In other cases, it may be appropriate to have explicit steps to enable this "trusted" status for the duration of the collaborative session (in conjunction with Connection Actions (C5)).

**C2: Action Dependencies**

It is also important to consider whether a sender or receiver must await the other's actions during transfer. In physical workspaces, a sender simply needs to decide between a (synchronous) Handoff and (asynchronous) Deposit (Pinelle et al., 2003). Digital workspaces afford a wider array of potential designs that may or may not require explicit synchronization between the sender and receiver (Nacenta et al., 2005; Ramos et al., 2009). For example, in a classroom setting, a teacher may want to ensure that items sent to students are attended to promptly. Whereas in contexts like collaborative sensemaking where there are periods in which collaborators work independently, it may be inappropriate to hold up a collaborator and, thus, an asynchronous transfer may be more appropriate.

**C3: Immediate Usability[7]**

This design consideration refers to whether the receiver can use the transferred item with no further interface interactions, e.g. opening a file, enlarging or repositioning an image. Immediate Usability[7]may or may not be desirable, depending on the task context. For instance, when transitioning from loosely coupled to tightly coupled work, showing an enlarged version of the shared item may be disruptive to ongoing independent work. Scott et al. (2017) assert that designing the post-transfer state of shared content is highly dependent on contextual factors, such as the task requirements. Our research showed

---

[7] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

that displaying the shared item in an immediately usable format during joint work periods was advantageous for the collaboration flow. Indeed, some participants in our user sessions asked their partner to share content in full screen format to facilitate ongoing conversations and joint analysis.

In other situations, some participants chose Fullscreen-Handoff transfer over Deposit to send data during joint discussions to assist the receiver in immediately viewing the data. Such assistive behaviour fosters communication grounding (Homaeian et al., 2021) and facilitates tightly coupled work (Homaeian et al., 2018; Isenberg et al., 2012). Given the potentially disruptive nature of automatically displaying a large item on the receiver's screen, this design consideration should be considered in concert with C4 (Interruption Potential). The trade-offs of a given transfer design being helpful in some moments and potentially disruptive in others suggests the benefit of providing flexible transfer techniques in collaborative multi-device environments, similar to physical shared workspaces in which people can use different transfer mechanics (Pinelle et al., 2003).

**C4: Interruption Potential**

It is also important to consider whether a transfer technique has the potential to interrupt a receiver's ongoing, independent work, and whether that is desirable. Many existing cross-device transfer techniques such as Face-to-Mirror (Marquardt, Hinckley, et al., 2012), Pick-Drag-Drop (Rädle et al., 2014), and Slam-to-Share (Grønbæk et al., 2020) adopt a pattern where the receiver is automatically interrupted upon transfer. Whether such interruptions are appropriate highly depends on the context and flow of the collaborative activity. Interrupting the receiver's ongoing work by automatically opening a transferred item in their main workspace might disrupt important work (Homaeian et al., 2018, 2021), and require them to cognitively reorient to the new work context. On the other hand, it might minimize overall interaction effort for a group already engaged in tightly coupled work. In some contexts, it might be sufficient for the sender to time the interruption using social protocols.

**C5: Connection Actions**

Collaborators may enable cross-device transfer in a number of different ways (Brudy et al., 2019). For instance, Bumping (Hinckley, 2003a) and ConnecTable (Tandler et al., 2001) require collaborators to place their devices physically together to enable cross-device transfer. On the other hand, proxemics-based techniques might only require devices to be nearby, in the same social or conceptual space (e.g. (Marquardt, Ballendat, et al., 2012; Rädle et al., 2014; Segerstad & Ljungstrand, 2002)). Whereas techniques like our high-fidelity prototypes may rely upon a connection being established once at the beginning of a collaborative session, and then rely on virtual interfaces like portals to facilitate transfer. Requiring explicit connection actions before a transfer can be initiated adds additional time and effort to the transfer process and, thus, will likely be disruptive to ongoing, tightly coupled work. Minimizing such connection actions, even temporarily, in contexts when multiple transfers may be desired during periods of tightly coupled work would help to facilitate collaboration.

### 5.6.2 Impact of Degrees of Synchronicity on Collaboration

As part of our corroboration activity, we found that examining the degree of synchronicity of different transfer techniques helped to identify the phases of mixed-focused collaboration they were most likely to support. The degrees of synchronicity are four ordinal values for grouping cross-device transfer techniques. Notably, they also provide a vocabulary to talk about the impact of given techniques on collaborative processes. Further, our corroboration activity helped reveal how different techniques might complement each other and what shortcomings they may have for transferring content across personal devices. Mapping transfer techniques to degrees of synchronicity (Table 5-2) provides a vocabulary for communicating the likely impact of a given technique or set of techniques on the different phases of mixed-focus collaboration.

Transfer techniques that utilize Instant synchronicity enable the transferred item to be readily usable (C3, Immediate Usability[8]) without the need for further interactions on the target display. Thus, such techniques are likely to support active discussions during tightly coupled work (Homaeian et al., 2018, 2021). Note that any technique with Instant synchronicity would check off C3 in Table 5-2. However, it would not necessarily have Interruption Potential (C4). Consider the case of sharing audio content. Playing an audio on the target device does not have to update the screen and, thus, the receiver could carry on with independent visual work while listening to the audio. Another example would be sharing small images like icons that could open in a way that do not block the work area of the receiver.

Cross-device transfer techniques that adopt an Asynchronous pattern are likely better suited to supporting loosely coupled work periods in mixed-focus collaboration. Previous research has found that interaction techniques that give individuals freedom to perform their tasks without having to depend on or interrupt their partner facilitate loosely coupled work (Homaeian et al., 2018; Jamil et al.,

[8] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called ‘Immediately Usable’, as ‘usability’ has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

2011). Techniques with Asynchronous synchronicity give the receiver the power to complete, or pause, their current task before attending to the transferred data.

Techniques that adopt Expectant or Sequential synchronicity are likely to support transitions to loosely coupled work periods. Such techniques can be designed in a way that do not interrupt the independent work of the receiver and allow them to develop awareness of the transfer. Thus, the receiver can quickly wrap up their work and then attend to the transfer. With Expectant synchronicity, there is social pressure on the receiver (since the sender awaits their response) and therefore, they may feel pressured to respond quickly. Therefore, we believe techniques adopting Expectant synchronicity (e.g. Stitch-and-Hold (Ramos et al., 2009) and Tilt-to-Preview (Marquardt, Hinckley, et al., 2012)) are closer to 'Likely to support tightly coupled work' compared to those adopting Sequential synchronicity (e.g. Collaborative Handoff (Marquardt, Ballendat, et al., 2012) and Corresponding Gestures (Nacenta et al., 2005)), in which the receiver has a predefined, and reasonable, amount of time to react to the transfer. Since the sender is not held up waiting for the receiver the complete the transfer with Sequential synchronicity, they are free to return to independent work, as desired. So, these techniques are closer to 'Likely to support loosely coupled work'.

## 5.7 Reflection on Our Research through Design Process

Criteria for contributions made by a Research through Design approach are rigor in process, novelty, relevance, and extensibility (Hoök & Lowgren, 2012; Zimmerman et al., 2007). Regarding **rigor**, we documented our research process by describing the methods applied, the rationale behind our choices, and how our design considerations emerged in our investigations. We described some alternative Handoff designs that were filtered away due to our research context and goals but that could be pursued by ourselves or other researchers in the future. For instance, Handoff with a glow effect (Figure 5-1) is likely to grab the receiver's attention in a subtle way without interrupting their screen and thus may facilitate transitions to joint work periods. However, our goal was to explore techniques closer to the original Handoff described in the theory of mechanics of collaboration, which involved holding up a party during transfer. Our work builds on exiting theory and HCI research asserting the importance of interface design on how people conduct group work around technology (e.g. (Convertino et al., 2009; Homaeian et al., 2021; Jamil et al., 2011; Pinelle et al., 2003)).

Throughout our research process, we investigated how the mechanics of collaboration (Pinelle et al., 2003) could be operationalized in our digital environment to facilitate transfer for mixed-focus collaboration. The theory was useful in identifying gaps in the literature with respect to flexible transfer techniques in collaborative environments, and for guiding our designs based on transfer in physical workspaces. However, we found a broader range of useful design criteria for our digital environment than the theory implies. In our corroboration activity, we identified and adapted Harris's framework (Harris, 2019) that helped us better understand and articulate the constraints and nuances of temporal coordination between the sender and receiver, and thus their degree of synchronicity.

Our exploration of the under-studied question of how temporal coordination affects cross-device transfer techniques on collaborative processes produced **novel** insights, including our design considerations, the degree of synchronicity between collaborators, and the likely impact of transfer design choices on mixed-focus collaboration. Our design considerations can be used alongside existing frameworks to establish connections between devices, such as proxemic-based techniques (Grønbæk et al., 2020; Marquardt, Hinckley, et al., 2012; Rädle et al., 2014).

Regarding **relevance**, we contribute knowledge that problematizes the impact of cross-device transfer designs on mixed-focus collaboration. We articulate that design details such as how a transfer is initiated or who is interrupted and to what degree are crucial when building interfaces that facilitate work involving joint and independent work styles and shifts between them. We based our argument on our own findings and previous HCI research.

Our contributions have analytical and generative potential thus the knowledge that we contribute is **extensible**. We hope that HCI researchers and technology designers will adopt our design considerations to inspire designs that deeply consider the impact of cross-device transfer technique on collaborative processes to improve the ability of multi-display environments to support complex collaboration. Our design considerations can also be used analytically to understand how existing designs might be employed in mixed-focus collaborative contexts.

## 5.8 Conclusion and Limitations

Our Research through Design process highlights a need for the HCI community to more deeply explore how the design and choice of cross-device transfer techniques impact collaborative processes. The Handoff and Deposit mechanics of transfer serve different purposes in collaboration. Thus, they provide collaborators with flexible transfer options that suit the ongoing flow of group work. Our findings suggest that designers should tailor the transfer techniques within a cross-device environment to support both independent and joint work periods and shifts between them.

To enable designers to provide appropriate support, we developed five design considerations that incorporate degrees of synchronicity (Harris, 2019) to describe how different design choices of temporal coordination might influence a group's collaborative process. Our Research through Design process enabled us to iteratively design and evaluate Handoff and Deposit techniques, and to derive five design considerations that help articulate how certain design choices for cross-device transfer techniques may affect individual or collaborative behaviour in mixed-focus collaboration: Transfer Acceptance, Action Dependencies, Immediate Usability[9], Interruption Potential, and Connection Actions. These design considerations provide guidance for early design stages and for evaluating existing cross-device transfer techniques. They provide a vocabulary for further work that investigates the impact of cross-device transfer techniques on phases of mixed-focus collaboration.

As a single study, we also acknowledge limitations of our work. Although cross-device environments may facilitate content sharing between personal and shared devices, we focused on supporting content transfer across personal displays, and specifically across tablets. Future work can build on our findings to investigate other cross-device configurations, such as tablet to tabletop/wall or tabletop/wall to tablet transfers. We also conducted our research in the context of a specific sensemaking task between two peers. Future research is warranted that explores our design considerations in other collaborative contexts, like larger groups, groups with a hierarchical structure of roles, or where privacy is a concern.

[9] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

# Chapter 6: Joint Action Storyboards: A Framework for Visualizing Communication Grounding Costs

## 6.1 Preface

This chapter presents the paper published at the Proceedings of the ACM on Human-Computer Interaction (Homaeian et al., 2021), in which I was the primary author. I made minor edits to the paper content to suit the purpose and formatting of this dissertation. In particular, I added Table 6-1 to compare the proposed Joint Action Storyboards (JASs) framework with existing methods for studying the impact of technology on collaboration. I also added footnotes to clarify that it is more accurate to call JASs an 'inspection' rather than a 'discount' evaluation method.

The work presented in this chapter addresses RQ3 and led to Contribution 3: A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes. While conducting Projects 1 (Chapter 3) and 2 (Chapter 5), I developed JASs as a method to help me to articulate the impact of cross-device interaction techniques under study on collaborative processes. I found that existing methods fell short of providing a tool that was designed for CSCW systems, included interaction with technology and breakdowns in interaction, included mental processes of collaborators, and finally allowed for a fine-grained analysis to link specific user interface elements of a technique to the impact on collaborative processes.

I conducted the literature review to situate JASs and describe how it complements or contrasts existing methods. The literature review also discusses Communication Grounding (Clark & Brennan, 1991) as the theory that JASs are based on, how it has been useful to CSCW and HCI researchers, and ways in which JASs extends concepts related to the theory. I applied JASs in a number of case studies related to the TOUCH and TILT techniques (see Chapter 3 for the user study of the two techniques). I then performed several case studies of interaction techniques published in the literature as well as the Skype and Zoom conferencing tools, to demonstrate that JASs are applicable to other systems and the framework's benefits for HCI and CSCW research. All case studies allowed for refinement of JASs.

Building and maintaining common ground is vital for effective collaboration in CSCW. Moreover, subtle changes in a CSCW user interface can significantly impact grounding and collaborative processes. Analyzing a technology's impact on common ground is a common approach used in CSCW and HCI literature to understand the impact of technology on collaboration. Yet, researchers and technology designers lack tools to understand how specific user interface designs may hinder or facilitate communication grounding. This chapter presents Project 3, which leverages the well-established theory of communication grounding to develop a visual framework, called Joint Action Storyboards (JASs), to analyze and articulate how interaction minutiae impact the costs of communication grounding. JASs can depict an integrated view of mental actions of collaborators, their physical interactions with each other and the CSCW environment, and the corresponding grounding costs incurred. We present the development of JASs and discuss its various benefits for HCI and CSCW research. Through a series of case studies, we demonstrate how JASs provide an analysis tool for researchers and technology designers and serve as a tool to articulate the impact of interaction minutiae on communication grounding.

## 6.2 Introduction

Previous research in HCI asserts the critical role of building and maintaining common ground, or shared beliefs, assumptions, and understanding for effective collaboration (Brennan et al., 2006). In their seminal work, Clark and Brennan (1991) introduced communication grounding as the dynamic and interactive process of establishing and maintaining common ground conversational parties. For example, during collaboration, people's common ground includes what they both know about each other, the environment, and the task. Each collaborator then formulates utterances or executes actions based on what they expect the other parties to already know (Clark & Brennan, 1991). The communication grounding framework conceptualizes characteristics or affordances of communication media that impact language use and therefore communication grounding, e.g. visibility and audibility. When a medium lacks one affordance, people use alternative, and often more effortful, approaches for grounding (Gergle et al., 2004a, 2004b). Clark and Brennan (1991) also defined a set of grounding costs that can impact the effort required to establish common ground, depending on the affordances of a given medium. The communication grounding framework has been indispensable to the HCI community in understanding and predicting the costs and benefits of communication media (Brennan & Lockridge, 2006; Gergle, 2017; Monk, 2003), and has been extended to include more recent advances in computing like tangibility and mobility (Kraut et al., 2002) and multitasking ability and awareness (Fox Tree et al., 2011).

However, as communication and collaboration technologies become more complex and vary in form and function, including personal and shared devices like smartphones, tablets, and large wall and tabletop displays, the application of Clark and Brennan's original framework becomes less clear (Monk, 2003). Moreover, technological advancements might hinder communication grounding in synchronous collaborative settings even though people can readily use communication channels such as speech (Clark & Brennan, 1991; Convertino et al., 2008; Homaeian et al., 2018). Affordances lacking on one device may be compensated for one another. Interactions between multiple devices and/or people may involve a myriad of tradeoffs between their affordances and consequential grounding costs. Meanwhile, even small subtle changes to a CSCW user interface can significantly impact collaboration (Gutwin & Greenberg, 1998). So, it is often unclear how a specific interface or interaction design may impact communication grounding and ultimately collaborative processes (Convertino et al., 2008, 2009; Homaeian et al., 2018; Koulouri et al., 2017). Thus, researchers lack tools to examine the specific impact of the interface design of a CSCW system on the grounding process to help uncover the positive and negative effects of an interface design on collaboration.

To address this need, we developed a visual framework, called Joint Action Storyboards (JASs), that adapts the concept of joint actions from Clark's original framework (1996) to break down momentary, collective actions between participants in synchronous collaboration, whether remote or collocated. JASs provide a tool to understand and communicate how subtle interface designs can hinder or support communication grounding. JASs can also help identify potential opportunities to improve the design of the interface to better support collaboration. Clark's notion of joint actions focuses on social processes (primarily verbal exchanges) and mental actions of conversational parties (Clark, 1996). In the context of CSCW, we expand this notion by including physical interactions with the environment. Therefore, by analyzing collaborators' joint actions, researchers and technology designers can see mental and social processes as well as physical interactions that must take place to update the group's common ground (Clark, 1996; Monk, 2003). The mental actions underlie physical interactions (with collaborators or technology), which serve to mediate communication and coordination (Clark, 1996; Monk, 2003). JASs are designed to focus on momentary actions, which we call instances of interest, as the unit of analysis. While brief in time, these instances of interest are typically joint actions that occur frequently during a collaboration session and are critical to the progression of a collaborative task. Thus, they have the potential to significantly impact the grounding process. The visual nature of JASs allows one to depict the context, for example, user interface elements and spatial positioning of collaborators, in which an instance of interest takes place for the analyst to take into account (Martin & Hanington, 2012). Moreover, the visualizations help generate empathy (Martin & Hanington, 2012).

Our work is a continuation of efforts by other CSCW and HCI researchers to provide frameworks and analytic tools that can help us understand, describe, and analyze CSCW around rapidly-evolving technological systems, for instance, Hierarchical Task Analysis (Preece et al., 2007), Cognitive Task Analysis (Lee et al., 2013; Silva et al., 2007), Hybrid Cognitive Task Analysis (Nehme et al., 2006), and Groupware Task Analysis (Van Der Veer et al., 1996). Compared with JASs, such frameworks and tools either focus on modeling expert user behaviour or have a coarser analysis granularity focused on high-level concepts related to task or collaborative workflow. Thus, they are not suitable for uncovering how specific design features can impact low-level collaboration processes and interaction minutiae. Additionally, although effective CSCW relies on communication grounding (Brennan et al., 2006; Isenberg et al., 2012), existing frameworks fall short on helping researchers and technology designers understand if a given design supports or impedes communication grounding (Convertino et al., 2008, 2009). The JASs framework provides a fine-grained analysis tool to understand and articulate the impact of a specific technique on communication grounding at the user interface level.

JASs may be used as a discount[10] evaluation method, for instance, to assess how well a technology supports or hinders communication grounding prior to running a user study and by considering potential technology use cases. JASs may also be used alongside other methods, for example, Clark and Brennan's affordances framework (Clark & Brennan, 1991), questionnaires, conversational analysis, thematic analysis, and observations, to study the impact of technology on communication grounding to provide a holistic view of the system. Those existing methods usually capture data that are observable in the physical world, making them appropriate for identifying certain instances where technology potentially impacts communication grounding. However, communication grounding includes mental actions that take place inside collaborators' minds, making them difficult to identify and analyze using the above methods. The concept of joint actions adapted in JASs captures such internal mental actions, allowing for a fine-grained analysis of grounding costs. JASs are also applicable to the design stage of a project as a discount[10] method. In this case, one may identify instances of interest by creating hypothetical collaborative scenarios. The framework can then be used as a communication tool between technology designers and evaluators of the CSCW system.

[10] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

We present the development of JASs through a case study in which we analyze grounding costs incurred by two existing cross-device interaction techniques, called TOUCH and TILT, that we previously designed (Homaeian et al., 2018) to support co-located collaborative sensemaking around geospatial data. TOUCH provided a touch-based approach for selecting data on a shared, large tabletop to view on a connected personal display, while TILT involved remotely selecting the data using on-board motion sensors on the personal display. Our study of these techniques found that TOUCH afforded effective tightly coupled work, whereas TILT better afforded independent data exploration (loosely coupled work). However, their findings, derived from thematic analysis of their collected video data, did not articulate precisely how or why the respective interface techniques impacted low-level collaboration processes, such as communication grounding. As technology designers, we sought a more fined-grained analysis method that would help us identify and articulate, to ourselves and others, how specific design features (i.e. user interface and interaction designs) of a CSCW system impacted collaboration minutiae, to help us improve our designs. This goal inspired us to explore grounding costs imposed by the two techniques, and to understand the subtle impact of the two design approaches on communication grounding. We developed JASs while trying to probe these differences. We then apply JASs to a series of collaborative case studies to demonstrate the framework's key benefits for HCI and CSCW research.

In summary, we contribute JASs, a visual framework to analyze grounding costs in synchronous collaborative technologies (remote or co-located) that provides HCI researchers and technology designers with an integrated tool to:

1. depict collaborators' mental actions, interactions with CSCW technologies, and the physicality of the system,
2. articulate the impact of specific user interface elements of CSCW technologies on grounding costs,
3. evaluate the impact of specific user interface elements on communication grounding as an analytical tool, and
4. analyze interaction minutiae to reveal potential design opportunities.

## 6.3 Related Work

The ability of team members to establish common ground is crucial to effective collaboration in synchronous CSCW systems (Brennan et al., 2006). This is especially true during mixed-focus work, when people come together after periods of individual work to share and merge their findings as a group (Isenberg et al., 2012). In these settings, grounding spans multiple collaborators and often multiple devices, and includes mental actions and physical interactions with colleagues and the CSCW system, and is, therefore, a complicated and difficult process to analyze (Convertino et al., 2008, 2009). It is important to take into account interaction minutiae and breakdowns in the analysis to understand how subtle interface design choices support or impede grounding (Clark & Brennan, 1991; Gutwin & Greenberg, 1998). Yet, given the ubiquity of multi-user and multi-device environments, there is a pressing need for CSCW and HCI researchers to develop new tools that can aid the research and design of grounding in these settings (Convertino et al., 2008, 2009; Gergle, 2017). Such tools can facilitate and fill gaps in research on more complex multi-display environments by the CSCW community (Wallace et al., 2017).

Existing tools tend to fall short of providing this aid by including interactions among people only, modeling error-free behaviour, or focusing on a whole system rather than specific interface design elements (Table 6-1). For example, CSCW and HCI researchers often use conversational coding and questionnaires (e.g. (Convertino et al., 2009; Fox Tree & Clark, 2013; Gergle et al., 2013; Kirk et al., 2007)) to study the impact of specific technological settings on communication grounding. These research tools are useful to understand communication structure and participants' perception of the impact of technology on communication grounding. However, they do not capture physical interactions with technology or the underlying mental actions, which are fundamental to the grounding process and are impacted by user interface features (Clark & Brennan, 1991; Monk, 2003).

**Table 6-1. Project 3. Existing methods versus JASs for analyzing the impact of technology on collaboration. A dot means the given method satisfies the corresponding column with respect to the analysis**

| | Suitable for CSCW | Includes interactions with technology | Includes mental processes | Includes breakdowns in interactions | Unit of analysis |
|---|---|---|---|---|---|
| JASs | • | • | • | • | Momentary frequent interactions |
| Conversational analysis | • | | | Only if evident in verbal communication | Entire collaborative scenario |
| Video analysis and observations | • | • | | • | Entire collaborative scenario |
| Interviews and questionnaires | • | | | • | Entire collaborative scenario |
| Inspection and discount evaluation methods | • | • | In some methods, e.g., Cognitive Walkthroughs | • | One task |
| Hybrid Cognitive Task Analysis, Groupware Task Analysis | • | • | • | • | Whole system or general mission |
| Keystroke Level Model, Touch Level Model, | | • | | | A unit task |
| GOMS, Hierarchical Task Analysis | | • | • | | One task |
| Cognitive Task Analysis | | • | • | • | Whole system or general mission |

Conversely, user- and task-level analysis methods provide a means of understanding interactions with computer interfaces but are designed to model error-free interactions with computer systems. Predictive models like GOMS (Dix et al., 2004; Preece et al., 2007), The Keystroke Level Model (Card et al., 1980; Preece et al., 2007), Touch Level Model (Rice & Lartigue, 2014), and task analysis methods such as Hierarchical Task Analysis (Preece et al., 2007) offer high precision in understanding these physical interactions (and in some cases cognitive processes), but are largely designed to analyze single user contexts and fail to account for interaction breakdowns. Therefore, such methods are not effective for studying user interface designs of CSCW technology that get in the way of the grounding process. Cognitive Task Analysis (Lee et al., 2013; Silva et al., 2007), Hybrid Cognitive Task Analysis (Nehme et al., 2006), and Groupware Task Analysis (Van Der Veer et al., 1996) provide tools to understand collaborative workflows and consider cognitive overload during interactions with an interface. However, they have a broader unit of analysis compared to that of JASs. They focus on a whole system or a general mission and therefore are not suitable for studying interaction minutiae. Discount[11] evaluation methods, such as Heuristic Evaluation and Walkthroughs (Preece et al., 2007) may be adapted to inspect usability problems in CSCW systems, for example by using the mechanics of collaboration (Pinelle et al., 2003) to model a collaborative task. However, those methods also have a broader unit of analysis and thus may miss to identify opportunities for a design improvement to alleviate grounding costs. Moreover, JASs are not only an analytical tool but also a communication tool to articulate the impact of user interface elements on collaborative processes.

In this chapter, we develop an analytical framework that helps researchers and designers examine mental actions and interactions with CSCW technology to analyze how certain interface design elements facilitate or impede communication grounding. We decided to focus on understanding grounding, and the grounding costs incurred with specific interfaces, first in a co-located CSCW setting. We chose this setting as a starting point for our investigations because grounding costs are generally low in face-to-face settings (Clark & Brennan, 1991); yet, co-located CSCW technologies such as multi-display environments can introduce new complexities that can hinder communication and collaboration processes (Scott et al., 2015). For example, sharing information across displays in a multi-display system to facilitate a joint discussion can potentially interfere with the flow of conversation, and thus communication grounding, if a cross-device interaction technique is overly cumbersome.

In developing this analytical framework, we bridged three distinct areas of CSCW research: communication grounding theory, analytical frameworks, and theories for understanding collaborative processes.

### 6.3.1 Communication Grounding Theory

The theory of communication grounding (Clark & Brennan, 1991) has been widely used by HCI researchers to predict and understand how a given technology may support or impede communication (Brennan & Lockridge, 2006; Monk, 2003). It describes the low-level processes that humans use during communication to establish and maintain common ground throughout a conversation. It this work, Clark and Brennan (1991) describe a number of costs that can be incurred by the speaker and/or the listener during a conversation. These costs are context dependent and rely heavily on the setting in

[11] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

which the conversation occurs. For instance, in a face-to-face environment where conversational partners with no visual or auditory impairments have access to rich verbal and non-verbal communication channels it is easy to convey intended meaning and notice misunderstandings. Thus, for many types of conversations, face-to-face is considered the ideal grounding environment. On the other hand, when holding a conversation over the phone, speakers and listeners have no access to non-verbal communication, for instance, to convey a wry smile with a sarcastic comment or interpret the reaction that a message evoked. These grounding costs are impacted by different communication affordances that distinct communication contexts have, including, for instance, whether or not parties can see each other (visibility), hear each other (audibility), talk at the same time (simultaneity), review what was said (reviewability), and so on (Clark & Brennan, 1991). These affordances can be thought of as 'resources for grounding' (Monk, 2003). That is, the more affordances a given communication context provides, the better it will generally be at supporting grounding.

However, as CSCW technologies rapidly evolve, using this original framework to predict or explain problems for a given system becomes less clear (Monk, 2003). For example, consider a multi-device co-located environment that has personal and shared devices. This environment has visibility, but people's attention can be focused on personal devices and therefore others' actions may not be immediately visible to them. Moreover, although Clark's theory of communication grounding is valuable to guide the design of communication technologies, it requires specialized knowledge to use (Monk, 2003). Also, as the theory is employed and extended by researchers (Brennan & Lockridge, 2006; Fox Tree et al., 2011; Kraut et al., 2002; Monk & Watts, 2000), its limitations are better understood, as well as new assumptions needed for applying it to the latest technologies (Monk, 2003). For instance, researchers have extended Clark and Brennan's framework to include more affordances, such as tangibility (Kraut et al., 2002), that did not exist when the theory of communication grounding was first established. In another work, Brennan et al. (Brennan et al., 2006) introduced a data view mapping mechanism to reconcile two contradicting needs of collaborators in a multi-display system: the need to establish common ground among collaborators and the need to have private views to manipulate data.

Our work continues these efforts by the HCI and CSCW communities by extending Clark and Brennan's original framework to a more accessible visual tool that can be used by researchers and designers to understand and communicate how the design of specific user interface elements impacts grounding costs in different collaborative scenarios. We also leverage Clark's (1996) concept of joint action ladders, which describe how communication between two people progresses. Joint action ladders capture momentary collective actions, in which a participant gets their partner to notice, perceive, and understand a verbal or non-verbal message, and finally consider responding. Each joint action ladder increments the group's common ground with new content. In this paper, we refer to 'joint action ladders' as 'joint actions' for simplicity. Clark (1996) uses the concept to describe how face-to-face verbal communication takes place. Our visual framework adapts the definition of joint actions in the context of CSCW, and thus includes interactions with technology.

## 6.4 Joint Action Storyboards

We use the concept of joint actions (Clark, 1996) to examine interactions with CSCW systems using a storyboard format, depicting an instance of interest as the unit of analysis. We define an instance of interest as a brief yet frequent interaction between collaborators and the CSCW technology. Instances may be identified by examining existing data, observed breakdowns in communication, or by creating hypothetical use case scenarios for the CSCW technology under study. Each frame in the storyboard represents a joint action and the corresponding grounding costs incurred. In a joint action, one executes a verbal or non-verbal action for a partner's attention (Figure 6-1). Meanwhile, the partner is noticing, perceiving, understanding the action, and at last considering a response.

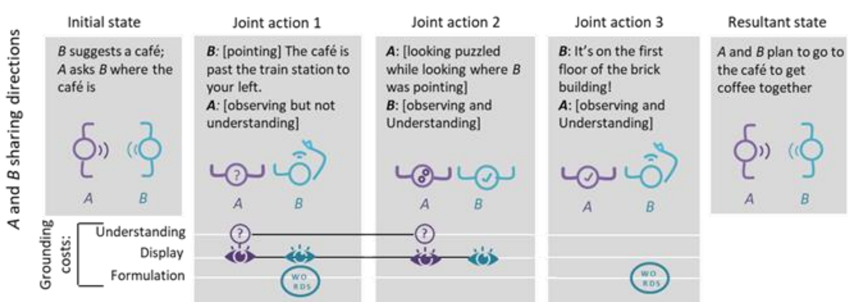



**Figure 6-1. Project 3. JASs depicting an instance of interest in which two people share directions to a café**

This unit of analysis marks a fundamental difference between JASs and previous frameworks. Many existing frameworks, like the mechanics of collaboration (Pinelle et al., 2003) or Groupware Task Analysis (Van Der Veer et al., 1996) focus on high-level concepts and categorizations with respect to the entire collaborative activity. Our use of joint actions (Clark, 1996), however, enables fine-grained analysis of interaction with the system that may hinder or support the process of communication grounding.

Notably, by combining these different perspectives into a single framework, JASs consider multiple levels of analysis, e.g. individual and group levels (Carroll et al., 2008; Engeström, 1990; J. E. McGrath, 1984). At the group level, JASs depict verbal and physical interactions with teammates. At the individual level, the framework shows the collaborator's mental actions. Physical interactions with the CSCW system correspond to both individual and group levels.

In summary, the JASs framework is a qualitative analysis and communication tool for HCI researchers and technology designers that focuses on interaction minutiae. They can be used to analyze the impact of technology on communication grounding, and also provide a tool and vocabulary to articulate how subtle design decisions could impact communication grounding. When examining hypothetical cases, JASs also serve as a discount[12] evaluation method to flag opportunities for revising the system's design.

## 6.5 How to Create JASs

JASs consist of two main parts that illustrate the collaborators' joint actions and the grounding costs incurred as they communicate (Figure 6-1). The top part of JASs depicts collaborators' initial states, followed by a sequence of joint actions, and finally the resultant state. The bottom part of JASs shows grounding costs incurred due to the specific user interface elements of the CSCW system. Each cost points to a potential opportunity for researchers to improve the user interface design to more effectively support communication grounding.

The development of JASs comprises four steps:

1. Choose an instance of interest
2. Break down the instance to joint actions
3. Create a storyboard of the joint actions
4. Mark grounding costs

[12] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

In the following subsections, we will walk through the above steps by applying the framework to an introductory example of two people sharing directions to a café.

### 6.5.1 Choose an Instance of Interest

The first step in creating JASs is deciding which instance of interest is to be visualized. A researcher or technology designer needs to identify patterns of collaborative behaviour by either creating hypothetical scenarios or gathering and qualitatively analyzing data using existing techniques such as thematic analysis (Boyatzis, 1998). Gathering data can be done by running observations, field studies, or laboratory studies. Expected use cases of the system or uses of specific features can be used to generate hypothetical scenarios. An instance of interest shows a case where technology seems to support or get in the way of collaboration. In identifying such cases, it is useful to keep in mind the communication and coordination mechanisms (Pinelle et al., 2003), e.g. verbal/non-verbal messages or data transfer, and collaborative work styles (Isenberg et al., 2012; Neumayr et al., 2018; Tang et al., 2006) that are important in the progression of the collaborative task. Since a given instance is to be analyzed according to the exact series of actions by the participants, the instances should be short-lived, i.e. seconds long. Longer instances may not be representative of common behaviour in the CSCW system and may be broken down to shorter connected instances.

An instance of interest should represent an interaction that happens or is expected to happen often during collaboration, and thus, impacts grounding costs during the collaborative task. To identify such instances, we advise looking at prolonged interactions with the system (e.g., data sharing or manipulation during joint discussions), as well as frequent brief interactions (e.g., notification mechanisms):

1. *prolonged interactions* (e.g., where collaborators would be expected to be interacting with or discussing content for some minutes / hours) to ensure that access to and perception of the needed informational content, or even others' interactions with relevant task processes, does not incur significant grounding costs, and

2. *frequent brief interactions* (e.g., short-lived (milliseconds or seconds) group or system interactions) to ensure that the interface or interaction design aspects supporting those interactions do not introduce undue grounding costs that could accumulate over time and impact the broader flow of communication grounding process and collaboration in general.

Our instance of interest in the introductory example of two people sharing directions to a café is when one participant points to and describes the location of the coffee shop with respect to the surrounding buildings.

### 6.5.2 Break Down the Instance to Joint Actions

In this step, the instance of interest is broken down into the verbal and non-verbal exchanges between the participants and their (possibly concurrent) physical interactions with the environment (Figure 6-2). An example of a joint action is one telling their partner "The café is past the train station to your left." Meanwhile the partner is listening and understanding the message. We refer to the two people involved in the joint action as the initiator and the recipient. Importantly, in a given joint action during communication, a person may be the initiator or the recipient depending on who executes an action for the other's attention.

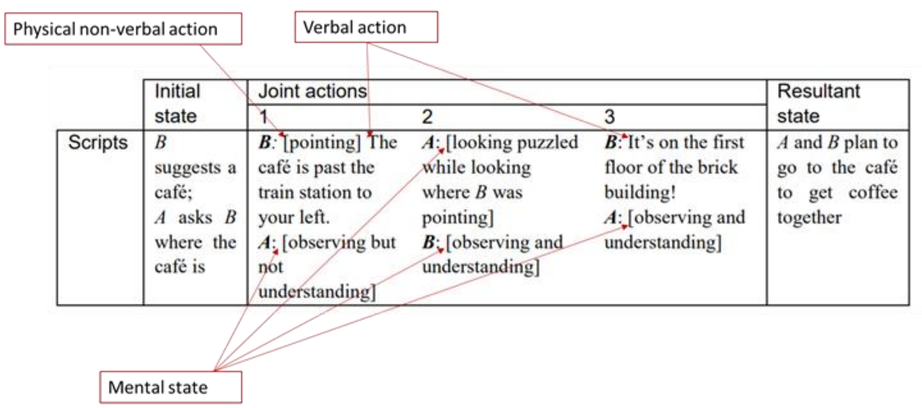



**Figure 6-2. Project 3. Joint actions of participants *A* and *B* while sharing directions**

Clark (1996) describes mental actions of conversational participants during their communications. In any joint action, the initiator must get the recipient to notice, perceive, and understand the message, and finally consider executing a response (Clark, 1996). At this point, the group's common ground is updated with new information. This new information includes knowledge of the communication that just took place. The recipient then assumes the role of the initiator and proceeds with a verbal or non-verbal response, which is yet another joint action and further increments common ground. If the recipient does not notice, perceive, or understand an action as expected by the initiator, the action is still joint but broken down. Including such failed joint actions in the analysis provides an opportunity to study where the user interface elements may hinder communication grounding.

In the above example, the recipient becomes the initiator and responds by, for example, looking puzzled while looking where their partner was pointing. As Clark (1996) describes, the recipient of a joint action may only be in one of the following mental states with regards to the message. Note that the mental state of the recipient then shapes what happens in the next joint action:

1. Observing and understanding
2. Observing but not understanding
3. Not perceiving
4. Not noticing

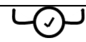
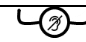
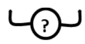
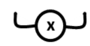
Figure 6-2 shows the joint actions for our example of two people, *A* and *B*, navigating a nearby café without a shared map. Note that there is a joint action each time one participant says or does something. The reaction of the recipient then follows as another joint action. It is important to include verbal, physical non-verbal, and mental actions of the participants (Figure 6-2) in the script as they are instrumental in creating the visualizations in the next step. The initial and resultant states are also included to provide context to the story.

Participants' representative labels (*A* and *B*) are highlighted in the scripts. The initiator's corresponding script appears first in the joint action. This ordering is a verification tool to make sure collaborators' responses to each other are captured in the sequence of joint actions (Clark, 1996). Notably, the two conversational parties normally alternate the roles of initiator and recipient in subsequent joint actions. Even if *A* does not notice *B*'s speech or their interaction with the environment, the subsequent joint action shows *A* is still doing whatever they were engaged in previously without any reaction. Meanwhile, *B* observes and understands that they were not noticed by *A*. In collaboration around technology, collaborators often transition between (sometimes brief) periods of loosely coupled and tightly coupled work. In this case, the participants may keep their roles as initiators and recipients in subsequent joint actions. Also, an interaction technique may require multiple steps to be performed immediately one after the other. In such cases, collaborators keep their initiator and recipient roles in some subsequent joint actions until the recipient executes a response for the other.

### 6.5.3 Create a Storyboard of the Joint Actions

We create storyboards in this step to visually capture the interactions between the participants and their environment, and the participants' mental states (Table 6-2) as those interactions take place. Depicting this contextually rich story of the joint actions generates empathy (Martin & Hanington, 2012) and provides a tool to illustrate and understand how the participants adapt their collaborative processes to the specific user interface features of the CSCW system. Key entities that must be included are the participants and parts of environment they interact with.

**Table 6-2. Project 3. Mental states of participants. The view angle of the head icons may be changed as necessary**

| Mental state | Icon | Mental state | Icon |
|---|---|---|---|
| Observing and understanding |  | Not perceiving |  |
| Observing but not understanding |   | Not noticing |  |

The scripts generated in the previous step are noted above the images to provide a narration for the storyboards. Also, grey backgrounds group visualizations and scripts of individual joint actions. The head icons represent the two participants, *A* and *B*, and their corresponding mental states (Figure 6-1). Table 6-2 shows a sample of icons representing the mental action of the participants. Depending on the context under study, other icons may be used for a given mental action, for instance an icon depicting 'not seeing' or 'not feeling the haptic feedback' for the 'not perceiving' mental action. A concise label describing the instance of interest is displayed at the left side of the Initial state to make the illustration more self-descriptive. Participants' representative icons are distinguished by colour in the visualizations. The labels representing each participant, in our case A and B, are placed below the corresponding parties' images in addition to the colours to aid the readability and salience of the visualizations (Figure 6-1).

### 6.5.4 Mark Grounding Costs

In this step, grounding costs incurred at each joint action are marked below the corresponding participant's icon. We used the eleven communication grounding costs introduced by Clark and Brennan (1991). However, these costs were primarily based on using a medium to support conversation only, like a letter or telephone. Thus, we adapted some grounding costs' definitions, i.e. Production, Reception, Understanding, Delay, and Asynchrony (Table 6-3), for use in modern collaborative environments. For instance, collaborative software is the means of not only communication between team members, but also accessing material and functions that are essential to performing the task (e.g.

creating a joint artefact). Grounding costs are incurred by the initiator, the recipient, or both parties (Table 6-3).

**Table 6-3. Project 3. Grounding costs and their definitions**

| Icon | Grounding Cost | Definition | Incurred by |
|---|---|---|---|
| | Formulation | Time and effort needed to formulate utterances | Initiator |
| | Reception | Costs of receiving a message, e.g. due to having to interact with the system | Recipient |
| | Production | Cost of producing a message, e.g. by typing or interacting with the system to retrieve data being referred to | Initiator |
| | Understanding | Cost of understanding a message, e.g. due to lack of contextual cues | Recipient |
| | Start-up | Costs of getting someone to notice a conversation has started | Both |
| | Display | Costs of presenting a gesture or an object, e.g. a piece of data to collaborators | Both |
| | Fault | Costs of making a mistake during communication | Both |
| | Repair | Costs of recovering from a mistake | Both |
| | Delay | Costs paid due to pauses during collaboration, e.g. loss of audio, or due to a need to pause one's ongoing work, e.g. to understand a screen update or to communicate with a partner about that | Initiator, Recipient, or Both |
| | Asynchrony | Incurred when a message is produced and received at different times, or in CSCW incurred when people transition between loosely coupled and tightly coupled work | Both |
| | Speaker-change | Costs needed to change the speaker to let the other party have a turn. These costs are generally low in synchronous CSCW | Both |

Notably, these costs are not independent of each other and multiple costs may be incurred by a participant in a given joint action (Clark & Brennan, 1991). Lowering one cost may cause other costs to rise (Brennan & Lockridge, 2006; Clark & Brennan, 1991). For instance, in our example, *B* could pay higher Formulation costs to lower Understanding costs for their partner *A*. It is important to mark all relevant grounding costs incurred due to the technology to provide a holistic view of the impact of user interface elements on communication grounding, and how the interface may be redesigned to counter or alleviate the costs. For a more elaborate list of costs' definitions, see the Appendix.

When identifying grounding costs, one needs to include costs that incur only due to the user interface elements of the system. This is to ensure a focused analysis of how the specific features of the CSCW environment facilitate or hinder communication grounding, and potentially identify opportunities to improve the user interface. For example, an initiator always needs to get the recipient's attention. If the two partners are co-located and can talk or if they are already engaged in tightly coupled work, then start-up costs are negligible and should not be included in the JASs. Also, in face-to-face communication, grounding costs for verbal dialogue exchange are minimal and are not considered in the analysis of the user interface features.

We recommend starting with the first joint action in the storyboard and scanning the grounding costs in Table 6-3 to see which are incurred by the collaborators. As demonstrated in Figure 6-1, draw a straight line below the visualizations for every identified cost and label the line accordingly. Then, recolour the corresponding grounding cost icon to match the image representing the participant who pays the cost and insert the icon on the line below the participant image. A grounding cost appears in subsequent joint actions until it is countered. Sustained costs persist across more than one join action, depicted by a back line connecting the respective cost icons. Momentary costs, however, appear in a single joint action at a time. Although joint actions in our storyboards do not necessarily last for the same amount of time, the distinction between sustained and momentary costs provides a notion of the amount of impact on grounding, depicted by the number of joint actions the costs span.

In our introductory example, sustained Understanding costs are incurred by *A* as they try to understand the directions with respect to the surrounding area (Figure 6-1). These costs persist until *B* clarifies the address they gave earlier. Participant *B* pays formulation costs when there is no map for reference as they need to describe the directions to the café. Additionally, sustained Display costs are noted for both participants as *B* tries to point to and show the location of the building to *A*. Those costs are countered when *B* specifies the characteristics of the target building.

## 6.6 Case Study: Analysis of Cross-Device Interaction Design

We were first motivated to explore visualizations of communication grounding when performing an analysis of our previous work (Homaeian et al., 2018). Our system supported collaborative sensemaking between two people tasked with assessing the feasibility of shipping routes within a given geographic region using a multi-device environment comprised of personal tablet computers and a shared tabletop display. The tabletop showed a map of the region that was overlaid with data icons and displayed two bounding boxes around regions of interest (ROIs) that represented each of the two collaborators' tablets. By moving their ROI over a data icon, one would update their tablet's view to show only detailed data associated with that geographical region.

We studied how two interaction techniques, TOUCH and TILT, influenced collaboration in this setting (Homaeian et al., 2018). We reported that TOUCH and TILT impacted group work during a specific type of collaborative behaviour: showing a piece of data to a partner. When investigating that behaviour, we found that current methods of studying common ground, like conversational analysis and questionnaires, do not consider interaction with technology or the collaborators' mental actions. We wished to understand the grounding costs incurred by each technique to help us to understand the role that TOUCH and TILT played in facilitating collaboration. Since we were interested in the impact of technology on communication grounding, a process shaped by what goes on the participants' minds as well as their interactions with each other and their environment, it was crucial to include people's mental and physical steps in our analysis.

Although we had reported (Homaeian et al., 2018) that TOUCH and TILT supported joint and independent work periods differently, their analysis did not communicate how specific design choices led to that difference. Our visual framework enabled us to not only analyze the different grounding costs incurred by TOUCH and TILT, but also to articulate how interface design choices influenced them. JASs, by adapting the concept of joint actions (Clark, 1996) from the theory of communication grounding, allowed us to take into consideration the participants' mental actions and physical interactions with the environment as they used TOUCH and TILT to increment their common ground. We now show how JASs helped us conduct these analyses for the collaborative behaviour of showing data to a partner.

### 6.6.1 Showing Data to a Partner

We were initially motivated by difficulties in understanding how our (Homaeian et al., 2018) participants shared data using the TOUCH and TILT interfaces. Notably, the tabletop display did not distinguish between users. Therefore, with TOUCH, participants often moved their partner's ROI to assist them in viewing data. With TILT, however, this was not possible, and each participant always moved their own ROI. While subtle, these differences felt like they had a substantial impact on how the groups performed their tasks.

We found that existing methods like conversational analysis did not help in understanding these scenarios, since they do not consider people's interactions with the environment. Minutiae like collaborators' mental actions and positions around the shared tabletop, the orientation and location of data being discussed, and where individuals were looking while their partners interacted with the

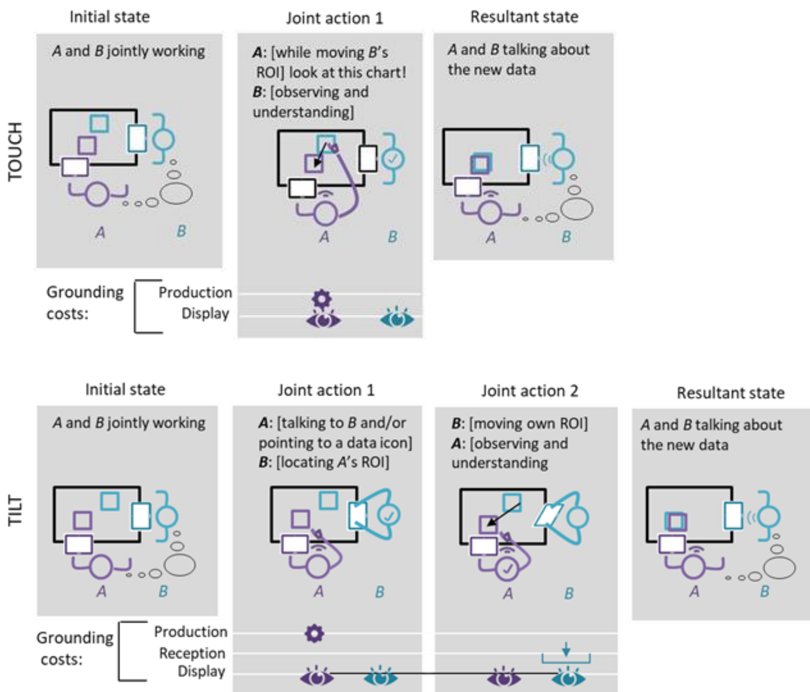



**Figure 6-3. Project 3. Applying JASs to TOUCH and TILT techniques: JASs reveal that the TOUCH interface (Top) facilitated more effective communication grounding compared to the TILT interface (Bottom)**

system had substantial impacts on communication grounding. Yet, existing analysis techniques tend to focus some of these factors and did not provide a satisfactory way of linking all of them.

We developed JASs for scenarios when one participant wishes to show a piece of data to their partner during tightly coupled work for each of the TOUCH and TILT interfaces (Figure 6-3 Top and Bottom, respectively). Our JASs show that the TILT interface required more collective effort, in the form of mental actions and interactions with the environment, than the TOUCH interface. In particular, twodifferences stand out based on our analysis. First, with the TILT interface, both participants incur sustained Display costs. Second, with TILT, Participant B first needs to retrieve and view the data on their personal tablet to facilitate an effective discussion, resulting in Reception costs that are not present when using the TOUCH interface (i.e., Figure 6-3 Top, Joint action #1).

### 6.6.2 Breakdowns in Data Sharing

While we found that the TOUCH interface afforded more effective grounding, we also found instances where it caused confusion when sharing information (Figure 6-4). Specifically, there were cases where one collaborator would move the others' ROI while they were focused on their personal tablet, surprising them. In these scenarios, there was no verbal communication, and so conversational analysis was not useful for understanding the impact on grounding. Even though conversation was absent, these groups were engaged in communication grounding, and we wanted to be able to articulate these costs and understand how they were linked to interface design choices. Note that in Joint actions #2 and #3 in Figure 6-4, the participants kept their roles as the initiator and recipient, unlike the pattern in most JASs storyboards, where the participants swap roles each frame of the JASs. This pattern is broken in this case because of the brief loosely coupled work period in which the collaborators were focused on their personal devices to understand a screen update, or lack thereof.

In these cases, JASs serve as a useful tool to broadly think about the different grounding costs that may influence an instance, and their relationship to the user interface and physical workspace. They provide a systematic method of assessing grounding costs, accessible to novice and expert evaluators that can directly inform the design of complex, collaborative systems. For instance, in the scenario described in Figure 6-4, our analysis suggests that the user interface could be redesigned to inform the owner of a tablet once their screen is updated due to the movement of the associated ROI. As the Joint action #2 in Figure 6-5 depicts, the border of the tablet screen could flash to provide awareness of the ROI movement and the subsequent screen update. This design decision potentially alleviates sustained Understanding and Delay costs (Figure 6-4 Joint actions #2 and #3) and helps the group recover from the mistake faster (fewer joint actions in Figure 6-5).

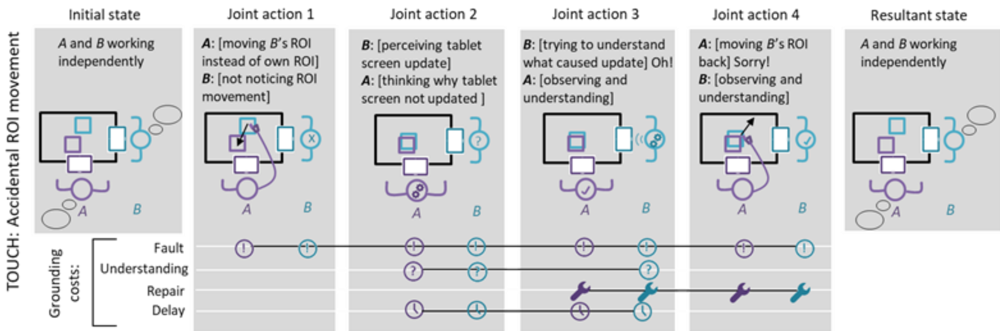



**Figure 6-4. Project 3. Using JASs to articulate breakdowns in grounding: even though TOUCH was more effective for grounding, groups paid several grounding costs when mistakes happened**

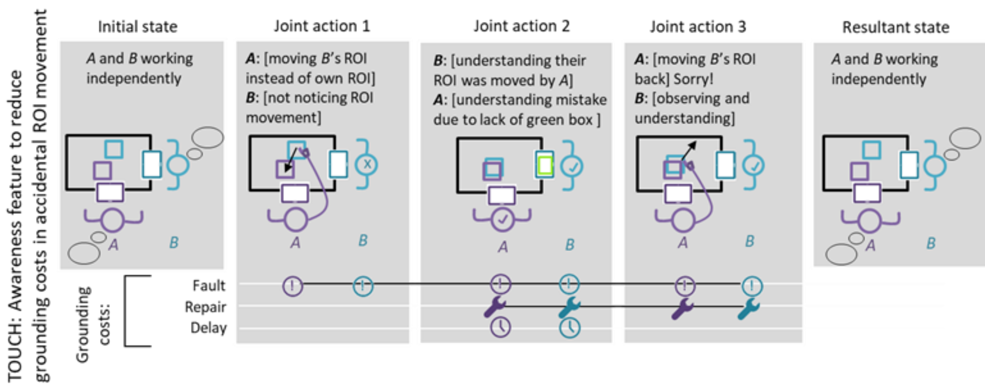



**Figure 6-5. Project 3. Using JASs to show a potential design alternative: highlighting one's tablet display to associate screen update with ROI movement could alleviate some grounding costs in case of accidental ROI movements**

## 6.7 Applying JASs to Other CSCW Systems

To demonstrate the key benefits of our framework, we next examine communication grounding in three case studies of techniques from the CSCW literature and a commercial tool. First, we show how our framework can be used as a discount[13] evaluation method to analyze common ground and identify areas for improvement in the context of Marquardt et al.'s Tilt-to-Preview technique (Marquardt, Hinckley,

---

[13] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

et al., 2012). Second, we show how JASs can be used to depict physicality and the spatial environment for two digital tabletop sharing techniques. Finally, we show how our framework can be used to understand the impact of design choices on grounding during remote communication through an analysis of communication breakdown within a video conferencing system.

### 6.7.1 Discount[13] Evaluation Tool for Common Ground

JASs are particularly useful as a discount[13] evaluation method to understand the impact of specific user interface elements on grounding costs. To demonstrate this process, we performed an analysis of Marquardt et al.'s (Marquardt, Hinckley, et al., 2012) GroupTogether, a system to explore cross-device interaction techniques for "micro-mobility". One technique in that system, called Tilt-to-Preview, supports tablet-to-tablet data sharing between two people standing beside each other. When a collaborator wishes to share an image, they tilt their tablet towards their partner's tablet, A tinted edge then appears on their partner' tablet, together with a transient copy of the image that partially covers the receiver's screen. The receiver may touch the image to keep a permanent copy. In a preliminary user study, this cross-device transfer technique was found to be effortful by participants due to the added weight of sensors installed on the tablets (Marquardt, Hinckley, et al., 2012). However, our analysis also shows that its design requires sustained Production costs.

The JASs produced for this expected use case focus on the interaction minutiae of the required steps to complete the transfer of digital content from one device to another using the Tilt-to-Preview technique (Figure 6-6). Note that *A* keeps their role as the initiator in Joint actions #1 and #2 as the technique requires two steps to transfer the image: 1) tilting tablet and touching image (which automatically tints the edge of *A*'s tablet), and 2) sustaining tilt and touch actions (which automatically tints the edge to *B*'s tablet also). The JASs highlight the sustained Production costs that people incur every time they share content using this technique. This insight is articulated by depicting the joint actions of the collaborators while employing the Tilt-to-Preview technique and the solid black line pointing to sustained Production costs spanning the entire instance of interest (e.g. Production costs at the bottom of Joint actions #1 to #3 in Figure 6-6). These identified Production costs suggest an opportunity for design improvement.

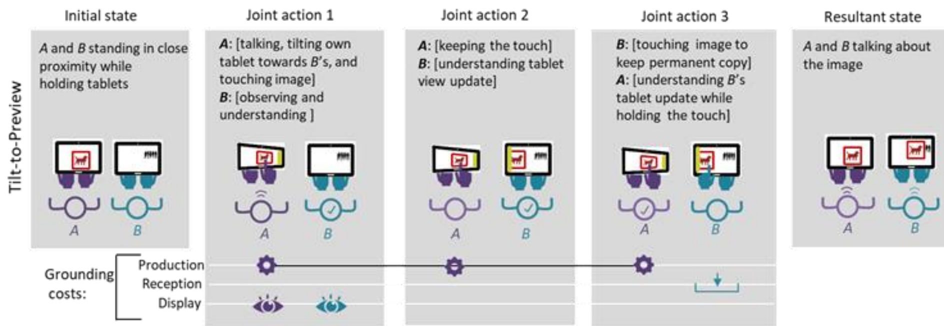



**Figure 6-6. Project 3. Applying JASs as a discount[14] evaluation method reveals sustained Production costs in data sharing with Tilt-to-Preview** (Marquardt, Hinckley, et al., 2012)

While the JASs do not explicitly capture the magnitude of the grounding costs, they identify specific interaction and interaction sequences that could be considered for redesign. For instance, in this example, is it really necessary for the sender (*A* in Figure 6-6) to sustain both a device tilt AND a finger touch on the content item until the recipient (*B* in Figure 6-6) accepts the content? Would a less effortful design achieve the same goal and minimize Production costs? Alternatively, removing the requirement for the sender to keep touching the content would eliminate the more effortful of the two tilt / touch-while-holding-the-device-steady actions and reduce Production costs. Another interesting instance of interest not depicted in Figure 6-6, is when *B* is working independently and not anticipating a sudden change in their tablet view. A JASs analysis would show Understanding costs for *B* as they try to understand why unexpected content appeared on their screen (not currently included in Figure 6-6 because both parties are anticipating the transfer). In an alternative interface design, the tinted edge on the receiver's screen could appear shortly ahead of the transient copy of the shared item to help counter the Understanding costs.

### 6.7.2 Capturing Physicality in Interaction

JASs' visual format depicts physical interactions between collaborators and a CSCW system that are often difficult to understand and articulate using traditional analysis techniques. For example, rotation

[14] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007)

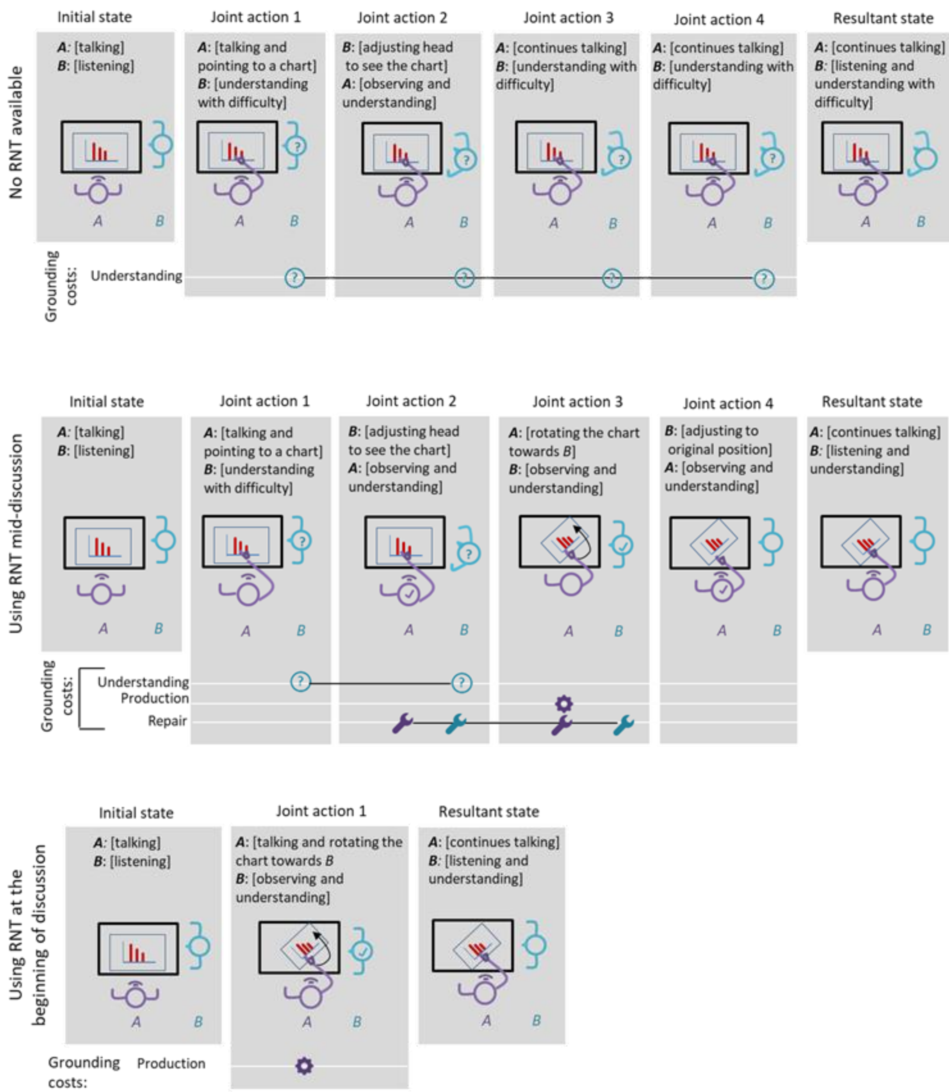



**Figure 6-7. Project 3. Illustrating physicality of CSCW technology and its importance during communication grounding. Top: Without RNT, *B* incurs sustained Understanding costs during the entire discussion. Middle: Using the RNT technique, *A* eliminates further understanding costs for *B*. Bottom: Using the RNT technique at the beginning of a discussion eliminates several grounding costs**

and translation (RNT) techniques for digital tabletops foster communication, coordination of actions, and comprehension of material during collaboration around tabletops (Hancock et al., 2006; Kruger et al., 2004, 2005; Wigdor et al., 2006). However, traditional analysis techniques often fail to articulate the connections between physical and mental actions and features of the system. In these cases, JASs provide a comprehensive method to understand and articulate how interface design can influence collaborative process.

To better understand and articulate these interactions, we developed three JASs (Figure 6-7) that show different scenarios in which content is shared on a tabletop display: without RNT, when RNT is used to repair a breakdown in communication grounding, and when RNT is used to prevent breakdowns in communication grounding. In each scenario, the storyboard format of JASs captures both the physicality of sharing content around a tabletop display, and the associated mental actions and communication grounding costs.

When discussing materials displayed on the tabletop, without RNT, the recipient needs to either re-orient their head to the shared content, or do so mentally, to comprehend what is being shared (Figure 6-7 Top). Either of these activities would make the grounding process more effortful for the group. When the sender repairs a communication breakdown with RNT, they rotate the image to assist the recipient (Figure 6-7 Middle). Comparing the two JASs in Figure 6-7 Top and Middle reveals that while Participant A incurs Production and Repair costs, by doing so they eliminate sustained Understanding costs for their partner. This insight is depicted by the absence of grounding costs in Joint action #4 in Figure 6-7 Middle compared to Joint action #4 in Figure 6-7 Top. Finally, when RNT is available and the sender anticipates their collaborator's needs, only Production costs are incurred (Figure 6-7 Bottom).

### 6.7.3 Beyond Collocated Collaboration: Skype[15]

While we were motivated to develop JASs by our research on technologies that support synchronous, collocated collaboration, they are also applicable to a wide range of CSCW applications, including synchronous remote work. To demonstrate how JASs can be applied in these contexts, we analyzed a familiar use case where two people are conversing remotely over the commercial video conferencing tool Microsoft Skype[15] (Figure 6-8). Our analysis communicates the impact of the respective user interface elements on communication grounding and helps identify opportunities to improve the Skype[15] interface to better support grounding.

[15] https://www.skype.com/

We analyzed an instance of interest where the Wi-Fi signal suddenly becomes weak and audio and video jitter is introduced (Figure 6-8). The speaker may not notice the situation immediately and continue talking, leading to sustained Production costs (Joint actions #1-3, Figure 6-8 Top), as they continue talking until it becomes clear that there is a connection issue (Joint action #4, Figure 6-8 Top). Meanwhile, the listener pays Understanding costs as they try to see if the connection has been lost or not (Joint action #2, Figure 6-8 Top). The speaker will have to repeat the information they had conveyed during the connection failure once it is re-established. In the situation where the speaker is discussing content from a shared screen (e.g. sharing a PowerPoint presentation with their remote partner, as is common in virtual meetings), it may take some time for the speaker to notice the connection issues. Both the speaker and listener pay sustained Delay and Repair costs as their communication is interrupted (Delay: all Joint actions, Figure 6-8 Top; Repair: Joint actions #4-8, Figure 6-8 Top). Finally, if the listener decides to hang up and call back, the speaker incurs Understanding costs (Joint actions #4-5, Figure 6-8 Top), as they are left wondering what happened.

As much as possible, these tools should visualize any detected internet connectivity issues, and also status issues of connected parties to help minimize Understanding costs. For instance, in the commercial video conferencing tool Zoom[16] , when a remote party's internet connection is poor, a red signal icon on their video / user box is displayed along with the text "<user name>'s network bandwidth is low.". Figure 6-8 Bottom shows the JASs for a hypothetical redesign of Skype[15] that adds a similar connectivity awareness feature that makes the speaker aware of their partner's poor internet connection status (Joint action #1, Figure 6-8 Bottom). As the JASs shows, this allows the speaker to proactively initiate a repair, and eliminates Understanding costs for them. These process changes enabled by interfaces modifications that provide more awareness of the situation ultimately make the grounding process less effortful for the group.

[16] http://zoom.us

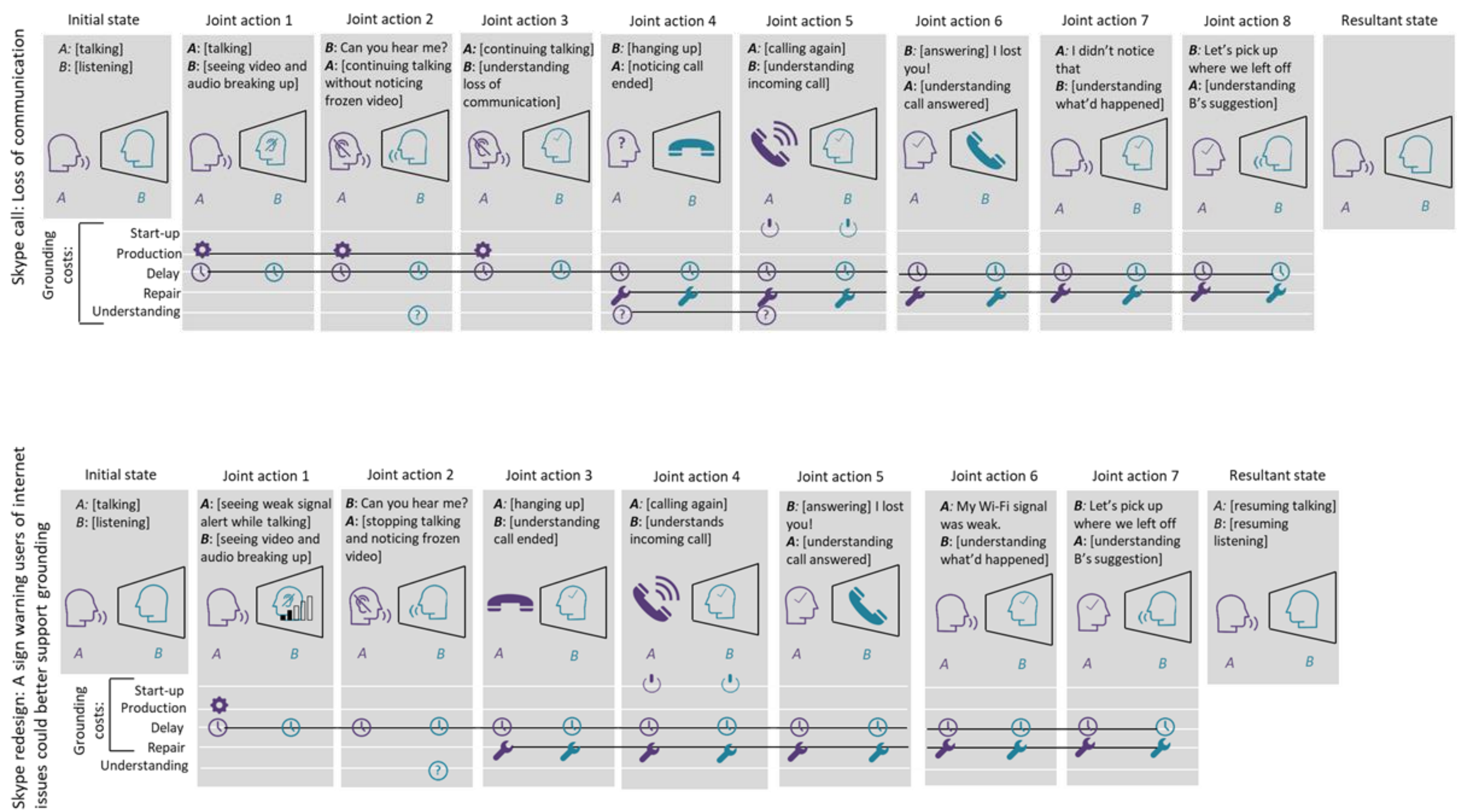



**Figure 6-8. Project 3. JASs analysis of interruption during a remote synchronous collaborative scenario (Top: Skype call). Bottom: Applying JASs to articulate a design alterative to alleviate some grounding costs**

## 6.8 Initial Experiences in Applying JASs in Practice

To better understand the level of expertise required to apply the JASs analysis technique to a CSCW use case, we ran a pilot study in the form a workshop with 4 HCI faculty and graduate students in our research institute. In a 90-minute session, we first gave a tutorial of how the JASs framework works by walking through the example of sharing directions to a café (Figure 6-1). Workshop participants were then asked to create JASs for the Tilt-to-Preview (Marquardt, Hinckley, et al., 2012) use case described in Section 6.7.1

We found that participants were able to identify some of the joint actions. However, there was some uncertainty around how to deal with overlap between costs. There was also some uncertainty about how many, or which, mental states could be represented for the recipient in a given joint action (i.e., only the following four: not noticing, not perceiving, not understanding, or observing and understanding). These informal experiences with the JASs tool showed that some level of expertise was needed to create JASs. Based on this finding, and comments from our workshop participants, we included a detailed description of the process of creating JASs in Sections 6.4 and 6.5 to help clarify the knowledge and the steps needed to create effective JASs representations.

## 6.9 Discussion

Our work was motivated by our own challenges in analyzing existing data, particularly in understanding how interfaces facilitate communication grounding, and finding that existing analysis techniques fell short. Clark and Brennan's (Clark & Brennan, 1991) communication grounding framework provided a well-established foundation for HCI researchers and designers to draw on when examining communication effectiveness, yet it did not provide a sufficient means of linking communication effectiveness to CSCW tools. Like other CSCW researchers (Brennan et al., 2006; Convertino et al., 2009; Gergle et al., 2013), we sought to leverage this strong foundation to help researchers and designers understand the impact of today's technologies on collaboration, and communication grounding specifically. By combining communication grounding with joint actions, JASs provide a novel method to link physical and mental interactions in CSCW environments, visualize and analyze interaction minutiae, and articulate design changes in complex and evolving CSCW settings.

JASs are a qualitative analysis tool. As with other qualitative analysis tools (e.g. heuristic evaluation (Preece et al., 2007), task analysis (Preece et al., 2007), and GOMS (Dix et al., 2004; Preece et al., 2007)), the goal of the analysis is not reaching consensus among researchers but to articulate design decisions and identify design opportunities. Agreement between individual researchers is not necessarily required, or even desirable, since "codes are the process not the product" (McDonald et al., 2019, p. 33). Indeed, we believe the diversity and subjectivity of each researcher is valuable for capturing a broad range of perspectives and that a unique grounding cost or design opportunity flagged by one researcher does not discount aspects of the design identified by others, similar to unique usability issues identified by different heuristic evaluation inspectors. Similar to other analytic frameworks and tools, however, a skilled analyst will take some time to learn and apply the tool effectively. While we attempt to provide sufficient background on communication grounding and grounding costs as a stand-alone guide for creating JASs in this paper, as with any tool, the more practice, and contextual background the analyst has, the more insightful they will be at applying the tool.

As is true with other qualitative analytic tools, a researcher's existing knowledge about a CSCW system may influence what part of the data or system they pick for further examination using JASs. In this case, JASs allow for a fine-grained analysis of an instance of interest by linking physical and mental actions of the participants to the specific user interface elements. In fact, in our analysis of TOUCH and TILT (Homaeian et al., 2018), we were aware that the two techniques benefitted collaborative processes differently. What JASs provided was a tool and vocabulary to articulate how that difference was tied to the user interface elements, something that was not possible using the analysis methods employed in our original work (Homaeian et al., 2018).

Our case studies demonstrate how JASs may be applied outside of traditional collocated, synchronous collaboration settings. While, space constraints do not allow an exhaustive list, we envision that they are applicable in a range of contexts, including augmented- or mixed-reality technologies.

### 6.9.1 Linking Physical and Mental Interactions and Grounding Costs

JASs provide an analysis structure, vocabulary, and visual framework to help CSCW researchers and designers understand the impact of the system design on communication grounding. While researchers highly familiar with the grounding process and grounding costs may not need these tools, as researchers who have both taught and used these concepts in existing analysis approaches (e.g. conversational analysis, qualitative video coding), we recognize how complex and context-dependent the grounding process and costs are. We have found the use of specific instances of interest and the visual framework of the storyboard structure to be highly useful to help focus analytic efforts on key aspects of group interactions with CSCW technology.

A key advantage of JASs is that they convey an integrated view of the physical and mental interactions involved in the instance of interest, together with the relevant grounding costs, to provide an overall depiction of the situation that helps analysts understand and communicate the strengths and weaknesses of the studied interface or interaction design features. Indeed, through developing JASs for the presented case studies, we have revealed design opportunities to help minimize grounding costs. For instance, the JASs analysis of Tilt-to-Preview (Marquardt, Hinckley, et al., 2012) revealed an opportunity to reduce sustained Production costs incurred with the current system design (Figure 6-6) and JASs analysis of our (Homaeian et al., 2018) TOUCH interface revealed an opportunity to reduce Understanding costs that can arise in some situations with the current design (Figure 6-3 and Figure 6-4).

### 6.9.2 Focused Analysis of Interaction Minutiae

CSCW research has shown that small design changes in a user interface design can impact collaboration (Gutwin & Greenberg, 1998). Yet, traditional collaborative analysis methods like conversational analysis (i.e. word counting or word coding) or video analysis are insufficient for understanding the impact of a tool on collaboration, or for understanding what specific aspects of the technology should be improved. Analysis frameworks like JASs can provide the necessary structure, vocabulary, and concepts to help researchers focus on key aspects of a group's interaction directly or indirectly involving the technology, at an appropriate level of detail, to help uncover challenges that may be overlooked by all but the keenest analyst using other tools. For instance, during discussions around a piece of data using the TOUCH and TILT techniques (Homaeian et al., 2018), often people didn't verbally instruct a partner to move their ROI to the respective location on the map. This subtle behaviour would render current communication grounding techniques, such as conversational analysis, less effective. However, JASs captures how people adapted their grounding process to the unique affordances of TOUCH and TILT by looking at the details of people's interaction with the CSCW.

The use of "instances of interest" in our JASs approach was intentional. Clark and Brennan (1991) and others (Gutwin & Greenberg, 1998) have shown how the minutiae of communication and collaboration processes around CSCW can impact the entire experience over time. For example, Gutwin and Greenberg (1998) discuss that even a subtle change such as highlighting a button when pressed has an important role in providing awareness to the team about an action that a collaborator executed. Instances of interest focus on interaction minutiae; they enable a focused analysis of how specific user interface design choices might impact people's experiences around CSCW technology.

### 6.9.3 Articulating Design Changes in CSCW Environments

JASs' storyboard format enables the creation of simple diagrams that depict the spatial layout and body orientation of people relative to each other and relative to the technology they are using, or even the environment in which they are working. Indeed, effective grounding involving CSCW systems depends heavily on group members' ability to notice and perceive both verbal and nonverbal communication from collaborators, as well as any displayed information (textual, visual, graphical, auditory, etc.) (Clark & Brennan, 1991). Deictic referencing (pointing, gesturing, etc.) is important for communication and grounding (Bekker et al., 1995; Clark & Brennan, 1991). The multitude of form factors, devices, number of devices, and various interface and interaction design options available in today's technologies can introduce many challenges for effective non-verbal communication that can impact both the informational and integrational (i.e., procedural) aspects of communication (Argyle, 1969).

Thus, for CSCW technologies that involve mobility or physical interaction or collocated collaboration, the spatiality of people and any technology they are using may be extremely important to examine when assessing how well a tool supports grounding. This is perhaps obvious for the use cases examined in our case studies that involved collocated CSCW technologies, like cross-device interactions or discussions of content on a digital tabletop. For instance, in the RNT Case Study (Figure 6-7), the orientation of collaborators to each other, and relative to the tabletop and its displayed content was essential for understanding the potential barriers to grounding that groups can face in that technology setting.

However, this may also be relevant to capture when examining collaboration involving augmented- or mixed-reality tools, where one or more collaborator is interacting with one's physical surroundings as part of the digital interactions. Moreover, even a remote video call may involve physicality in which spatial interactions are relevant. Many of us have experienced video calls where one person is walking around a space with a smartphone, tablet, or laptop, trying to show their remote partner(s) something in the physical space. This can often be very frustrating and disorienting for all parties. By capturing the relative spatial relationships of all parties and devices and relevant interfaces involved, JASs could help identify features of the available video chat tools that either hinder or support communication grounding.

## 6.10 Limitations

By design, JASs focus on the minutiae of collaborative interactions, and the impact that CSCW technology interfaces have on those interactions. Similarly, JASs are intended to specifically assess the impact of a technology on a group's communication processes. Due to this focus, we envision JASs being used in conjunction with other assessment tools and measures commonly used in CSCW research and practice (e.g., conversational analysis, qualitative video analysis, interaction log analysis), that focus on other aspects of the communication or collaboration.

We designed the JASs visualizations to accommodate a wide range of technologies, and to be adaptable to new types of devices as they emerge. However, when using JASs as a "discount[17] usability" technique for technology design, observations of group interaction with the system are unavailable to identify suitable instances of interest. In this case, expected use cases involving collaborative interactions with the technology will need to be generated first, and then specific instances of interest can be identified from those use cases. We believe that the exercise of generating these instances, and envisioning interaction with a new device or system are also beneficial activities in themselves.

Clark and Brennan, as well as others, have noted that their communication grounding framework was not exhaustive (Clark & Brennan, 1991; Fox Tree et al., 2011). Indeed, additional grounding costs and communication medium (or technology) affordances have been proposed by Brennan and others in subsequent research. For example, Brennan et al. (2006; 1999) defined additional grounding costs such as monitoring and face management, that refer to the cost of monitoring a partner's focus of attention or the objects they are manipulating within the environment, and the cost of maintaining politeness in a conversation, respectively. These costs are paid by either party. We did not include these costs in our JASs analyses, as they were generally consistent in the instances of interest under consideration. However, these or other additional relevant grounding costs could easily be considered in the analysis by adding extra cost lines at the bottom of each joint action frame in the storyboard.

[17] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

Finally, JASs were designed to assess grounding costs for small-groups. Visualizing the mental and physical interactions for a large number of people may not be feasible using current representations. However, we could imagine scenarios where a large number of "audience" members, using the same or similar system designs (software and hardware) might be represented collectively as a single "audience", "student", or other role in the JASs diagrams. We have even conducted thought experiments of applying this tool to help assess the many available video conferencing and virtual classroom tools being used for remote course delivery during the current COVID-19 pandemic to understand the grounding costs involved in these systems. Further work is needed to understand the feasibility of this approach.

## 6.11 Conclusion

We presented the development of JASs, a visual framework for analyzing and articulating the impact of specific user interface designs on communication grounding. We demonstrated JASs' benefits over existing methods for HCI and CSCW research by applying the framework to a number of case studies of interaction techniques from the literature. We also discussed that by capturing collaborators' mental and physical interactions with each other and the CSCW environment in in integrated view, JASs enable a focused analysis of interaction minutiae and provide a vocabulary and tool for researchers and technology designers to communicate the impact of user interface designs on communication grounding. Finally, we discussed the limitations of our method.

We believe that JASs can be useful in understanding interaction with novel devices and in novel settings. For instance, we are increasingly taking advantage of home assistants like Amazon Alexa and Google Home, in which communication grounding occurs between a human and an artificial intelligence (AI) collaborator. Similarly, collaborative augmented- and virtual-reality applications are an active area of HCI research, and undoubtedly need to support communication grounding in virtual, rather than physical spaces. The JASs visual framework is both powerful and flexible enough to articulate communication grounding in these use cases and is a promising avenue for future work.

## 6.12 Acknowledgements

Head icons in Figure 6-8 are adapted from icons made by Kiranshastry from flaticon.com. Delay costs icons in Table 6-3, Figure 6-4 and Figure 6-5, and Figure 6-8 are adapted from icons made by dmitri13 from flaticon.com. Production costs icons in Table 6-3, Figure 6-3, Figure 6-6, Figure 6-7,

and Figure 6-8 are adapted from icons made by Freepik from flaticon.com. Finally, Repair costs icons in Table 6-3, Figures Figure 6-4, Figure 6-5, Figure 6-7, and Figure 6-8 are adapted from icons made by Pixel perfect from Flaticon.com.

# Chapter 7: Discussion

I this chapter, I will discuss my thesis contributions, what I learned about designing for individuals versus groups, and the transferability of my findings to other technological and social contexts. Finally, I reflect on the research methodologies that I employed.

## 7.1 Contributions

This section discusses how findings in research projects 1-3 lead to the thesis contributions (Figure 7-1)

| Overarching RQ | Specific RQs | Research projects | Answers to RQs | Thesis contributions |
|---|---|---|---|---|
| **RQ-T:** How does the user interface design of cross-device interaction techniques impact mixed-focus collaboration? | **RQ1:** How does the choice of TOUCH and TILT cross-device interaction techniques impact mixed-focus collaboration? | **Project 1:** Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration *(Homaeian et al. CHI'18)* | TILT supported independent work, whereas TOUCH facilitated joint work. Providing both techniques gave collaborators flexibility. Yet, it did not alleviate all limitations of individual techniques. | 1. Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration<br>2. Design considerations for cross-device interaction techniques to support mixed-focus collaboration |
| | **RQ2:** What are some possible ways to design coordination in cross-device transfer to support flexibility of work styles in mixed-focus collaboration? | **Project 2:** Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration *(Homaeian et al. PACMHCI '22)* | There are design criteria that impact synchronicity between the sender and receiver. The synchronicity framework provides a conceptual model to articulate temporal coordination in cross-device transfer and consequential impact on mixed-focus collaboration. | |
| | **RQ3:** How can we articulate the (sometimes subtle) impact of specific user interface designs on communication grounding? | **Project 3:** Joint Action Storyboards: A Framework for Visualizing Communication Grounding Cost *(Homaeian et al. PACMHCI '21)* | The concept of joint actions can be used to show collaborators' mental actions, and interactions with each other and the system in collaborative instances. JASs visualizes joint actions and the corresponding grounding costs. | 3. A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes |

**Figure 7-1. Thesis and project contributions, replicated from Figure 1.1**

### 7.1.1 Problematizing the Impact of Cross-Device Interaction Techniques on Mixed-Focus Collaboration

The HCI research community continues to introduce novel cross-device interaction techniques (Brudy et al., 2019). Yet, there is more research needed to investigate properties of those techniques that affect how people conduct group work (Convertino et al., 2008, 2009). Projects 1 and 2 contribute towards that research gap by confirming that the choice of cross-device interaction technique for supporting mixed-focus collaboration indeed matters. Interaction design choices can impact the flow of individual work periods, joint discussions involving system interaction, and transitions between these two work styles. My findings suggest that collaborative XDEs should provide flexible transfer options that people can choose to suite the ongoing flow of group work.

Compared to TILT, the TOUCH technique supported groups in tightly coupled work periods as collaborators were able to more easily coordinate 'showing' data to each other. As the JASs analysis shows (Figure 6-3), TOUCH had fewer grounding costs and thus afforded more effective communication grounding. TILT supported independent work periods as collaborators were able to reach all areas on the tabletop without having to rely on their partner. However, it was perceived as more effortful compared to TOUCH, which supported direct touch interactions with the tabletop.

Project 2 involved an in-depth investigation of coordination in cross-device transfer, specifically temporal coordination. The findings showed that the design and availability of Handoff and Deposit techniques influenced collaborative processes. For example, some participants avoided the Freeze-Handoff technique, which paused the target screen, during our user observation sessions with the high fidelity prototypes. These participants resorted to Deposit to transfer data to their partner, forcing the receiver to interact with interface before they could view the data needed for their ongoing discussion. This observation led to the redesign of Freeze-Handoff to show an enlarged version of the data to the receiver, which was appreciated by collaborators. The new Fullscreen-Handoff design allowed groups to view data under discussion with less disruptions to the collaborative flow. This project led to design considerations that highlight how a transfer technique could impact mixed-focus collaboration.

Both projects provide evidence that the user interface design choices made during the development of a cross-device transfer interaction technique can negatively impact collaboration, and that this problem needs more attention in HCI and CSCW literature. Moreover, given the proliferation of technology that has given rise to new forms of interaction, researchers and designers need frameworks and tools to help them design and understand how interface design choices may support or hinder collaboration. My other two contributions are towards that goal: Projects 1 and 2 provide design considerations for XDEs and cross-device transfer, respectively, and Project 3 provides a visual framework to analyze and communicate the impact of interface design on communication grounding, a key aspect of effective collaboration.

### 7.1.2 Design Considerations for Temporal Coordination in Cross-Device Interaction

Two projects in this dissertation investigated how cross-device transfer can impact mixed-focus collaboration. Project 1 generally explored communication and coordination in an XDE with a shared tabletop display. Project 2 focused on temporal coordination in transfer between personal devices in XDEs. Both projects resulted in design considerations for cross-device interaction. This contribution complements existing guidelines and frameworks in the literature, which do not provide guidance on how specific coordination mechanisms and degrees of synchronicity in cross-device transfer may hinder or foster collaborative processes. Existing research has categorized transfer techniques based on various characteristics, e.g. reach range (Nacenta et al., 2005), proxemics of devices and people (Hinckley et al., 2004; Marquardt, Hinckley, et al., 2012; Rädle et al., 2014). My design considerations have the potential to be useful regardless of such categorization. They focus on temporal coordination and provide a novel perspective through the lens of impact on mixed-focus collaboration.

Transfer in XDEs requires a high degree of spatial and temporal coordination. Spatial coordination depends on the form factor of devices available in the environment and their screen space. It has been studied extensively following the theory of tabletop territoriality (Scott et al., 2004). However, temporal coordination is less understood in the literature and is device agnostic; the sequence of actions by the sender and receiver to initiate and complete transfer is independent of the size of their devices. Project 2 explored temporal coordination in transfer between personal devices in XDEs and resulted in five design considerations. Adapting Harris's synchronicity framework (Harris, 2019) was helpful to describe temporal coordination based on the degree of synchronicity between the sender and receiver. The degrees of synchronicity give HCI researchers and practitioners a conceptual model and a language to articulate temporal coordination of transfer and its potential impact on collaborative processes.

Project 1 resulted in four design considerations: DC1) Giving the receiver the option to open the data later (temporal coordination), DC2) A mechanism for synchronized data viewing (temporal coordination), DC3) Using the shared screen to view transferred data (spatial coordination), and DC4) Allowing collaborators to aid each other in viewing data (temporal coordination). Harris's framework (Harris, 2019) adapted in Project 2 is applicable and useful when communicating how to address the design considerations in Project 1.

With the Instant synchronization design pattern, the receiver can use the shared item without interacting with the interface. Therefore, this design pattern can be used to facilitate synchronized data viewing on personal tablets (DC2): one party could initiate and complete transfer for both devices. Moreover, Instant synchronization allows a party to 'assist' their partner with using the shared data instantly (DC4).

Expectant, Sequential, and Asynchronous designs can be adopted to allow the receiver to buffer the shared item without interrupting their ongoing work (DC1). For instance, the technique can transfer a thumbnail of the item and hold up the sender until the receiver attends to the thumbnail (Expectant pattern), or hold up no one and instead give the receiver a predefined amount of time to interact with the thumbnail (Sequential pattern). Alternatively, the technique can impose no time constraint on when the receiver attends to the shared item (Asynchronous pattern).

Choosing how to address the design considerations and thus design patterns to facilitate temporal coordination in cross-device transfer depends on the task context. The coupling style of a group can be determined by group dynamics, background, and culture. Task requirements, e.g. interactions between roles and time constraints also play a role in how closely collaborators work with each other. (Pinelle et al., 2003). For instance, if joint discussions are needed to view and filter data, then the Instant design pattern is useful as it reduces collaborative effort in data access and viewing. However, it could be disruptive if the task is dominated by long independent work periods. In this case, a Sequential pattern that does not automatically interrupt the target screen could be effective as it allows the receiver to quickly wrap up in-progress work and then open the shared item.

The JASs framework developed in Project 3 is a useful tool to analyze how temporal coordination required by a given interface design may impact communication grounding and ultimately collaborative processes. Grounding costs associated with the interface and interactions, which are also contextual, are marked to understand if a given design pattern interferes with or supports the target collaborative phases.

### 7.1.3 A Visual Framework for Analyzing and Articulating the Impact of User Interface Designs on Collaborative Processes

In this research, I contributed a visual framework (JASs) that HCI researchers and practitioners can use to understand how user interface designs may impact communication grounding (Project 3). While conducting Projects 1 and 2, I identified a need for JASs as existing tools fell short on helping me articulate how specific interface features impact collaboration. Existing methods were designed to model single user systems (e.g. task analysis) or error-free interactions (e.g. GOMS), have a broad unit of analysis (e.g. heuristic evaluation), or ignore interactions with technology (e.g. conversational analysis). JASs fills this gap by including interactions with the interface and collaborators, and underlying mental actions, which are fundamental to communication grounding and the broader collaborative activity (Clark & Brennan, 1991; Isenberg et al., 2012).

Through a series of case studies, I demonstrated the benefits of JASs for HCI research: it can be used as a discount[18] evaluation or summative evaluation tool, it captures physicality of the environment and interactions, and it is applicable to synchronous co-located and remote collaborative systems. JASs is an accessible framework that does not require specialized knowledge with communication grounding. The unit of analysis is momentary yet frequent interactions with the system that are critical in the task. Therefore, grounding costs incurred in those interaction can build up over time. By visualizing the grounding costs, JASs helps researchers identify redesign opportunities and communicate the impact of such redesigns to their research team or the community.

In Project 3, I explored potential benefits of JASs through a series of case studies, showing JASs seems to be a good tool for eliciting design conversations. As more researchers apply JASs in their own projects, further knowledge about JASs' benefits will be generated and verified and will increase our understanding of JASs' scope of applicability.

Notably, the icons used in JASs in this dissertation represent able-bodied users only. The set of icons should be extended to be more inclusive, especially for analyzing systems that are designed to accommodate a wide variety of abilities.

## 7.2 Trade-offs in Designing for Groups and Individuals

This dissertation provides evidence towards a tension faced by technology designers in addressing requirements of individuals as well as groups (Gutwin & Greenberg, 1998). I reported trade-offs with TOUCH and TILT, and with Handoff and Deposit. Although cultural and social factors can impact how collaborators employ techniques in XDEs (Janis, 1982; Pinelle et al., 2003), my findings suggest there are benefits in offering flexible transfer techniques in XDEs as they can alleviate trade-offs experienced with a single technique.

Compared to TILT, the TOUCH technique fostered more group awareness through direct touch interactions with the shared tabletop. Yet, it limited individuals' ability to access out-of-reach parts of the tabletop, a function offered by the remote control feature of TILT. However, with TILT, maintaining

---

[18] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

awareness was harder as collaborators had to locate their partner's ROI on the map to keep track of what part of the map they were studying. Also, the user-agnostic property of the tabletop enabled people to assist their partners in viewing data related to ongoing discussion in TOUCH. With TILT, this assistive behaviour was not possible and thus TILT limited groups' ability to effectively share data; they incurred more grounding costs (Figure 6-3).

The 'individual freedom in achieving collective goals' offered by TOUCH, however, sometimes compromised group awareness: collaborators could automatically update their partner's tablet view with data and thus potentially interrupt their ongoing independent work. This finding highlights the tension faced by designers in addressing the needs of individuals as well as groups in shared workspaces (Gutwin & Greenberg, 1998). The BOTH condition, better supported independent and joint work by allowing collaborators to choose which of the two techniques they preferred in the moment. However, it did not solve all coordination issues: each of the TILT and TOUCH techniques were still helpful in some moments and disruptive in other time. For example, sometimes collaborators experienced interruptions to their screen with the TOUCH techniques. Yet, improved support for collaboration in the BOTH condition points to benefits of giving users a choice of cross-device interaction techniques in XDEs.

Indeed, people use two mechanics to transfer objects in physical shared workspaces: Handoff and Deposit (Pinelle et al., 2003). Collaborators coordinate the timing of transfer according to the flow of collaboration and the purpose of the transfer: whether the receiver should immediately take the shared item or if it can be left somewhere in the space for later retrieval. If an XDE offers one type of transfer, then people may experience frequent interruptions to their independent work (e.g., with Handoff only) or they may find group discussions involving data sharing overly effortful (e.g., with Deposit only). Therefore, careful design of temporal coordination in cross-device transfer is important to support mixed-focus collaboration. In Project 2, I explored several Handoff and Deposit designs for transferring data between personal devices. The resulting design considerations offer insight into how temporal coordination may be designed and balanced to facilitate individual as well as tightly coupled work styles.

## 7.3 Design Implications for Other Collaborative Environments

The design considerations (DCs) developed in Projects 1 and 2 (Table 7-1) were based on studies in a synchronous co-located collaborative environment comprised of tablets and a tabletop. When deciding on the transferability of the DCs and other findings of this dissertation to other systems, one needs to consider contextual factors that impact collaborative processes, e.g., technological settings and task requirements such as interaction between roles and time constraints (Pinelle et al., 2003).

**Table 7-1. Design considerations developed in Projects 1 and 2 mostly draw attention to temporal coordination in XDEs, and are thus free of device form factor and size.**

| | |
|---|---|
| Project 1<br><br>(all pertain to temporal coordination except DC3) | 1) Giving the receiver the option to open the data later<br>2) A mechanism for synchronized data viewing<br>3) Using the shared screen to view transferred data (spatial coordination)<br>4) Allowing collaborators to aid each other in viewing data |
| Project 2:<br><br>(all pertain to temporal coordination) | 1) Transfer Acceptance<br>2) Action Dependencies<br>3) Immediate Usability[19]<br>4) Interruption Potential<br>5) Connection Actions |

Most of the design considerations are focused on temporal coordination in cross-device transfer, i.e., the sequence of actions by the sender and receiver. Thus, they are device agnostic and independent of device size. For instance, they are useful in other XDEs, such as personal tablets and walls, or environments with a single shared display, such as a tabletop or wall, to support mixed-focus collaboration. Moreover, previous research shows that people partition a shared tabletop display into group, personal, and storage territories to spatially coordinate their work (Scott et al., 2004). Project 2 DCs were developed for tablet-to-tablet transfer and in Project 1 data viewing was possible only on tablets. Yet, when designing for a collaborative environment with a shared display, one can consider how the DCs come into play with spatial coordination. For instance, transferring an item to the group territory has a different 'Interruption Potential' than the personal territory of the receiver. Similarly,

[19] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called 'Immediately Usable', as 'usability' has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

‘Immediate Usability[20]’ and ‘giving the receiver the option to open the data later’ may be possible by receiving the item in the personal territory and group territory, respectively.

Additionally, the design considerations in Table 7-1 could be arguably useful in designing systems to facilitate mixed-focus collaboration for physically-distributed groups. Variable coupling styles, i.e., tightly and loosely coupled styles and transitions between them, are present in synchronous remote work as well as in co-located environments and thus need to be supported in collaborative systems (Pinelle et al., 2003). In remote environments, verbal and non-verbal communication channels may be limited or less effective compared with co-located environments. Also, collaborators may not have access to a shared view. Therefore, grounding costs are higher when people work remotely (Clark & Brennan, 1991). Such contextual information together with design considerations in Table 7-1 can guide designers in designing cross-device transfer in remote system. For instance, in a shared physical space showing data to a partner by turning one’s personal device facilitates joint discussions (as reported in Project 1 (Homaeian et al., 2018)). However, the same action is not possible in remote environments or it may take several interaction steps to share one’s screen view with a partner. Thus, having ‘Immediate Usability[20]’ for transferred items is a way of counting grounding costs due to lack of co-presence (Clark & Brennan, 1991). Another example is that in a physically distributed environment, information gathering about collaborators’ activities is more difficult compared to co-located settings, e.g. body position and gaze direction (Pinelle et al., 2003). Therefore, designing a transfer technique that has ‘Interruption Potential’ should be done carefully as interrupting a partner’s independent work may have higher grounding costs due to lack of contextual cues.

Finally, the idea of providing flexible transfer techniques to facilitate mixed-focus collaboration is potentially useful given any technological settings for group work. This concept is rooted in the mechanics of collaboration, which state low-level operations for group work whether collaborator are co-located or physically distributed. Given the ongoing flow of collaboration, people resort to different mechanics for transfer, for example, whether the receiver should take the item immediately or it can be retrieved later (Pinelle et al., 2003). The design considerations in Projects 2 draw one’s attention to how to facilitate that flexibility in temporal coordination of transfer and the potential impact on collaborative processes. Project 1 findings also offer insight in supporting the flexibility of collaborative processes

[20] Post publication footnote: Further reflection after this paper was accepted has led to the conclusion that this design consideration is more appropriately called ‘Immediately Usable’, as ‘usability’ has a certain definition in HCI and Human Factors fields, e.g. efficiency, learnability, and effectiveness (Preece et al., 2007).

in mixed-focus collaboration. For example, by 'Allowing collaborators to aid each other in viewing data' (Table 7-1) TOUCH facilitated tightly coupled work and transitions from loosely coupled work. Project 2 specifically looked at degrees of synchronicity between collaborators and how it may be designed to support flexible collaborative processes.

Task requirements are other factors that can impact design implications for contexts beyond the ones studied in this dissertation. For example, if a hierarchical structure exists between collaborative roles, e.g. a student-teacher relationship, Actions Dependencies has a different implication compared to the peer collaboration tasks that I studied. In the former, it could trigger a timely response by the receiver. However, in the latter, Action Dependencies could lead to unnecessarily effortful interactions. Another example is a context where there are time constraints to generate an output, e.g. emergency response. In this case, the design consideration Interruption Potential in addition to Immediately Usable may be the way to get team member's attention. In a peer collaboration environment, however, Immediately Usable may be sufficient for transitions to joint work periods.

## 7.4 Reflection on Research Methodologies

While Project 2 followed a Research through Design process throughout the development of the cross-device transfer techniques, the original intent was to conclude the design process with a formal user study following the user observations with the high fidelity prototypes, and not complete the in-depth design reflections and analyses that led to the design considerations presented in Chapter 5. The user study aimed to investigate the impact of Handoff and Deposit techniques on face-to-face collaboration. The user study was completely designed, including ethics approval, and was ready to run in winter 2020, just as the World Health Organization declared the COVID-19 pandemic and the university suspended all in-person activities on campus. Thus, I was unable to run the user study. I discussed a contingency plan with my supervisors. In this section, I present the reasons that shaped the plan, what I learned by pursuing the new research direction, and what would I have learned if I had had the chance to run my user study.

### 7.4.1 Pivot to Formalizing the Research through Design Process

I had collected data in user observation sessions and had learned a great deal about cross-device transfer design for mixed-focus collaboration during the system design process. Moreover, during interactions with members of our research group at the Games Institute, I had learned about Research through

Design as a method of inquiry in HCI. I had realized that my approach in the Handoff and Deposit project was indeed Research through Design: the research problem did not have a single optimal solution, stakeholders (groups versus individuals) had conflicting needs in the context, and my understanding of the problem and its framing had been developing through iterative design activities. More importantly, I was designing and developing an XDE to realize a system with flexible transfer techniques and planned to study how people would use the system to solve a collaborative sensemaking task. After discussions with my supervisors, I decided to pivot to this new research opportunity by conducting Project 2: I formalized my ongoing Research through Design process by formulating design considerations for temporal coordination in cross-device transfer to support mixed-focus collaboration. I corroborated my findings with the literature to find any inconsistencies or gaps in my design considerations. That activity led to an additional design consideration and the adaptation of Harris's framework (Harris, 2019). The framework is useful for articulating design options for temporal coordination in cross-device transfer and the potential impact on collaboration.

A benefit of Research through Design contributions to HCI literature is that the research process is reported (Zimmerman & Forlizzi, 2014). Therefore, details such as insights gained during the process and design options considered but not pursued are documented, which are often not shared in other publications. Such details could inspire exploratory research and also increase the community's understanding of the constraints and possibilities that shaped the way the design space was explored (Dove et al., 2016). The design considerations that came out of Project 2 were the result of insights and knowledge that I gained while I was designing Handoff and Deposit techniques for my user study. My original design concepts were based on the mechanics of collaboration (Pinelle et al., 2003), which brings to attention 'which party is held up' during transfer. As I was reviewing literature and exploring coordination mechanisms for my tablet-to-tablet transfer context (e.g. (Brudy et al., 2019; Marquardt, Hinckley, et al., 2012; Rädle et al., 2015; Scott et al., 2014)), I discovered the many design choices for spatial and temporal coordination to 'hold up a party'. The design considerations in Project 2 emerged from this iterative design process and reflections on the potential impact on mixed-focus collaboration.

### 7.4.2 What Would I Have Learned by Running My User Study?

If I had run my user study as planned in winter 2020, I would have not engaged in the formalized Research through Design process that led to the design considerations. However, I would have learned about the causal relationship between the availability of Fullscreen-Handoff and Deposit techniques

(Figure 5-2) and collaborative processes. I would have recruited a larger number of participants compared with the user observations in the Research through Design Process. Therefore, I would have been able to study prevalence patterns in user behaviour. However, in the RtD process (Project 2), I performed a more nuanced *analytical* evaluation (Preece et al., 2007) of cross-device transfer techniques. Through iterative design activities, consulting the mechanics of collaboration (Pinelle et al., 2003) and the synchronicity framework (Harris, 2019), and corroboration with the literature, I drew a set of design considerations and predicted collaborative behaviour given how given techniques addressed those considerations (see Table 5-2). The primary contribution of the user study would have been empirical by providing new knowledge based on qualitative and quantitate analysis of the data gathered. The RtD process was mainly qualitative with a theoretical contribution. It informs what HCI researchers and practitioners do when designing cross-device transfer techniques, and what kind of impact on mixed-focus collaboration to expect (Wobbrock & Kientz, 2016).

## 7.5 Chapter Summary

This chapter connected the three research projects in the dissertation (Projects 1-3) by describing how the process and outcomes of one impacted the following project(s). It also elaborated on the findings of the projects that led to the thesis contributions:

1. Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration (Projects 1 and 2)
2. Design considerations for cross-device interaction techniques to support mixed-focus collaboration (Projects 1 and 2)
3. A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes (Project 3)

Two overarching points were discussed in a meta-discussion: (1) My findings provide evidence for a trade-off that designers face in designing collaborative systems (Gutwin & Greenberg, 1998): giving individuals freedom in the system comes at the expense of group awareness of collaborators' actions in the environment. (2) I discussed design implications for cross-device transfer in collaborative systems beyond the ones that were studied in Projects 1-3, for example, transfer between shared and personal displays, and transfer in remote systems.

I reflected on my pivot to formalizing the Research through Design process due to the COVID-19 pandemic in winter 2020. I talked about the benefits and lessons learned had I been able to run my user study at that time, and the knowledge that I gained by the conducting the in-depth analysis as part of the RtD process Project 2.

Finally, I discussed limitations of research performed in this dissertation and provided directions for future research based on my findings.

# Chapter 8: Conclusion

This thesis began by studying the impact of two cross-device interaction techniques, TOUCH and TILT, on collaboration (RQ1) in Project 1. The data was collected in an exploratory study (Goyal, 2016) and I re-analyzed the data to understand how the two techniques impacted different phases of collaborative sensemaking. As I learned about the limitations and benefits of TOUCH and TILT for group work, and reviewed the HCI literature related to collaboration in XDEs, new research directions presented themselves.

I was intrigued to investigate design options for cross-device transfer that would support mixed-focus collaboration. This led to RQ2 and therefore, in Project 2, I explored temporal coordination and flexible cross-device transfer techniques that would support independent and joint work periods and shifts between the two work styles.

One interesting and unexpected finding of Project 1 was that the TOUCH technique facilitated assistive behaviour by collaborators and thus helped them reduce collaborative effort. As I was researching methods to help articulate the link between TOUCH's and TILT's user interface and their impact on collaboration, I formulated RQ3 and developed the joint action storyboards (JASs) design and analysis framework in Project 3. JASs are a visual framework for analyzing and communicating the impact of specific interface features on communication grounding. Projects 2 and 3 overlapped in time and the JASs framework was helpful in evaluating Handoff and Deposit interface designs in Project 2.

My thesis makes the following three key contributions to HCI literature:

1. Problematizing the impact of cross-device interaction techniques on mixed-focus collaboration (Projects 1 and 2)
2. Design considerations for cross-device interaction techniques to support mixed-focus collaboration (Projects 1 and 2)
3. A visual framework for analyzing and articulating the impact of user interface designs on collaborative processes (Project 3)

## 8.1 Limitations

Like any piece of research, the work presented in this dissertation has limitations. Perhaps the most important one is generalizability. A main contribution this dissertation is a set of design considerations for temporal coordination in cross-device transfer. They describe how specific design choices may foster or hinder people's ability to conduct mixed-focus collaboration. They are grounded in a Research through Design process that consisted of iterative design and corroboration activities. However and as with any other theoretical contribution in HCI, more research is needed to employ the design considerations in similar and different task contexts and technological settings to provide evidence for their utility and also add to their descriptive and predictive power (Lazar et al., 2017; Wobbrock & Kientz, 2016). The research problem, i.e. the impact of temporal coordination in cross-device transfer techniques on mixed-focus collaboration is understudied in HCI literature. Thus, we conducted our user observations in a controlled laboratory setting to gain a baseline understanding of how the degree of synchronicity may play a role in facilitating or hindering phases of mixed-focus collaboration. Our participants were mainly graduate students at the University of Waterloo. Therefore, the design considerations should be used carefully in XDEs for field studies, where participants will be in their natural settings and uncontrolled factors may influence the way groups interact with the XDE (Lazar et al., 2017).

The JASs framework has a theoretical foundation. It is based on communication grounding (Clark & Brennan, 1991), which describes momentary joint actions performed by conversational participants to increment they common ground (Clark, 1996). I developed JASs while trying to articulate the connection between TOUCH and TILT's interface and the impact on collaboration. The framework was applied in a series of case studies to show how it complements existing techniques and its benefits for HCI researchers and practitioners. Nonetheless, JASs are designed for collaboration between pairs. The visualizations get complicated for scenarios involving more than two people. Moreover, by definition, JASs are for analyzing interaction minutiae. Thus, they should be used alongside other methods commonly used in HCI research, such as observations, video analysis, and conversational analysis, to identify interaction instances where the user interface elements are likely to impact communication grounding. To use JASs as a discount[21] evaluation tool, expected usage scenarios may be generated

[21] Post publication footnote: It is more accurate to call JASs an 'inspection' method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

first and then instances of interest are identified for a JASs analysis. Generating the use cases is a useful activity in itself as it helps the researchers envision how the system may be used by target audience and fit in their context.

## 8.2 Future work

Over the course of this dissertation, I identified a number of directions for future research that are discussed in the following subsections. In particular, there are opportunities to run empirical studies that increase our knowledge about the impact of temporal coordination in cross-device transfer on mixed-focus collaboration. I also propose a direction that can further demonstrate the utility of JASs in HCI research.

### 8.2.1 Extension of Our Understanding of Temporal Coordination in XDEs

It is well-established in HCI research that in spatial coordination, people naturally avoid interference (Scott et al., 2004; Tse et al., 2004). An interesting research opportunity is to investigate how people behave in *temporal* coordination of cross-device transfer. The user study planned to run in winter 2020 (described in Section 7.4.2) was intended to explore the impact of the Fullscreen-Handoff and Deposit techniques on mixed-focus collaboration. The findings of the Research through Design process in Project 2 identified new questions about temporal coordination that would be interesting to explore in a similar user study that could lay the foundation for a theoretical contribution. These research questions would focus on understanding how the temporal coordination of cross-device transfer impact different phases of mixed-focus collaboration, given the techniques available in each condition (Fullscreen-Handoff only, Deposit only, and both Fullscreen-Handoff and Deposit as shown in Figure 5-2). The findings would uncover patterns of collaborative behaviour, such as whether people avoid disrupting their partner's work, or when or if they might interrupt their partner.

The results of the above study would provide a baseline for understanding the impact of temporal coordination design in cross-device transfer on collaborative processes. As a follow up study, one could investigate the role of more nuanced designs of transfer techniques in supporting or hindering mixed-focus collaboration. For instance, an Instant synchronization pattern that requires Action Dependencies by, for example holding up the sender until the receiver accepts transfer (Table 5-2). An alternative direction for a follow up study is using different task contexts, for instance, a hidden profile task that encourages tightly coupled work, a task with equal data access that can be completed in long periods of independent work followed by discussions to find patterns and confirm hypotheses.

User observations in Project 2 revealed that the participants avoided using the Freeze-Handoff technique but appreciated Fullscreen-Handoff, even though both techniques interrupted the ongoing work of the receiver. It would be interesting to study the prevalence of that behaviour with a larger sample size. The findings together with results emerging out of the research directions proposed above would help understand when people choose to interrupt a collaborator and the role that temporal coordination facilitated by available cross-device transfer techniques plays in that regard.

### 8.2.2 Exploring Further Benefits of JASs for HCI Research

JASs provides a methodological contribution to HCI literature. The framework was evaluated and its benefits were demonstrated through a series of case studies. Future investigations could gather feedback from HCI researchers and practitioners about the utility of JASs in their respective design contexts. For example, participants could apply JASs in their ongoing HCI projects involving interface design as a discount[22] evaluation tool or they could use JASs to evaluate existing user interface designs. The investigation could be in the form of a diary study followed by interviews.

The findings could potentially uncover utilities of JASs beyond the ones discussed in this dissertation, for instance in new technological and task settings such as virtual reality and augmented reality, and one-to-many collaborative contexts. Such studies could also lead to new insights and understandings about the role of JASs for sparking conversation among a research team and exchange of perspectives. In our own case studies and demonstration of the framework to our broader research group at the Games Institute, we found that different people might not come up with the same JASs for a given scenario. This is indeed the case with some other qualitative analysis tools (e.g. Task Analysis and Heuristic Evaluation (Preece et al., 2007)) that the goal is not reaching consensus among researchers (McDonald et al., 2019). For instance, researchers may identify different grounding costs associated with an interaction, since the costs are contextual and not independent of each other (Clark & Brennan, 1991). This feature of JASs is beneficial for taking into considerations various aspects of

---

[22] Post publication footnote: It is more accurate to call JASs an ‘inspection’ method as a JASs analysis could involve users (Nielosn & Mack, 1994; Preece et al., 2007).

the interface and task domain (raised by different researchers) when analyzing the impact of user interface elements on communication grounding.

Although the visual language in JASs in this dissertation could be used by other researchers, it should be evaluated to make sure visualizations in a given JASs are interpreted as intended by the creator of the JASs. One way to do so is by conducting usability testing of icons to assess their Findability, Recognition, Information Scent, and Attractiveness[23].

[23] https://www.nngroup.com/articles/icon-testing/

## References


Argyle, Michael. (1969). *Social Interaction*. Methuen, London.

Bachl, Stefan, Martin Tomitsch, Karin Kappel, and Thomas Grechenig. (2011). The effects of personal displays and transfer techniques on collaboration strategies in multi-touch based multi-display environments. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (Vol. 6948 LNCS, pp. 373–390). DOI: https://doi.org/10.1007/978-3-642-23765-2_26

Bekker, Mathilde M., Judith S. Olson, and Gary M. Olson. (1995). Analysis of gestures in face-To-face design teams provides guidance for how to use groupware in design. In *Proceedings of the 1st Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS '95)* (Vol. 23-25-Augu, pp. 157–166). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/225434.225452

Biehl, Jacob T., William T. Baker, Brian P. Bailey, Desney S. Tan, Kori M. Inkpen, and Mary Czerwinski. (2008). IMPROMPTU: A new interaction framework for supporting collaboration in multiple display environments and its field evaluation for co-located software development. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI '08)* (pp. 939–948). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1357054.1357200

Bier, Eric A., Maureen C. Stone, Ken Pier, William Buxton, and Tony D. DeRose. (1993). Toolglass and magic lenses: the see-through interface. In *SIGGRAPH* (pp. 73–80). Anaheim, CA: ACM. DOI: https://doi.org/10.1145/166117.166126

Bortolaso, Christophe, Matthew Oskamp, Greg Phillips, Carl Gutwin, and T. C. Nicholas Graham. (2014). The effect of view techniqueson collaboration and awareness in tabletop map-based tasks. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)* (pp. 79–88). New York, New York, USA: Association for Computing Machinery. DOI: https://doi.org/10.1145/2669485.2669504

Bortolaso, Christopher, Matthew Oskamp, T. Graham, and Doug Brown. (2013). OrMiS: a tabletop interface for simulation-based training. In *Proceedings of the ACM international conference on Interactive tabletops and surfaces (ITS'13)* (pp. 145–154). St. Andrews, Scotland, United Kingdom: ACM. DOI: https://doi.org/10.1145/2512349.2512792

Boyatzis, Richard E. (1998). *Transforming qualitative information : thematic analysis and code development*. Sage Publications.

Brennan, Susan E., and Calion B. Lockridge. (2006). Computer-Mediated Communication: Cognitive Science Approach. In *Encyclopedia of Language & Linguistics* (pp. 775–780). Elsevier. DOI: https://doi.org/10.1016/b0-08-044854-2/00861-0

Brennan, Susan E., Klaus Mueller, Greg Zelinsky, I. V. Ramakrishnan, David S. Warren, and Arie Kaufman. (2006). Toward a Multi-Analyst, Collaborative Framework for Visual Analytics. In *Proceedings of the IEEE Symposium On Visual Analytics Science And Technology (VAST '06)* (pp. 129–136). IEEE. DOI: https://doi.org/10.1109/VAST.2006.261439

Brennan, Susan E., and Justina O. Ohaeri. (1999). Why do electronic conversations seem less polite? the costs and benefits of hedging. In *Proceedings of the International Joint Conference on Work Activities Coordination and Collaboration (WACC '99)* (pp. 227–235). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/295665.295942

Brudy, Frederik, Joshua Kevin Budiman, Steven Houben, and Nicolai Marquardt. (2018). Investigating the Role of an Overview Device in Multi-Device Collaboration. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)* (pp. 1–13). New York, New York, USA: ACM Press. DOI: https://doi.org/10.1145/3173574.3173874

Brudy, Frederik, Christian Holz, Roman Rädle, Chi Jui Wu, Steven Houben, Clemens Nylandsted Klokmose, and Nicolai Marquardt. (2019). Cross-device taxonomy: Survey, opportunities and challenges of interactions spanning across multiple devices. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)* (pp. 1–28). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/3290605.3300792

Brudy, Frederik, Steven Houben, Nicolai Marquardt, and Yvonne Rogers. (2016). CurationSpace: Cross-Device Content Curation Using Instrumental Interaction. In *Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces (ISS '16)* (pp. 159–168). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2992154.2992175

Brudy, Frederik, David Ledo, Michel Pahud, Nathalie Henry Riche, Christian Holz, Anand Waghmare, Hemant Bhaskar Surale, Marcus Peinado, Xiaokuan Zhang, Shannon Joyner, Badrish Chandramouli, Umar Farooq Minhas, Jonathan Goldstein, William Buxton, and Ken

Hinckley. (2020). SurfaceFleet: Exploring Distributed Interactions Unbounded from Device, Application, User, and Time. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (pp. 7–21). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3379337.3415874

Canadian Sea Ice Service. Latest ice conditions. (2015). Retrieved from https://www.ec.gc.ca/glaces-ice/

Canadian Sea Ice Service. Latest ice conditions. (2020). Retrieved from https://www.ec.gc.ca/glaces-ice/

Card, Stuart K., Thomas P. Moran, and Allen Newell. (1980). The keystroke-level model for user performance time with interactive systems. *Journal of Communications of the ACM*, *23*(7), 396–410. DOI: https://doi.org/10.1145/358886.358895

Carroll, John M., Gregorio Convertino, Mary Beth Rosson, and Craig H. Ganoe. (2008). Toward a conceptual model of common ground in teamwork. In Letsky, M. P., N. W. Warner, S. M. Fiore, & C. A. P. Smith (Eds.), *Macrocognition in Teams: Theories and Methodologies* (pp. 87–105). Elsevier. DOI: https://doi.org/10.1201/9781315593166-6

Chokshi, Apoorve, Teddy Seyed, Francisco Marinho Rodrigues, and Frank Maurer. (2014). EPlan multi-surface: A multi-surface environment for emergency response planning exercises. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)* (pp. 219–228). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2669485.2669520

Clark, Herbert H. (1996). *Using Language*. Cambridge University Press.

Clark, Herbert H., and Susan E. Brennan. (1991). Grounding in communication. In Resnick, L. B., J. M. Levine, & S. D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 127–149). Washington, DC, US: American Psychological Association. DOI: https://doi.org/10.1037/10096-006

Cockburn, Andy, Amy Karlson, and Benjamin B. Bederson. (2009). A review of overview+ detail, zooming, and focus+ context interfaces. *ACM Computing Surveys*, *41*(1), 1–31. DOI: https://doi.org/10.1145/1456650.1456652

Convertino, Gregorio, Helena M. Mentis, Mary Beth Rosson, John M. Carroll, Aleksandra Slavkovic, and Craig H. Ganoe. (2008). Articulating common ground in cooperative work: Content and process. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)* (pp. 1637–1646). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1357054.1357310

Convertino, Gregorio, Helena M. Mentis, Mary Beth Rosson, Aleksandra Slavkovic, and John M. Carroll. (2009). Supporting content and process common ground in computer-supported teamwork. In *Proceedings of the SIGCHI Conference on Human factors in Computing Systems (CHI '09)* (pp. 2339–2348). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1518701.1519059

Creswell, John W. (2014). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches*. Sage Publications.

Dachselt, Raimund, and Robert Buchholz. (2009). Natural throw and tilt interaction between mobile phones and distant displays. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems (CHI EA '09)* (pp. 3253–3258). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1520340.1520467

Dalsgaard, Peter, and Kim Halskov. (2012). Reflective design documentation. In *Proceedings of the Designing Interactive Systems Conference, DIS '12* (pp. 428–437). New York, New York, USA: ACM Press. DOI: https://doi.org/10.1145/2317956.2318020

Dix, Alan, Janet Finlay, Gregory Abowd, and Russell Beale. (2004). *Human-computer interaction*. Pearson Education UK.

Doeweling, Sebastian, Tarik Tahiri, Philipp Sowinski, Benedikt Schmidt, and Mohammadreza Khalilbeigi. (2013). Support for collaborative situation analysis and planning in crisis management teams using interactive tabletops. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13)* (pp. 273–282). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2512349.2512823

Dove, Graham, Nicolai Brodersen Hansen, and Kim Halskov. (2016). An argument for design space reflection. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction (NordiCHI '16)* (pp. 1–10). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2971485.2971528

Engeström, Yrjö. (1990). *Learning, working and imagining : twelve studies in activity theory*. Orienta-Konsultit Oy.

Fei, Shenfeng, Andrew M. Webb, Andruid Kerne, Yin Qu, and Ajit Jain. (2013). Peripheral array of tangible NFC tags: Positioning portals for embodied trans-surface interaction. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13)* (pp. 33–36). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2512349.2512820

Fisheries and Oceans Canada. (2020). Retrieved April 8, 2021, from https://www.dfo-mpo.gc.ca/index-eng.html

Fleck, Rowanne, Yvonne Rogers, Nicola Yuill, Paul Marshall, Amanda Carr, Jochen Rick, and Victoria Bonnett. (2009). Actions speak loudly with words: Unpacking collaboration around the table. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '09)* (pp. 189–196). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1731903.1731939

Forlizzi, Jodi, John Zimmerman, and Erick Stolterman. (2009). From design research to theory: Evidence of a maturing field. In *Proceedings of the Conference on the International Association for Societies of Design Research*. IASDR Press.

Fox Tree, Jean E., and Nathaniel B. Clark. (2013). Communicative Effectiveness of Written Versus Spoken Feedback. *Journal of Discourse Processes*, *50*(5), 339–359. DOI: https://doi.org/10.1080/0163853X.2013.797241

Fox Tree, Jean E., Sarah A. Mayer, and Teresa E. Betts. (2011). Grounding in Instant Messaging. *Journal of Educational Computing Research*, *45*(4), 455–475. DOI: https://doi.org/10.2190/EC.45.4.e

Gamma, Erich, Richard Helm, Ralph Johnson, and John M. Vlissides. (1994). *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley Professional.

Gaver, William. (2012). What should we expect from research through design? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)* (pp. 937–946). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2207676.2208538

Gergle, Darren. (2017). Discourse Processing in Technology-Mediated Environments. In Schober, M. F., D. N. Rapp, & M. A. Britt (Eds.), *The Routledge Handbook of Discourse Processes* (pp.

191–221). Routledge.

Gergle, Darren, Robert E. Kraut, and Susan R. Fussell. (2004a). Action as language in a shared visual space. In *Proceedings of the ACM conference on Computer supported cooperative work (CSCW '04)* (pp. 487–496). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1031607.1031687

Gergle, Darren, Robert E. Kraut, and Susan R. Fussell. (2004b). Language efficiency and visual technology: Minimizing collaborative effort with visual information. *Journal of Language and Social Psychology*, *23*(4), 491–517. DOI: https://doi.org/10.1177/0261927X04269589

Gergle, Darren, Robert Kraut, and Susan Fussell. (2013). Using visual information for grounding and awareness in collaborative tasks. *Journal of Human–Computer Interaction*, *28*(1), 1–39. DOI: https://doi.org/10.1080/07370024.2012.678246

Goyal, Nippun. (2016). *Investigating Data Exploration Techniques Involving Map Based Geotagged Data in a Collaborative Sensemaking Environment*. *Systems Design Engineering*. University of Waterloo, Waterloo, ON, Canada.

Grønbæk, Jens Emil, Mille Skovhus Knudsen, Kenton O'Hara, Peter Gall Krogh, Jo Vermeulen, and Marianne Graves Petersen. (2020). Proxemics Beyond Proximity: Designing for Flexible Social Interaction Through Cross-Device Interaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–14). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3313831.3376379

Gutwin, Carl., and Saul. Greenberg. (2002). A Descriptive Framework of Workspace Awareness for Real-Time Groupware. *Journal of Computer Supported Cooperative Work (CSCW)*, *11*(3), 411–446. DOI: https://doi.org/10.1023/A:1021271517844

Gutwin, Carl, and Saul Greenberg. (1998). Design for individuals, design for groups: tradeoffs between power and workspace awareness. In *Proceedings of the 1998 ACM conference on Computer supported cooperative work (CSCW '98)* (pp. 207–216). Seattle, WA, USA: ACM. DOI: https://doi.org/10.1145/289444.289495

Haller, Michael, Jakob Leitner, Thomas Seifried, James R. Wallace, Stacey D. Scott, Christoph Richter, Peter Brandl, Adam Gokcezade, and Seth Hunter. (2010). The NiCE discussion room: Integrating paper and digital media to support co-located group meetings. In *Proceedings of the*

*SIGCHI Conference on Human Factors in Computing Systems (CHI '10)* (Vol. 1, pp. 609–618). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1753326.1753418

Hamilton, Peter, and Daniel Wigdor. (2014). Conductor: Enabling and understanding cross-device interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)* (pp. 2773–2782). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2556288.2557170

Hancock, Mark S., Frédéric D. Vernier, Daniel Wigdor, Sheelagh Carpendale, and Chia Shen. (2006). Rotation and translation mechanisms for tabletop interaction. In *Proceedings of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP '06)* (Vol. 2006, pp. 79–86). DOI: https://doi.org/10.1109/TABLETOP.2006.26

Harris, John Joseph. (2019, May 21). *Leveraging Asymmetry and Interdependence to Enhance Social Connectedness in Cooperative Digital Games*. University of Waterloo.

Hinckley, Ken. (2003a). Bumping Objects Together as a Semantically Rich Way of Forming Connections between Ubiquitous Devices. In *The Fifth International Conference on Ubiquitous Computing (UbiComp '03)* (pp. 263–264). Springer.

Hinckley, Ken. (2003b). Synchronous gestures for multiple persons and computers. In *Proceedings of the 16th annual ACM symposium on User interface software and technology (UIST '03)* (pp. 149–158). ACM. DOI: https://doi.org/10.1145/964696.964713

Hinckley, Ken, Gonzalo Ramos, Francois Guimbretiere, Patrick Baudisch, and Marc Smith. (2004). Stitching: Pen gestures that span multiple displays. In *Proceedings of the working conference on Advanced visual interfaces (AVI '04)* (pp. 23–31). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/989863.989866

Holmquist, Lars Erik, Friedemann Mattern, Bernt Schiele, Petteri Alahuhta, Michael Beigl, and Hans W. Gellersen. (2001). Smart-its friends: A technique for users to easily establish connections between smart artefacts. In *International conference on Ubiquitous Computing* (Vol. 2201, pp. 116–122). Springer Verlag. DOI: https://doi.org/10.1007/3-540-45427-6_10

Homaeian, Leila, Nippun Goyal, James R. Wallace, and Stacey D. Scott. (2018). Group vs Individual: Impact of TOUCH and TILT Cross-Device Interactions on Mixed-Focus Collaboration. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*

(p. 73). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3173574.3173647

Homaeian, Leila, James R. Wallace, and Stacey D. Scott. (2021). Joint Action Storyboards: A Framework for Visualizing Communication Grounding Costs. *Proceedings of the ACM on Human-Computer Interaction*, *5*(CSCW1), 1–27. DOI: https://doi.org/10.1145/3449102

Homaeian, Leila, James R. Wallace, and Stacey D. Scott. (2022). Handoff and Deposit: Designing Temporal Coordination in Cross-Device Transfer Techniques for Mixed-Focus Collaboration. *To Appear in Proceedings of the ACM on Human-Computer Interaction*.

Hoök, Kristina, and Jonas Lowgren. (2012). Strong concepts: Intermediate-level knowledge in interaction Design research. *ACM Transactions on Computer-Human Interaction*, *19*(3), 1–18. DOI: https://doi.org/10.1145/2362364.2362371

Hornbæk, Kasper, Benjamin B. Bederson, and Catherine Plaisant. (2002). Navigation patterns and usability of zoomable user interfaces with and without an overview. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *9*(4), 362–389. DOI: https://doi.org/10.1145/586081.586086

Houben, Steven, Nicolai Marquardt, Jo Vermeulen, Clemens Klokmose, Johannes Schoning, Harald Reiterer, and Christian Holz. (2017). Opportunities and challenges for cross-device interactions in the wild. *Interactions*, *24*(5), 58–63. DOI: https://doi.org/10.1145/3121348

Isenberg, Petra, Sheelegh Carpendale, Anastasia Bezerianos, Nathalie Henry, and Jean-Daniel Fekete. (2009). CoCoNutTrix: Collaborative Retrofitting for Information Visualization. *IEEE Computer Graphics and Applications*, *29*(5), 44–57. DOI: https://doi.org/10.1109/MCG.2009.78

Isenberg, Petra, Danyel Fisher, Meredith Ringle Morris, Kori Inkpen, and Mary Czerwinski. (2010). An exploratory study of co-located collaborative visual analytics around a tabletop display. In *2010 IEEE Symposium on Visual Analytics Science and Technology* (pp. 179–186). IEEE. DOI: https://doi.org/10.1109/VAST.2010.5652880

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

Isenberg, Petra, Tobias Isenberg, Tobias Hesselmann, Bongshin Lee, Ulrich Von Zadow, and

Anthony Tang. (2013). Data visualization on interactive surfaces: A research agenda. *IEEE Computer Graphics and Applications*, *33*(2), 16–24. DOI: https://doi.org/10.1109/MCG.2013.24

Jakobsen, Mikkel R., and Kasper HornbÆk. (2014). Up close and personal: : Collaborative Work on a High-resolution Multitouch Wall Display. *ACM Transactions on Computer-Human Interaction*, *21*(2), 1–34. DOI: https://doi.org/10.1145/2576099

Jamil, Izdihar, Kenton O'Hara, Mark Perry, Abhijit Karnik, and Sriram Subramanian. (2011). The effects of interaction techniques on talk patterns in collaborative peer learning around interactive tables. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)* (pp. 3043–3052). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1978942.1979393

Janis, Irving L. (1982). *Groupthink: psychological studies of policy decisions and fiascoes*. New York: Houghton Mifflin.

Javed, Waqas, Sohaib Ghani, and Niklas Elmqvist. (2012). Polyzoom: multiscale and multifocus exploration in 2d visual spaces. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12)*. Austin, Texas, USA: ACM. DOI: https://doi.org/10.1145/2207676.2207716

Jetter, Hans Christian, Jens Gerken, Michael Zöllner, Harald Reiterer, and Natasa Milic-Frayling. (2011). Materializing the query with facet-streams - A hybrid surface for collaborative search on tabletops. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)* (pp. 3013–3022). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1978942.1979390

Jin, Haojian, Christian Holz, and Kasper Hornbæk. (2015). Tracko: Ad-hoc mobile 3D tracking using bluetooth low energy and inaudible signals for cross-device interaction. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)* (pp. 147–156). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2807442.2807475

Kirk, David, Tom Rodden, and Danaë Stanton Fraser. (2007). Turn it this way: Grounding collaborative action with remote gestures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)* (pp. 1039–1048). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1240624.1240782

Koulouri, Theodora, Stanislao Lauria, and Robert D. Macredie. (2017). The influence of visual feedback and gender dynamics on performance, perception and communication strategies in CSCW. *International Journal of Human Computer Studies*, *97*, 162–181. DOI: https://doi.org/10.1016/j.ijhcs.2016.09.003

Kraut, Robert E., Susan R. Fussell, Susan E. Brennan, and Jane Siegel. (2002). Understanding effects of proximity on collaboration: Implications for technologies to support remote collaborative work. In Hinds, P. J. & S. Kiesler (Eds.), *Distributed work* (pp. 137–162). MIT Press.

Krogh, Peter Gall, and Ilpo Koskinen. (2020). *Drifing by Intention: Four Epistemic Traditions from within Constructive Design Research*. Cham: Springer. DOI: https://doi.org/10.1007/978-3-030-37896-7

Kruger, Russell, Sheelagh Carpendale, Stacey D. Scott, and Saul Greenberg. (2004). Roles of orientation in tabletop collaboration: Comprehension, coordination and communication. *Computer Supported Cooperative Work*, *13*(5–6), 501–537. DOI: https://doi.org/10.1007/s10606-004-5062-8

Kruger, Russell, Sheelagh Carpendale, Stacey D. Scott, and Anthony Tang. (2005). Fluid integration of rotation and translation. In *Proceedings of the SIGCHI conference on Human factors in computing systems (CHI '05)* (p. 601). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1054972.1055055

Lazar, Jonathan, Jinjuan Heidi Feng, and Harry Hochheiser. (2017). *Research Methods in Human-Computer Interaction*. *Research Methods in Human-Computer Interaction*. Elsevier Inc. DOI: https://doi.org/10.1016/b978-0-444-70536-5.50047-6

Lee, John D., Alex. Kirlik, and Marvin J. Dainoff. (2013). *The oxford handbook of cognitive engineering*. Oxford University Press. DOI: https://doi.org/10.1093/oxfordhb/9780199757183.001.0001

Lidwell, William., Kritina. Holden, Jill Butler, and Kimberly Elam. (2010). *Universal principles of design : 125 ways to enhance usability, influence perception, increase appeal, make better design decisions, and teach through design*. Rockport Publishers.

Lissermann, Roman, Jochen Huber, Martin Schmitz, Jürgen Steimle, and Max Mühlhäuser. (2014). Permulin: Mixed-focus collaboration on multi-view tabletops. In *Proceedings of the SIGCHI*

*Conference on Human Factors in Computing Systems (CHI '14)* (pp. 3191–3200). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2556288.2557405

Liu, Can, Olivier Chapuis, Michel Beaudouin-Lafon, and Eric Lecolinet. (2016). Shared interaction on a Wall-sized display in a data manipulation task. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)* (pp. 2075–2086). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2858036.2858039

Liu Jun, David Pinelle, Carl Gutwin, and Sriram Subramanian. (2008). Improving digital handoff in shared tabletop workspaces. In *2008 3rd IEEE International Workshop on Horizontal Interactive Human Computer Systems* (pp. 9–16). IEEE. DOI: https://doi.org/10.1109/TABLETOP.2008.4660177

Löwgren, Jonas. (2013). Annotated portfolios and other forms of intermediate-level knowledge. *Interactions*, *20*(1), 30–34. DOI: https://doi.org/10.1145/2405716.2405725

Mahyar, Narges, and Melanie Tory. (2014). Supporting communication and coordination in collaborative sensemaking. *Visualization and Computer Graphics, IEEE Transactions On*, *20*(12), 1633–1642. DOI: https://doi.org/10.1109/TVCG.2014.2346573

Marquardt, Nicolai, Till Ballendat, Sebastian Boring, Saul Greenberg, and Ken Hinckley. (2012). Gradual engagement: Facilitating information exchange between digital devices as a function of proximity. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12)* (pp. 31–40). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2396636.2396642

Marquardt, Nicolai, Ken Hinckley, and Saul Greenberg. (2012). Cross-device interaction via micro-mobility and F-formations. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)* (pp. 13–22). DOI: https://doi.org/10.1145/2380116.2380121

Martin, Bella., and Bruce M. Hanington. (2012). *Universal methods of design : 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Rockport Publishers.

McDonald, Nora, Sarita Schoenebeck, and Andrea Forte. (2019). Reliability and Inter-rater Reliability in Qualitative Research. *Proceedings of the ACM on Human-Computer Interaction*, *3*(CSCW), 1–23. DOI: https://doi.org/10.1145/3359174

McGrath, Joseph Edward. (1984). *Groups: Interaction and performance*. Eaglewood Cliffs, N.J.: Prentice-Hall, Inc.

McGrath, Will, Brian Bowman, David McCallum, Juan David Hincapié-Ramos, Niklas Elmqvist, and Pourang Irani. (2012). Branch-explore-merge: facilitating real-time revision control in collaborative visual exploration. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12)* (pp. 235–244). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2396636.2396673

Monk, Andrew. (2003). Common Ground in Electronically Mediated Communication: Clark's Theory of Language Use. In Carroll, J. M. (Ed.), *HCI Models, Theories, and Frameworks: Toward a Multidisciplinary Science* (pp. 265–289). Elsevier Inc. DOI: https://doi.org/10.1016/B978-155860808-5/50010-1

Monk, Andrew, and Leon Watts. (2000). Peripheral participation in video-mediated communication. *International Journal of Human Computer Studies*, *52*(5), 933–958. DOI: https://doi.org/10.1006/ijhc.1999.0359

Morris, Meredith Ringel, Jarrod Lombardo, and Daniel Wigdor. (2010). WeSearch: supporting collaborative search and sensemaking on a tabletop display. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work* - *CSCW '10* (pp. 401–410). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/1718918.1718987

Nacenta, Miguel A., Dzmitry Aliakseyeu, Sriram Subramanian, and Carl Gutwin. (2005). A comparison of techniques for multi-display reaching. In *CHI 2005: Technology, Safety, Community: Conference Proceedings* - *Conference on Human Factors in Computing Systems* (pp. 371–380). New York, New York, USA: Association for Computing Machinery. DOI: https://doi.org/10.1145/1054972.1055024

Nacenta, Miguel A., David Pinelle, Dane Stuckel, and Carl Gutwin. (2007). The effects of interaction technique on coordination in tabletop groupware. In *Graphics interface* (pp. 191–198). ACM.

National Snow and Ice Data Center. (2015). Retrieved from https://nsidc.org

National Snow and Ice Data Center. (2020). Retrieved from https://nsidc.org/

Nehme, Carl .. E., Stacey D. Scott, M. L. Cummings, and Carina Yumi Furusho. (2006). Generating Requirements for Futuristic Heterogeneous Unmanned Systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*(3), 235–239.

Neumayr, Thomas, Hans Christian Jetter, Mirjam Augstein, Judith Friedl, and Thomas Luger. (2018). Domino: A descriptive framework for hybrid collaboration and coupling styles in partially distributed teams. *Proc. ACM Hum.-Comput. Interact.*, *2*(CSCW). DOI: https://doi.org/10.1145/3274397

Nielosn, Jacob, and Robert L. Mack. (1994). *Usability Inspection Methods*. New York, New York, USA: Wiley.

Nielsen, Jakob, and Rolf Molich. (1990). Heuristic evaluation of user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '90)* (pp. 249–256). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/97243.97281

Norman, Geoff. (2010). Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education*, *15*(5), 625–632. DOI: https://doi.org/10.1007/s10459-010-9222-y

Paay, Jeni, Dimitrios Raptis, Jesper Kjeldskov, Mikael B. Skov, Eric V. Ruder, and Bjarke M. Lauridsen. (2017). Investigating cross-device interaction between a handheld device and a large display. In *roceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)* (Vol. 2017-May, pp. 6608–6619). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3025453.3025724

Pinelle, David, Carl Gutwin, and Saul Greenberg. (2003). Task analysis for groupware usability evaluation: Modeling shared-workspace tasks with the mechanics of collaboration. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *10*(4), 281–311. DOI: https://doi.org/10.1145/966930.966932

Pinelle, David, Miguel Nacenta, Carl Gutwin, and Tadeusz Stach. (2008). The effects of co-present embodiments on awareness and collaboration in tabletop groupware. In *Proceedings of Graphics Interface 2008 (GI '08)* (pp. 1–8). CAN: Canadian Information Processing Society.

Pirolli, Peter, and Stuart Card. (2005). The sensemaking process and leverage points for analyst technology as identified through cognitive task analysis. In *International Conference on Intelligence Analysis* (pp. 2–4).

Plaue, Christopher, and John Stasko. (2009). Presence & placement: exploring the benefits of multiple shared displays on an intellective sensemaking task. In *Proceedings of the ACM 2009 international conference on Supporting group work (GROUP '09)* (pp. 179–188). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1531674.1531701

Preece, Jenny, Yvonne Rogers, and Helen Sharp. (2007). *Interaction design : beyond human-computer interaction* (2nd ed.). John Wiley.

Rädle, Roman, Hans-Christian Jetter, Mario Schreiner, Zhihao Lu, Harald Reiterer, and Yvonne Rogers. (2015). Spatially-aware or Spatially-agnostic? : Elicitation and Evaluation of User-Defined Cross-Device Interactions. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15* (pp. 3913–3922). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2702123.2702287

Rädle, Roman, Hans Christian Jetter, Nicolai Marquardt, Harald Reiterer, and Yvonne Rogers. (2014). Huddlelamp: Spatially-Aware mobile displays for ad-hoc around-the-table collaboration. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)* (pp. 45–54). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2669485.2669500

Ramos, Gonzalo, Kenneth Hinckley, Andy Wilson, and Raman Sarin. (2009). Synchronous Gestures in Multi-Display Environments. *Human–Computer Interaction*, *24*(1–2), 117–169. DOI: https://doi.org/10.1080/07370020902739288

Reetz, Adrian, Carl Gutwin, Tadeusz Stach, Miguel A. Nacenta, and Sriram Subramanian. (2006). Superflick: a natural and efficient technique for long-distance object placement on digital tables. In *Proceedings of Graphics Interface 2006 (GI '06)* (pp. 163–170). CAN: Canadian Information Processing Society.

Rekimoto, Jun. (1997). Pick-and-Drop: A direct Manipulation Technique for Multiple Computer Environments. In *Proceedings of the 10th annual ACM symposium on User interface software and technology (UIST '97)* (pp. 31–39). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/263407.263505

Rice, Andrew D., and Jonathan W. Lartigue. (2014). Touch-level model (TLM): evolving KLM-GOMS for touchscreen and mobile devices. In *Proceedings of the ACM Southeast regional* *conference (ACM SE ’14)* (pp. 1–6). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2638404.2638532

Rogers, Yvonne, and Siân Lindley. (2004). Collaborating around vertical and horizontal large interactive displays: which way is best? *Interacting with Computers*, *16*(6), 1133–1152. DOI: https://doi.org/10.1016/j.intcom.2004.07.008

Russell, Daniel M., Mark J. Stefik, Peter Pirolli, and Stuart K. Card. (1993). The cost structure of sensemaking. In *Proceedings of the INTERACT ’93 and CHI ’93 Conference on Human Factors in Computing Systems (CHI ’93)* (pp. 269–276). Amsterdam, The Netherlands: ACM. DOI: https://doi.org/10.1145/169059.169209

Ryall, Kathy, Clifton Forlines, Chia Shen, and Meredith Ringel Morris. (2004). Exploring the effects of group size and table size on interactions with tabletop shared-display groupware. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work (CSCW ’04)* (pp. 284–293). ACM. DOI: https://doi.org/10.1145/1031607.1031654

Scott, Stacey D., Guillaume Besacier, Nippun Goyal, and Frank Cento. (2017). Investigating device-specific visual feedback for cross-device transfer in table-centric multisurface environments. *Concurrency and Computation: Practice and Experience*, e4084. DOI: https://doi.org/10.1002/cpe.4084

Scott, Stacey D., Guillaume Besacier, and Phillip J. Mcclelland. (2014). Cross-Device Transfer in a Collaborative Multi-Surface Environment without User Identification. In *2014 International Conference on Collaboration Technologies and Systems (CTS)* (pp. 219–226). IEEE. DOI: https://doi.org/10.1109/CTS.2014.6867568

Scott, Stacey D., and Sheelagh Carpendale. (2010). Theory of tabletop territoriality. In Müller-Tomfelde, C. (Ed.), *Tabletops-horizontal interactive displays* (HCI Series, pp. 357–385). Springer.

Scott, Stacey D., Sheelagh Carpendale, and K. M. Inkpen. (2004). Territoriality in collaborative tabletop workspaces. In *ACM conference on Computer supported cooperative work* (pp. 294–303).

Scott, Stacey D., T. C. Nicholas Graham, James R. Wallace, Mark Hancock, and Miguel Nacenta. (2015). “Local Remote” Collaboration: Applying Remote Group AwarenessTechniques to Co-

Located Settings. In *Proceedings of the 18th ACM Conference Companion on Computer Supported Cooperative Work & Social Computing (CSCW '15 companion)* (pp. 319–324). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2685553.2685564

Segerstad, Ylva Hård, and Peter Ljungstrand. (2002). Instant messaging with WebWho. *International Journal of Human Computer Studies*, *56*(1), 147–171. DOI: https://doi.org/10.1006/ijhc.2001.0519

Seifert, Julian, Adalberto Simeone, Dominik Schmidt, Christian Reinartz, Paul Holleis, Matthias Wagner, Hans Gellersen, and Enrico Rukzio. (2012). MobiSurf: Improving co-located collaboration through integrating mobile devices and interactive surfaces. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12)* (pp. 51–60). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2396636.2396644

Seyed, Teddy, Mario Costa Sousa, Frank Maurer, and Anthony Tang. (2013). SkyHunter: a multi-surface environment for supporting oil and gas exploration. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13)* (pp. 15–22). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2512349.2512798

Shadiev, Rustam, Wu Yuin Hwang, Yueh Min Huang, and Yu Shu Yang. (2015). Study of using a multi-touch tabletop technology to facilitate collaboration, interaction, and awareness in co-located environment. *Behaviour and Information Technology*, *34*(10), 952–963. DOI: https://doi.org/10.1080/0144929X.2014.942755

Shibata, Hirohito, Tomonori Hashiyama, Shun'ichi Tano, and Junko Ichino. (2016). A rhythmical tap approach for sending data across devices. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct (MobileHCI '16)* (pp. 815–822). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2957265.2961851

Shneiderman, Ben. (2016). *The New ABCs of Research*. *The New ABCs of Research*. Oxford University Press. DOI: https://doi.org/10.1093/acprof:oso/9780198758839.001.0001

Silva, Da, Stacey D. Scott, and M. L. Cummings. (2007). *Design Methodology for Unmanned Aerial Vehicle (UAV) Team Coordination*.

Simeone, Adalberto L., Julian Seifert, Dominik Schmidt, Paul Holleis, Enrico Rukzio, and Hans

Gellersen. (2013). A cross-device drag-and-drop technique. In *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia (MUM '13)* (pp. 1–4). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2541831.2541848

Spence, Robert, and Mark Witkowski. (2013). *Rapid serial visual presentation: design for cognition*. Springer Science & Business Media.

Stappers, Pieter Jan, and Elisa Giaccardi. (2017). Research through Design. In Soegaard, M. & R. Friis-Dam (Eds.), *The Encyclopedia of Human-Computer Interaction* (2nd ed., pp. 1–94). The Interaction Design Foundation.

Stasser, Garold, and William Titus Titus. (2003). Hidden profiles: A brief history. *Psychological Inquiry*, *14*(3–4), 304–313. DOI: https://doi.org/https://doi.org/10.1080/1047840X.2003.9682897

Sutcliffe, Steven W. T., Zenja Ivkovic, David R. Flatla, Andriy Pavlovych, Ian Stavness, and Carl Gutwin. (2013). Improving digital handoff using the space above the table. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)* (pp. 735–744). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2470654.2470758

Tandler, Peter, Thorsten Prante, Christian Müller-Tomfelde, Norbert Streitz, and Ralf Steinmetz. (2001). Connectables: dynamic coupling of displays for the flexible creation of shared workspaces. In *Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01)* (pp. 11–20). New York, New York, USA: ACM. DOI: https://doi.org/https://doi.org/10.1145/502348.502351

Tang, Anthony, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. (2006). Collaborative coupling over tabletop displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)* (pp. 1181–1190). ACM. DOI: https://doi.org/10.1145/1124772.1124950

Tokunaga, Nami, Jennifer Marlow, and Scott Carter. (2018). CollaboPlanner: Integrating mobile phones and public displays for collaborative travel planning. In *Companion of the 2018 ACM Conference on Computer Supported Cooperative Work and Social Computing (CSCW '18)* (pp. 25–28). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3272973.3272993

Tse, Edward, Jonathan Histon, Stacey D. Scott, and and Saul Greenberg. (2004). Avoiding interference: how people use spatial separation and partitioning in SDG workspaces. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work (CSCW ’04)* (pp. 252–261). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1031607.1031647

Van Der Veer, Gerrit C., Bert F. Lenting, and Bas A. J. Bergevoet. (1996). GTA: Groupware task analysis - Modeling complexity. *Acta Psychologica*, *91*(3), 297–322. DOI: https://doi.org/10.1016/0001-6918(95)00065-8

Vogt, Katherine, Lauren Bradel, Christopher Andrews, Chris North, Alex Endert, and Duke Hutchings. (2011). Co-located collaborative sensemaking on a large high-resolution display with multiple input devices. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (Vol. 6947 LNCS, pp. 589–604). Springer, Berlin, Heidelberg. DOI: https://doi.org/10.1007/978-3-642-23771-3_44

Voida, Stephen, Matthew Tobiasz, Julie Stromer, Petra Isenberg, and Sheelagh Carpendale. (2009). Getting practical with interactive tabletop displays: designing for dense data, “fat fingers,” diverse interactions, and face-to-face collaboration. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS ’09)* (pp. 109–116). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1731903.1731926

Wallace, James R., Nancy Iskander, and Edward Lank. (2016). Creating your bubble: Personal space on and around large public displays. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16)* (pp. 2087–2092). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/2858036.2858118

Wallace, James R., Saba Oji, and Craig Anslow. (2017). Technologies, Methods, and Values: Changes in Empirical Research at CSCW 1990-2015. *Proc. ACM Hum.-Comput. Interact*, *1*(CSCW), 1–18. DOI: https://doi.org/10.1145/3134741

Wallace, James R., Stacey D. Scott, Eugene Lai, and Deon Jajalla. (2011). Investigating the role of a large, shared display in multi-display environments. *Computer Supported Cooperative Work, 20*(6), 529–561. DOI: https://doi.org/10.1007/s10606-011-9149-8

Wallace, James R., Stacey D. Scott, and Carolyn G. MacGregor. (2013). Collaborative sensemaking on a digital tabletop and personal tablets: prioritization, comparisons, and tableaux. In

*Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)* (pp. 3345–3354). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2470654.2466458

Wallace, James R., Stacey D. Scott, Taryn Stutz, Tricia Enns, and Kori Inkpen. (2009). Investigating teamwork and taskwork in single- and multi-display groupware systems. *Personal and Ubiquitous Computing*, *13*(8), 569–581. DOI: https://doi.org/10.1007/s00779-009-0241-8

Wigdor, Daniel, Chia Shen, Clifton Forlines, and Ravin Balakrishnan. (2006). Effects of display position and control space orientation on user preference and performance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)* (Vol. 1, pp. 309–318). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1124772.1124819

Wobbrock, Jacob O., and Julie A. Kientz. (2016). Research contributions in human-computer interaction. *Interactions*, *23*(3), 38–44. DOI: https://doi.org/10.1145/2907069

Wozniak, Paweł, Nitesh Goyal, Przemysław Kucharski, Lars Lischke, Sven Mayer, and Morten Fjeld. (2016). RAMPARTS: Supporting sensemaking with spatially-aware mobile interactions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)* (pp. 2447–2460). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2858036.2858491

Wu, Anna, and Xiaolong Zhang. (2009). Supporting collaborative sensemaking in map-based emergency management and planning. In *Proceedings of the ACM 2009 international conference on Supporting group work (GROUP '09)* (pp. 395–396). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1531674.1531741

Yi, Ji Soo, Youn-ah Kang, John T. Stasko, and Julie A. Jacko. (2008). Understanding and characterizing insights: how do people gain insights using information visualization? In *Proceedings of the 2008 Workshop on BEyond time and errors: novel evaLuation methods for Information Visualization (BELIV '08)* (pp. 1–6). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1377966.1377971

Zadow, Ulrich von, Wolfgang Büschel, Ricardo Langner, and Raimund Dachselt. (2014). SleeD: Using a Sleeve Display to Interact with Touch-sensitive Display Walls. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)* (pp. 129–

138). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2669485.2669507

Zagermann, Johannes, Ulrike Pfeil, Roman Rädle, Hans-Christian Jetter, Clemens Klokmose, and Johannes Harald Reiterer. (2016). When tablets meet tabletops: The effect of tabletop size on around-the-table collaboration with personal tablets. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'16)* (pp. 5470–5481). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/2858036.2858224

Zagermann, Johannes, Ulrike Pfeil, Philipp von Bauer, Daniel Fink, and Harald Reiterer. (2020). "It's in my other hand!" - Studying the Interplay of Interaction Techniques and Multi-Tablet Activities. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). New York, NY, USA: ACM. DOI: https://doi.org/10.1145/3313831.3376540

Zimmerman, John, and Jodi Forlizzi. (2008). The Role of Design Artifacts in Design Theory Construction. *Artifact*, *2*(1), 41–45. DOI: https://doi.org/10.1080/17493460802276893

Zimmerman, John, and Jodi Forlizzi. (2014). Research through design in HCI. In Olson, J. S. & W. A. Kellogg (Eds.), *Ways of Knowing in HCI* (pp. 167–189). Springer New York. DOI: https://doi.org/10.1007/978-1-4939-0378-8_8

Zimmerman, John, Jodi Forlizzi, and Shelley Evenson. (2007). Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)* (pp. 493–502). New York, New York, USA: ACM. DOI: https://doi.org/10.1145/1240624.1240704

# Appendix

Chapter 5 (Project 2) appended materials include descriptions of the design and technology contexts, as well as the three task scenarios administered in user observation sessions. Chapter 6 (Project 3) appended material are detailed definitions of grounding costs.

**Design Context in Project 2: The Arctic Shipping Route Hidden Profile Task**

We adapted an existing experimental task and experimental cross-device platform (Figure 3-1) for this project. In the task, a pair of collaborators worked together to find an optimal shipping route between existing land-based ports and potential sites for sea-based oil rigs in the Arctic Ocean region (Goyal, 2016; Homaeian et al., 2018). We re-architected the task to make it a hidden profile task (Stasser & Titus, 2003), in which each participant is given some unique information only known to them that must be shared during the task to successfully solve it. This information sharing requirement was added to encourage participants to transfer data to each other's devices, and thus increasing the likelihood that they would use the Handoff and Deposit transfer techniques as a natural part of their collaborative task. An expertise role was assigned to each collaborator, i.e., shipping expert or weather expert. The weather expert had knowledge about weather and sea ice conditions, such as historical sea ice concentration and ice extent, location of floating icebergs, and trends in wind speed and ice temperatures. The shipping expert had access to information such as environmentally fragile ecosystems, historical air temperatures recorded by ships, and ice covered regions inhabited by mammals or used by local people for hunting or transportation.

Each expert initially had access only to their role-specific data. The data were in the form of charts, graphs, bulletin announcements, and images. The data showed the pros or cons of establishing possible shipping routes between each port and potential oil rig site in the area. The collective knowledge of both experts was needed to discover the optimal route. For instance, although high water surface temperatures (data known to the weather expert) might indicate ice-free waters, the presence of low air temperatures recorded by ships (data known to the shipping expert) could lead to foggy and dangerous shipping conditions. Initial training was provided to study participants on how to interpret different types of data for this sensemaking context.

Three task scenarios were developed using data publicly available on the web, including data from the Canadian Sea Ice Service ("Canadian Sea Ice Service. Latest ice conditions," 2020), National Snow and Ice Data Center ("National Snow and Ice Data Center," 2020), and Fishery and Oceans Canada ("Fisheries and Oceans Canada," 2020). Each scenario described a unique context and time period for which a feasible shipping route was to be identified, i.e., the month of December with the consideration of global warming's impact on recent maritime activities in the Arctic, the months of January to March when harsh winter conditions are present, and the months of April to July when ice is less likely to be a problem but routes could be busier due to increased maritime activities. In each scenario, the participants had access to historical data and needed to make a prediction about the feasibility of the routes given the context.

**Technology Context: Experimental Cross-Device System**

The system was designed to support dyads seated at adjacent sides of the interactive tabletop to best support joint work periods (Tang et al., 2006). Gutwin and Greenburg's guidance (Gutwin & Greenberg, 1998) for designing mixed-focus collaborative software were also considered in the interface design: workspace navigation, artefact manipulation, and view representation.

The large interactive tabletop enabled simultaneous multi-touch interactions and shared viewing to enable collaborative workspace navigation and use. The tabletop showed a geographic map of the Arctic region under study and task specific information, such as potential sites for sea-based oil rigs, existing land-based ports, and potential shipping routes between them. Each shipping route was overlaid with icons representing data associated with that region, e.g. docking fees, sea ice and air temperature information, etc. The participants used their personal tablets to view the data associated with the data icons so the shared map area was not obscured.

To support collaborative view representation, each tablet was represented by a Region of Interest (ROI) bounding box on the shared tabletop. Each ROI had a unique user-specific colour. By dragging an ROI on the tabletop, the linked tablet's view would update to display data associated with the icons within the ROI (i.e., the geographic area covered by the ROI). A "Bookmarks" tab on the tablet interface (named "Dropbox" in Homaeian et. al.'s (2018) original interface) allowed participants to save a data item and view it later regardless of the location of the corresponding ROI. When a data item was enlarged, the corresponding icon on the tabletop map would glow to depict the data's association with that geographic region on the map.

As the details of the data were viewed on the personal tablets only in this cross-device system, cross-device transfer was enabled between the tablet interfaces only. For the purposes of this design exploration, cross-device transfer between the tabletop and tablet interfaces was not considered (or possible in the system).

**Scenario 1: Summer**

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 during the spring/early summer months of **April to July in 2020**.

*** If you see 'No data available' on some images or if data for recent years is missing, check with you partner to see if they have other data that your team could use to estimate the missing data values.

Here is some of key factors that your team should consider:

Ice Expert:

- **Compare ice charts** and ice graphs between different routes.
- Check for **changing ice trends**. Changing trend can often help figure out future feasibility of route.
- **Bulletins** provide information on forecast.
- **Floating ice bergs** are very dangerous and must be avoided by ships. Icebergs tend to be more common in **above zero air temperatures**.
- **Fog** (**cold air** + **warm waters**) occurs when very cold air moves over warm waters. Fog can interfere with ship navigation, and search and rescue operations. Therefore, it is not recommended to sail in foggy areas.

Shipping Expert:

- Some **arctic animals** such as beluga whales **migrate** during the spring/summer months. A shipping route must not coincide with seasonal migration paths.
- **Fishing vessels** operate in some areas of the arctic. Avoid entering such areas.
- **Cargo ships** transport goods to northern communities, and have priority in using some routes. Look for such information and consider alternate routes.
- Take into account the availability/stability of **telecommunication** infrastructure. **Strong winds** may cause loss of telecommunication signals.
- **Air temperatures** recorded by ships in previous years are helpful in making your decision.

**Scenario 2: December**

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. Since you are planning for the future, it is important to consider the changing ice conditions. Your goal for this round is to find the best route for transporting oil during the month of **December in 2020**.

*** If you see 'No data available' on some images or if data for recent years is missing, check with you partner to see if they have other data that your team could use to estimate the missing data values.

Here are some of the key factors that your team should consider:

Ice Expert:

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.
5. Strong winds can cause **freezing spray (Wind speed > 30km/h, prevalent open ocean water, subzero temperatures**) in the presence of sub-zero temperatures and open waters/thin ice. Freezing spray could hinder onboard activity and should be avoided.

Shipping Expert:

6. Look for signs warning mariners of the existence of **fragile eco-systems** along the routes exposed due to thin ice. Such areas should be avoided to protect the environment.
7. **Increased shipping trends** over recent years/months means shipping in the respective waters will likely be feasible.
8. Some routes are subject to more **docking fees** compared to others. The shipping company needs to avoid these fees is possible. Docking fees apply to all routes branching out of **a given port**.
9. **Air temperatures** recorded by ships in previous years are helpful in making your decision.

Scenario 3: Icebreaker

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 cold months. From the data accessible by you and your colleague, your goal for this round is to find which oil rig will be most feasible to set up an extraction plant taking into account that an icebreaker can create a clear path of travel in the winter months (**January – March in 2020**).

*** If you see 'No data available' on some images or if data for recent years is missing, check with you partner to see if they have data that your team could use to estimate the missing data values.

Here are some key factors that your team should consider:

Ice Expert:

- An icebreaker can easily cut through **fresh/young ice** compared to ice that has become denser over years of accumulation.
- A trend of **changing ice extent/age of ice** over the years can help ice breaker easily cut through as it will reduce the density of accumulated thick ice.
- 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.
- Look for signs of **coast guard** activity or coast guard stations around the route. Coast guard can launch rescue mission if an icebreaker gets stuck. **Strong winds/old ice** may interfere with search and rescue missions.

Shipping Expert:

- Some ice-covered waters are inhabited by **Arctic mammals**, e.g. as polar bears and narwhales. Such areas are protected and cannot be used by marine vessels.
- **Buoy**s are useful as they mark underwater obstructions or shallow waters. However, **strong winds** may displace buoys by moving the thin ice around them. This could create a dangerous situation for ships and must be avoided.
- **Indigenous people use ice** in some regions as a platform for **hunting**. Such areas must be avoided by icebreakers. **Thin/first year ice** is much better for hunting compared to older ice.
- **Air temperatures** recorded by ships in previous years are helpful in making your decision.

## Definitions of Grounding Costs for Project 3

Detailed definitions of grounding costs (Clark & Brennan, 1991) as used in Chapter 6 (Project 3) and, in case of Production, Reception, Understanding, Delay, and Asynchrony costs, how they have been adapted for CSCW environments:

- Formulation costs refer to the time and effort involved in composing a message. The cost depends on the complexity of the message, whether it includes familiar or unfamiliar content, and if the content needs to be flawless. Formulation costs are lower when the group shares a visual space (Gergle et al., 2004b, 2004a).
- Reception costs refer to the effort that it takes to receive a message. They may include interacting with the system to view data a partner is referring to. If one has to wait a long time for the message to be produced or if the user interface requires significant interaction effort for the message to be accessed, the addressee pays a high cost.
- Production costs refer to the cost associated with interacting with technology to produce a message, for e.g., by typing. In CSCW, production costs may include interacting with the system to retrieve or share data that collaborators are discussing.
- Understanding costs refer to the effort involved in interpreting the received message, e.g. due to lack of contextual cues or complexity. If awareness features are not sufficient or up-to-date in the system, collaborators also pay understanding costs.
- Startup costs are the cost of getting a collaborator to notice that a partner has said something or is initiating communication. In co-located CSCW, startup costs are generally low as people can use verbal communication.
- Display costs are associated with using non-verbal communication, for e.g. nodding or pointing, or showing an object (e.g. a piece of data) to a collaborator.
- Fault costs are incurred when a partner makes a mistake during collaboration, for e.g. they send the wrong data item.
- Repair costs are the cost of recovering from a mistake, for e.g., understanding the situation and sending the right data.

- Delay costs are associated with pauses that occur during collaboration. In CSCW, partners may need to stop their ongoing work to, for e.g., make sense of an unanticipated screen update. In this case, only the affected party incurs Delay costs. If they need to interrupt a partner to talk about the update, then both parties pay the cost.

- Asynchrony costs are paid when collaborators transition between loosely coupled to tightly coupled work periods, as they need to shift their focus to the new work style and a potentially different context.

- Speaker-change costs refer to the costs needed to change from one speaker to another. These costs are generally low in synchronous CSCW (focus of JASs), especially with audibility, as there are sufficient cues for turn taking.