GROUP REACHING OVER DIGITAL TABLETOPS WITH DIGITAL ARM EMBODIMENTS

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ABSTRACT

In almost all collaborative tabletop tasks, groups require coordinated access to the shared objects on the table's surface. The physical social norms of close-proximity interactions built up over years of interacting around other physical bodies cause people to avoid interfering with other people (e.g., avoiding grabbing the same object simultaneously). However, some digital tabletop situations require the use of indirect input (e.g., when using mice, and when supporting remote users). With indirect input, people are no longer physically embodied during their reaching gestures, so most systems provide *digital embodiments* – visual representations of each person – to provide feedback to both the person who is reaching and to the other group members. Tabletop arm embodiments have been shown to better support group interactions than simple visual designs, providing awareness of actions to the group. However, researchers and digital tabletop designers know little of how the design of digital arm embodiments affects the fundamental group tabletop interaction of reaching for objects. Therefore, in this thesis, we evaluate how people coordinate their interactions over digital tabletops when using different types of embodiments. Specifically, in a series of studies, we investigate how the visual design (what they look like) and interaction design (how they work) of digital arm embodiments affects a group's coordinative behaviours in an open-ended parallel tabletop task. We evaluated visual factors of size, transparency, and realism (through pictures and videos of physical arms), as well as interaction factors of input and augmentations (feedback of interactions), in both a co-located and distributed environment. We found that the visual design had little effect on a group's ability to coordinate access to shared tabletop items, that embodiment augmentations are useful to support group coordinative actions, and that there are large differences when the person is not physically co-present. Our results demonstrate an initial exploration into the design of digital arm embodiments, providing design guidelines for future researchers and designers to use when designing the next generation of shared digital spaces.

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CHAPTER 1

INTRODUCTION

Horizontal surfaces, especially tables, are great for group work. From large boardroom tables to small desks with two students working on an assignment, tables enable groups to naturally organize their work. Tables provide a shared focus on work artifacts, allow people to sit comfortably, and allow people to move around the table to easily form sub-groups. However, traditional tabletops limit groups due to the constraints of the physical world and on the tools used to interact over tables. For example, it is difficult to reach objects on the far side of the table and to undo destructive physical actions, such as cutting a piece of paper.

Digital tabletops provide new opportunities for groups to collaborate by removing some constraints of the physical world and adding new functionality. For example, digital tabletops enable groups to easily make copies of work artifacts, and share changes amongst the group members. Groups can also easily undo actions, save work artifacts, and retrieve multiple versions later.

In both traditional and digital tabletops, people require access to objects on the tabletop's surface. Previous researchers in Human Computer Interaction (HCI) have focused on improving the efficiency of interaction techniques, focused on individual performance (e.g., to enable faster selection); however, when designing a system for group work, there is a tradeoff between designing for individuals (usually focused on speed and accuracy) and designing for the group activity (e.g., ensuring all group members are aware of what others are doing) (Gutwin 1998).

With traditional tabletops, the only mechanism to access objects on the table's surface is to physically reach for that object. These physical reaching actions are useful for group work: the large physical gestures are easy to see, and when two people reach simultaneously for the same object, they both detect a potential conflict and quickly coordinate using a turn-taking mechanism to deal with the conflict. However, this kind of physical access is limiting; for example, people can only interact with objects within their physical reach.

Although many digital tabletops do support physical input (typically through a touch screen), digital tabletops can support other kinds of input as well. For example, indirect input (e.g., when interacting with a mouse) removes the physical reach constraint, as people can now reach objects anywhere on the table. Indirect input can also be less tiring, as the small physical motions required to move a mouse are easier for long term use than physically reaching over a tabletop. However, indirect input means people are no longer physically embodied during their reaching gestures. This lack of physical embodiments may be detrimental to the group, as many of the coordinative behaviours groups depend on for successful interactions rely on social protocols surrounding physical arms (see Section 1.6.2 for a full discussion).

Instead, when using indirect input, most systems provide *digital embodiments* – visual representations of each person – to provide feedback to both the reacher and other group members. The most common digital embodiment is a simple cursor. Initial fundamental research in digital embodiments has shown that cursors are difficult to use during group work: cursors are small and hard to track on a large display (Ha 2006), cursors are difficult to design to ensure distinguishability when there are multiple people interacting (Moraveji 2009), and it is difficult to assign ownership of cursors because there is no obvious link between a cursor and the person controlling it (Nacenta 2007). These problems are in stark contrast to physical arms. People are continuously aware of the location of other people's physical bodies, people's arms have natural differences that make them distinguishable, and the physical link of an arm to a body makes it clear who owns each arm.

A potential improvement on cursors is *arm embodiments*, and researchers have shown they may be useful for group coordination (Nacenta 2007). The benefits include a visual link between the embodiment and the person using it, clearly indicating who is controlling each embodiment, as well as the fact that they are larger and therefore easier to see and track. However, researchers and digital tabletop designers know little of how the design of digital arm embodiments can affect the fundamental group tabletop interaction of reaching for objects.

1.1 Dissertation's Problem Statement

Researchers and designers know little of how the design of digital arm embodiments affects group reaching behaviour on a tabletop display.

1.2 Motivation

Researchers have long suggested that digital tabletops will be useful in a large range of situations, including architectural and urban planning, brainstorming, and scientific data visualization. Digital tabletops have made large strides in recent years, and are finding niche markets (e.g., air traffic control (Conversey 2011) and oil and gas pipelining tools[1]). As technological costs continue their decline, digital tabletops will become ubiquitous. Even if tabletops never become primary work systems, they may still be very effective at supporting secondary tasks. For example, even if a digital tabletop is only used for a weekly brainstorming meeting, the digital tabletop may greatly increase the efficiency of that meeting.

Regardless of the use case, it is important that digital tabletops support a group's natural coordinative processes, and not force groups to adapt to the constraints of the digital system (Wallace 2008). For example, systems should be easy to use and learn, and support walk-up interactions like the traditional whiteboard.

To build effective digital tabletop systems, it is important for researchers and designers to understand how the design of the system can affect a group's natural processes. However, we still know little of how digital tabletops can support fundamental behaviours of groups, such as reaching.

In this dissertation, we investigate how digital group reaching is different than physical group reaching, and how the design of digital arm embodiments affects group

[1] For example, http://www.nsercsurfnet.ca/projects/125

reaching behaviour. *Design,* in the context of digital arm embodiments, includes the visual design (what they look like) and the interaction design (how they work). We will show that the visual design, the way that input controls the embodiment, and the way that embodiments respond when interacting with others' embodiments, all affect group reaching behaviour.

1.3 Solution

Our solution is to provide an initial understanding of how the design of tabletop embodiments changes a group's reaching behaviour. This solution has four steps:

Step 1 – Understand physical reaching behaviour on traditional tabletops and digital tabletops

We will observe groups interacting over a traditional tabletop in a paper-based task to understand how groups coordinate access to shared objects when reaching with their physical arms. We will then compare this behaviour to physically reaching in an identical task implemented on a digital tabletop.

Step 2 – Determine how the visual design of digital tabletop embodiments affects reaching behaviour

Based on previous literature, we will design a set of digital tabletop embodiments that vary only in their visual design. We will then determine empirically (in a controlled lab study) how the visual design of digital embodiments affects a group's reaching behaviour. This study will compare the different visual designs to physically reaching in a digital system using the same task studied in part one.

Step 3 – Design digital arm embodiments that introduce constraints of physical arms and determine their effects on reaching behaviour

Based on attributes of physical arms, we will develop four augmented arm embodiments and evaluate how these affect a group's reaching behaviour. This study will use the same system as in part two.

Step 4 – Examine how input, visual design, and augmentation affect reaching behaviour when collaborators are distributed

The physical presence of the other person may affect how people interpret different visual designs and augmentations, and how people interact physically. We will extend the system studied in parts two and three to support distributed collaborators, and evaluate how removing the partner's physical body affects people's reaching behaviour.

1.4 Contributions of this Dissertation

The main contribution of this dissertation work is an initial understanding of how the design of digital tabletop arm embodiments affects a group's reaching behaviour.

This work also has several secondary contributions:

- Understanding of how a group's relationship (strangers, friends/co-workers, and intimate couples) affects group reaching behaviour.
- Design and initial understanding of how embodiment augmentations affect group reaching behaviour.
- Understanding of how distribution changes feelings of working with another person.
- Empirical evidence showing how the visual design of arm embodiments, from simple lines to full live video, affect group reaching behaviour.
- Understanding of how reaching with physical arms (in co-located and distributed settings) affects group reaching behaviour.

1.5 Organization of this Dissertation

This dissertation is presented in a manuscript style, where we present an overall architecture for the research and answer research questions through the manuscripts we have published throughout the work. There are three manuscripts that make up the core of this dissertation. They are presented in Chapter 2, Chapter 3, and Chapter 4.

1.5.1 Chapter Overviews

The remaining portions of this chapter provide a grounding on which the remainder of the dissertation depends. We present definitions, previous work, and describe how the task studied throughout this dissertation can generalize to many common tabletop tasks.

Chapter 2, Chapter 3, and Chapter 4 are mainly composed of the three manuscripts described above. Preceding each manuscript, we first motivate the work presented in the manuscript and place the work from the manuscript into the context of the dissertation questions. These chapters close with lessons learned from that manuscript, and how these lessons contribute to the next component of dissertation work.

Chapter 5 presents an overview of the contributions of the dissertation, and discusses how the results from the three manuscripts can inform the design of digital systems by describing the nine design guidelines stemming from the results presented in this dissertation. We close with a discussion of future opportunities for arm embodiments and the design of digital systems that effectively support group processes.

1.6 Grounding for the Work Presented in this Dissertation

In this section, we describe the background topics required to ground the work presented in this dissertation. First, we give definitions of terms used in this work. Second, we motivate the study of group reaching behaviour by describing how common this interaction is in real-world tasks. Third, we describe tasks previous researchers have used to study group tabletop interactions as justification for the task used throughout this work. Last, based on this grounding work, we describe the task and experimental details that are common across the work presented in this dissertation.

1.6.1 Reaching Gestures

A *reaching gesture* is defined as the mechanism people use to access an object. It is a common occurrence in everyday life, and is particularly important for many tabletop tasks (see Section 1.6.2). An example of a simple reaching gesture is someone reaching for and grabbing the saltshaker on the dinner table.

Group reaching is the subset of reaching gestures in which the reaching gesture occurs in a physical space shared by other people. In general, people avoid interfering with other people, so group reaching gestures typically include coordination with others. For example, people typically ask another person to pass the saltshaker at the dinner table instead of reaching through another's personal space.

A *digital reaching gesture* is the mechanism to spatially access the visual representation of a digital object. In a digital system, the *objects* people access are digital work artifacts and controls (e.g., a photo or the save icon). *Access* to a digital object includes any interaction, including selection and those in direct manipulation interfaces (e.g., pan and pinch to zoom). This dissertation focuses on reaching gestures as part of interaction (i.e., to access an item), so communicative gestures such as deixis (Genest 2011) is not directly studied in this work.

The *digital objects* studied in this dissertation must have a visual representation, and people interact with them by reaching for, and interacting with, the visual representation. This excludes digital actions accessed without reaching. For example, clicking the save icon is included, but using a keyboard shortcut instead is not included.

1.6.2 Physical Group Reaching over Traditional Tabletops

There are many real world scenarios where group reaching is essential. In general, people must physically touch an object to interact with it and must reach for the object in order to touch it, so most tasks require a reaching gesture before interaction. In this section, we present representative examples of everyday interactions, games, paper-artifact based tasks, and spatial layout tasks requiring group reaching.

1.6.2.1 Everyday Interactions

People encounter situations requiring group reaching over tabletops every day. For example, group reaching is required when eating a meal as a group, as well as mundane tasks such as adding milk to your coffee at Starbucks. In general, people avoid reaching through another's personal space when reaching for food or objects on the table. When eating at a table, people will typically ask to have that object passed to them (e.g., "Please pass the salt"), whereas people typically wait for their turn when adding milk or sugar to their coffee to the Starbucks counter. There is often an intricate dance between individuals, with close-proximity turn-taking to avoid physical collisions with other bodies, and to resolve conflicts when two people simultaneously grab a shared item (e.g., the same creamer).

These examples are interesting because of the breadth of interactions they cover. They include both shared objects (salt shaker, creamer) and single-use objects (dinner rolls, stir sticks). Note that both shared and single-use objects often require two reaching gestures: the first to grab the object, and a second to put it back (or throw it in the trash at Starbucks, which is typically also near the counter). These situations also encompass various group memberships. It is common to eat dinner with others with close-knit relationships (friends, co-workers, and family), but first dates and business lunches often occur between strangers. Similarly, at the Starbucks counter, people interact with people they are familiar with, as well as with strangers. These situations also encompass differently sized groups and table sizes, from small café tables with two people to huge wedding party tables.

1.6.2.2 Games

The second class of tabletop tasks where group reaching is required is games. There is a huge set of games that are played at a tabletop, including puzzles, card games, and board games.

First, a typical puzzle is a large picture split into small pieces that connect together to form a large picture. Groups typically dump the individual pieces in the center of the table for everyone to share. People quickly decide on which part of the puzzle they will focus on (e.g., one person works on the sky, another on the tiger), and begin collecting pieces that may be part of their section to make a pile near them. The group reaching gestures here include reaching for a piece of interest and passing a piece to another person (e.g., when one person has a piece they believe belongs in the puzzle section the other person is working on (Azad 2012)). Another reaching gesture is to move the shared box cover closer to inspect the final product.

Second, fast-paced card games sometimes require breaking the social protocols of group reaching in order to effectively play the game. For example, Speed[2] and Spoons[3] are two fast-paced card games where group reaching conflicts are essential to successfully playing the game. In Speed, two players race to play all of their cards. Players discard cards from their hand by incrementing or decrementing the number of the top card of either discard pile. For example, if the top card of a discard pile is a five, players can play a four or a six. Because both players play cards on both discard piles, the game is a race between the two players when both players have eligible cards. This situation often culminates in physical collisions, as both people try to place a card on the same discard pile simultaneously. These physical collisions are in stark contrast to people's typical behaviour of avoiding physical collisions. Breaking this social protocol is indeed part of the fun of Speed.

Spoons is a card game similar to Musical Chairs, in that there is one spoon fewer in the center of the table than there are players. Spoons is different than Speed in that play requires at least three people, and can easily support large groups of ten players. Each player has a hand of four cards. The dealer starts by picking up a new card, and discarding a card to the player to their right. This player picks up the card, and discards to their right. The goal of the game is to have four-of-a-kind as your hand, after which you can pick up one of the spoons. The remaining players race to pick up the other spoons; the player remaining without a spoon loses this round.

Spoons is particularly interesting because it requires both a main task (picking up and discarding cards) as well as a secondary task (monitoring people's reaching gestures into the center of the table to grab a spoon). Often, a player with a winning four-of-a-kind hand will try to sneak a spoon without others noticing. The difficulty of monitoring reaching gestures into the public, shared, space as well as working in your private workspace (your hand of cards) makes this game fun and challenging.

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[2] http://en.wikipedia.org/wiki/Speed_(card_game)

[3] http://en.wikipedia.org/wiki/Spoons

Third, and in contrast to the conflicts created in high-speed card games, most board games are turn-based. Turn-based interactions create a natural “lock-step” of interactions, preventing most group reaching conflicts. For example, in Chess, only one person interacts at a time, and so there is little need to worry about group reaching conflicts. Note that some turn-based board games do still have some implicit reaching rules. For example, in Monopoly, one player is typically assigned the role of “banker”, and is the only player allowed to reach into the bank to distribute money. In addition, the exchange of money (e.g., when purchasing a property or paying rent when landing on an owned property) requires group reaching coordination to ensure the handoff of money occurs seamlessly (though some players may throw money in frustration).

1.6.2.3 Paper-Artifact Based Tasks

There is a large class of group tabletop tasks focused around the manipulation of paper artifacts. These kinds of tasks include those with a single shared paper artifact and those with multiple paper artifacts.

Shared paper artifact tasks include those where people huddle around a shared artifact, such as a book. For example, two students working on an assignment may share a single copy of a textbook for reference, or a single copy of the assignment. In this case, the two students must coordinate access to a shared textbook (e.g., when one person grabs the book to look up a term), or must coordinate simultaneous access (e.g., they may move the assignment paper between them and both read through the problem). These tasks typically include individual work artifacts owned by each person. For example, each student has their own copy of the assignment answer, where they work individually.

Tasks with multiple paper artifacts are those with multiple work artifacts. For example, when a couple does their taxes or when co-workers fill out an expense report, they often spread out receipts over a table. These tasks require a lot of reaching gestures, as the group organizes the set of paper artifacts into categories or piles. In contrast to the homework example above, these tasks often also include a single shared artifact, such as the single expense report, instead of individual workspaces for each group member. Another common example of multiple paper artifact tasks is photo sharing, where groups organize a set of photos into piles.

1.6.2.4 Spatial Layout Tasks

Another kind of task requiring group reaching is spatial layout tasks. Typical examples of spatial layout tasks include scrapbooking, architectural planning (e.g., deciding on the layout of furniture in a room), and newspaper and magazine layouts.

In spatial layout tasks, the main interaction is moving the representations of objects around a main shared artifact (e.g., moving a picture of a couch around a room). This requires group reaching as, typically, only one person should move an object at a time. In addition to moving artifacts, there are other physical gestures in the shared space as part of the group communication (e.g., pointing gestures). In contrast to most group reaching gestures, these communicative gestures typically do not conflict with others, but instead may be used as signals to request the next turn (e.g., reaching to point to the map often signals others that you would like to speak).

1.6.3 Interference in Physical Reaching Gestures

As described in the examples above, an important aspect to group reaching is the social protocols that guide people's behaviour. These social protocols generally involve preventing interference between people. There are two common kinds of interference that occur during group reaching gestures: occlusion and physical collisions.

Occlusion is defined as the obscuring of the workspace. Because physical bodies are solid, people cannot see through them. In addition, it is difficult to see "around" another person's physical body. For example, when someone is reaching, the objects under their arm are difficult to see and interact with.

A physical collision is defined as the physical contact of two people's bodies. This may occur when two people simultaneously reach for a shared item, when someone tries to reach an item around where another person is working, or when moving around the tabletop (e.g., bumping into another person).

Both occlusion and physical collisions are interference because they prevent, or make more difficult, the group's interactions. When physically reaching over a tabletop, it is typically not possible to completely avoid interfering with others working on the same physical workspace; however, people generally try to avoid interfering with others.

People are typically conscious of when their bodies are occluding another's work artifacts, and will avoid physical collisions whenever possible (Andersen 1978, Hall 1966).

Combined, people's aversion to interfering with others is demonstrated through territoriality, the division of a space into personal and group territories. People have a natural tendency to avoid reaching into another person's personal space – the invisible bubble around a person's physical body that others only enter in specific situations (Hall 1966). In tabletop work, a person's personal space is extended out onto the tabletop. This space, called a personal workspace (Scott 2004), has the same social protocols as traditional personal space: people avoid reaching through, and avoid interacting with objects, in another's personal workspace. As most individual work takes place in the personal workspace, avoiding reaching through others' personal workspaces reduces the risk of occluding their work artifacts, as well as physically colliding with them.

1.6.4 Group Reaching in Digital Tabletop Systems

The previous discussion focused on physical reaching gestures for physical objects over traditional tabletops. This discussion is important to ground the work of group reaching over digital tabletop systems, which is described in this section.

There are two main mechanisms for reaching objects on a digital tabletop: physical reaching (typically with a touch screen tabletop) and digital reaching.

When working over a traditional tabletop, physical reaching is the only mechanism to access objects on the table. People have years of experience interacting around others' physical bodies, and have built a set of social protocols to guide people's interactions. For example, when two people reach simultaneously for the same object (say the saltshaker), they detect the potential conflict and quickly resolve it, often without any verbal coordination. Usually, one person will back off, letting the other person go first. These social protocols allow people to predict how others will interact, and often enable groups to coordinate access to shared items with little verbal communication (Hornecker 2008).

Although physical reaching has coordinative benefits for groups interacting over a tabletop, it is also limiting. For example, people can only interact with objects they can physically reach, so they may need to walk around a large table in order to grab the object they are interested in (Nacenta 2007), or ask someone to pass it to them.

Digital systems are not limited by many of the constraints of the physical world. For example, digital tabletops may not necessarily limit people to their physical reach by using indirect input with another input device (e.g., reaching with a mouse and cursor). This *digital reaching* allows people to interact with any item on the tabletop, regardless of its location. Although digital reaching is powerful for individuals, researchers know little of how digital reaching may affect a group's coordinative processes, such as coordinating access to shared objects through group reaching.

1.6.4.1 How are People Embodied?

A main difference between physical and digital reaching is how people are embodied. When physically reaching on a touchscreen tabletop, people are embodied by their physical arms: they are visually represented and provide input to the system using their physical arm and hand. When digitally reaching, people are no longer physically embodied in their reaching gestures, so most systems provide digital embodiments.

In a digital system, an embodiment is an appropriate body image to represent users and their actions to themselves and to others (Benford 1995). Essentially, embodiments are how people are visually represented and how they provide input to the system. The most common digital embodiment is a simple cursor.

Some fundamental research in digital embodiments has shown that cursors are difficult to use during group work: cursors are small and hard to track (Ha 2006), cursors are difficult to design to ensure distinguishability when there are multiple people interacting (Moraveji 2009), and it is difficult to assign ownership of cursors because there is no obvious link between a cursor and the person controlling it (Nacenta 2007). These problems are in stark contrast to physical arms. People are continuously aware of the location of other people's physical bodies, people's arms have natural differences that make them distinguishable, and the physical link of an arm to a body makes it clear who owns each arm.

A potential improvement on cursors is *arm embodiments*, and researchers have shown they may be useful for group work (Nacenta 2007). The benefits include a visual link between the embodiment and the person using it, as well as the fact that they are larger and therefore easier to see and track.

1.6.4.2 Interference in Digital Reaching Gestures

The interference described in Section 1.6.3 (occlusion and physical collisions) also applies to digital tabletop systems. Both types of interference can prevent others from working: occluding the view of an object makes it harder to interact with it, and, as physical bodies cannot occupy the same space simultaneously, physical blocking restricts where people can interact on a touchscreen tabletop.

With digital reaching, both kinds of interference can be reduced. A smaller digital embodiment makes it less likely that a person's interactions will occlude where another is interacting. In addition, because digital embodiments do not have the same physical constraints of physical arms, two digital embodiments can occupy the same tabletop space simultaneously: thus, there are no physical collisions.

The reduction of interference with digital embodiments is often perceived as a benefit over physical reaching. For example, people can now work faster because they no longer have to worry about interfering with others' work. People can also reach *through* another person's digital embodiment, enabling interactions that could not occur with physical arms.

However, removing constraints may not always be completely beneficial. Constraints (whether physical or social) help guide people's behaviour, enabling groups to predict what other people will do. Social constraints (e.g., of not interfering with others) ensure that group members stay aware of what other people are doing, an important component of successful group work. Physical constraints also enable a class of coordination mechanisms currently not possible with digital reaching. For example, people can move an item out of another's reach to claim ownership of it, or may place their physical arm down on the table's surface in order to block off a section of the table.

Thus, the lack of constraints of many digital embodiments may actually be detrimental to group work. A main contention of this dissertation work is indeed that digital embodiments may require *the addition* of constraints to support successful collaboration, an idea that we explore throughout this dissertation work.

1.6.5 Group Reaching in Previous Tabletop Studies

There is a wide range of tasks researchers have used in previous tabletop studies, ranging from spatial layout tasks, games, and group decision-making tasks. In this section, we outline a representative set of examples of tasks that require group reaching (tasks completed without group reaching are not presented).

1.6.5.1 Spatial Layout

A spatial layout task is one where a group must organize a set of objects into a particular layout. Previous studies used tasks ranging from seating allocation charts (Harris 2009, Marshall 2008, Marshall 2009, Yuill 2012), garden layouts (Rogers 2006), home-furniture layouts (Wu 2003, Tse 2007), and newspaper layouts (Birnholtz 2007). Another type of spatial layout tasks is photo sorting: making a collage based on a theme (Scott 2005), creating a comic strip (Pinelle 2008b), creating a storyboard (Nacenta 2007), and tagging photos (Morris 2006). Lastly, researchers have also used a tabletop magnetic poetry task, where the group must assemble a given poem from words displayed on the tabletop (Ryall 2004).

In each of these tasks, the objects to be laid out (people, furniture, plants, newspaper articles, pictures) are draggable elements on the tabletop. People reach out into the public space and move them around on, typically, a static background or template (e.g., an architecture drawing of a room or garden).

1.6.5.2 Games

There are a variety of custom designed games used in previous tabletop research. The most common are puzzles, like pieces of a larger image (Müller-Tomfelde 2008) or tangram puzzles (where geometric shapes are arranged into the silhouette of a larger shape) (Bolton 2012). Other researchers used novel games, such as a sheep herding game (Zhang 2007) and a shape binning game (Nacenta 2007). Lastly, researchers have also used commonly known games, such as Lego and Pictionary (Scott 2003). In each of these, the main interaction is similar to spatial layout tasks: a set of static items on the tabletop that people move around by dragging.

1.6.5.3 Group Decision-Making

Another large class of tabletop tasks are group decision-making tasks, those where the main goal is for the group to discuss alternatives and decide on a particular solution. These range from UML design diagram creation (Potvin 2012), visual analytics (Isenber 2010), itinerary- (Rogers 2004, Tse 2007) and route-planning (Tang 2006), and brainstorming (Clayphan 2011). These tasks are slightly different than other tasks, as there may not be a single correct answer; instead, the main measures of success include participation of the group, the number of ideas created, or consensus among the group members.

In many of these tasks, there is a create-discuss-iterate cycle, where group members create a solution and discuss changes for the next iteration of the solution. The creation portion typically involves group members interacting simultaneously on the tabletop (e.g., while deciding on a particular route). This portion requires group reaching as described before, by interacting in the public space to create and manipulate task artifacts. The discussion portion typically includes group reaching as well, typically for communicative gestures (such as deixis over a map (Genest 2011)) and annotations.

1.6.5.4 Systems for Specific Groups

Researchers have also used systems designed for a specific group (e.g., air traffic controllers (Conversy 2011)). These kinds of tasks may be difficult to generalize to other situations, as they were designed for specific interaction and background knowledge.

1.6.6 Experimental Details for Studies in this Dissertation Work

The main question addressed in this dissertation (how the design of digital arm embodiments affect group reaching behaviour) is answered through a set of controlled laboratory studies. To enable generalizations between studies, all studies use the same task and experimental protocol. In this sub-section, we first describe the previous work from the HCI literature our work builds upon. We then briefly describe the task used in the studies and how this task encapsulates important components of typical experimental tasks, followed by discussion of participant choice and the measures shared between studies.

1.6.6.1 Grounding from Previous Digital Tabletop Research

The work presented in this dissertation builds upon an initial exploration of reaching in digital tabletops by previous researchers. In this sub-section, we set the stage by describing the previous work on which we build the core of the work in this dissertation.

Initial research in collaborative digital tabletops focused on input techniques, including touch-, pen-, and mouse-based input, and how these input techniques change people's awareness, coordination, and feelings of invasion. For example, researchers found that touch input increases people's awareness of the other person's interactions (Ha 2006, Hornecker 2008) as compared to mouse-based input. When comparing a direct input technique to indirect input techniques, researchers found that physically reaching onto the table's surface to reach for items is the most similar to how people interact in the real world and the best technique all around, providing the best awareness of other people's actions (Nacenta 2007). In another study, touch input had more conflicts (e.g., grabbing the same item) than mouse-based input, though groups were able to resolve the conflict faster with touch input than mouse-based input (Hornecker 2008).

Though physical reaching techniques are more natural and support group processes well, one issue identified early on is that touch-based input has an intrinsic limitation of physical reach; it is much harder to reach and interact with items that are far away with touch-based input than with mouse-based input (Ha 2006, Nacenta 2007, Pinelle 2008a). Researchers also found that touch input is considered more invasive into people's personal space than mouse-based input, possibly because of the physical collisions with others (Ha 2006).

Due to the physical reach constraints, physical collisions, and awkwardness of close-proximity interactions with touch-based input, researchers began investigating digital reaching techniques, such as radar views (world-in-miniature), telepointers (cursor), laser beams (pen-based technique where the cursor appears on the table as if the pen was a laser pointer), and pantographs (cursor with lines visually connecting the cursor to the person controlling it) (Nacenta 2007). Researchers found that radar views had the most conflicts because people were less aware of what others were doing, that telepointers are difficult to associate with the person controlling them, and that laser beams are difficult to use for precise distant interactions (Nacenta 2007). Overall, researchers recommended using pantographs when both reaching and awareness are important (Nacenta 2007).

Building on this initial work, researchers focused on the design of digital *arm* embodiments, those represented by the pantograph technique from (Nacenta 2007). An initial exploratory study compared two cursors (a circle and an arrow pointing to the user), three pantograph embodiments (thin line, thick line above the workspace, and thick line below the workspace), a cartoon-shaped arm, and direct touch (Pinelle 2008a). This exploratory work showed that arm embodiments do not have the same social constraints as physical arms, and that people subjectively preferred the larger and more realistic-looking arm embodiments. Overall, people even preferred digital arm embodiments to physical input, suggesting arm embodiments may be better for groups than touch input. This exploratory work suggested that the input (mouse or touch) and the size, occlusion, and realism of arm embodiments are important factors of arm embodiment design, which we study in a controlled manner in Chapter 2.

1.6.6.2 Task Used in the Studies

The goal of selecting a task to study was to ensure generalizability to a variety of task types. It was important to select a common *interaction*, instead of a specific task situation, to ensure the results would be useful in a variety of situations. The interaction chosen is *dragging static task artifacts*.

The task used in this dissertation work is a poem-building task, based on magnetic poetry (Ryall 2004). Dyads (groups of two) sit side-by-side at a tabletop and are instructed to create haikus about an assigned topic. People create haikus from a set of shared words on the tabletop (see Figure 1). The words are static: people can drag whole words around the table and onto their individual haiku papers in front of them.

Each person's topic is chosen such that words from one topic are less useful for the other person. For example, Tree words (e.g., slow, grow, leaves) are less useful for a Car haiku than Car words (e.g., fast, road, crash). The words available for each trial were split: one third from the first topic, one third from the second topic, and the last third as "joiner" words (e.g., pronouns, articles, and conjunctions). Words were distributed across the table's surface, with the same word orientation and location between groups for the same condition. Topic word locations were switched, such that the words on each side of the table were more appropriate for the haiku on the other side of the table (see Figure 1). This switch encouraged people to reach to the other side of the table, increasing the likelihood of physical reaching conflicts (collisions and occlusion).

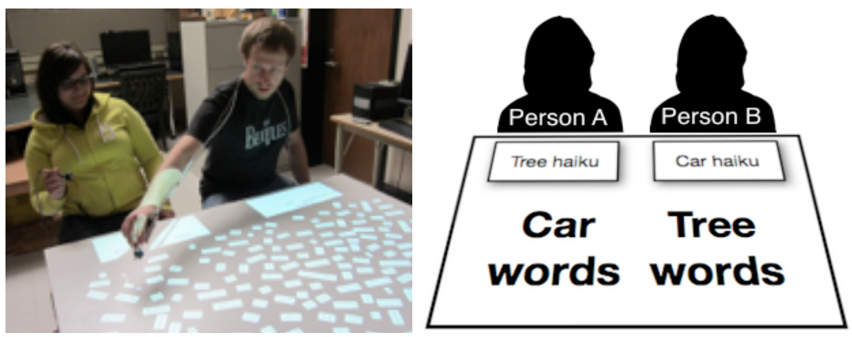

Figure 1 – Experimental setup

This task encompasses the following important components of tasks used in previous tabletop studies.

Group reaching for static task artifacts. In this haiku-building task, the only digital action is reaching and moving words around the table. People must reach into the shared public space to access words, move them into their personal territory (their piece of paper), and re-arrange the words within their territory to build their haiku. Thus, the haiku task is an example of a spatial layout task.

Task constraints. The open-ended nature of the task ensures that participants do not feel pressured by time constraints or competition, and thus follow the common social protocols guiding physical reaching gestures (see Section 1.6.2). Though open-ended, this task does have minor constraints by requiring people to build a haiku about a particular topic. This combination of an open-ended and constrained task are similar to many of the tasks described in the previous section, specifically puzzles, spatial layout, and decision-making tasks.

Discussion during the task. In addition to the main task of building a haiku, people may help their partner, leading to discussions and communicative gestures. For example, one person may ask if the other has seen a particular word, and the other person replies by gesturing to that word's location. This behaviour is common in many decision-making tasks, such as route- and itinerary- planning, and discussions over a map (for example, see (Genest 2011)).

1.6.6.3 Participants

The constructs investigated in this dissertation (specifically, an aversion to reaching into another's personal space) are based on the subjective idea of personal space. Researchers have shown that personal space is culturally mediated: some cultures are more comfortable with close-proximity interactions than others (Hall 1966).

In this work, we do not control for cultural backgrounds, but do collect a proxy of culture, namely people's first language (see Appendix A for a language breakdown of participants). As people are randomly assigned a partner, or choose their own partner such as a friend or co-worker, we cannot use culture as a factor in statistical analyses, due to there being uneven numbers of groups in each pairing. Even so, as all participants live in Canada, they may have adopted North American norms, regardless of their particular backgrounds.

In addition to cultural differences, gender pairings may also have an affect on personal space. For example, male-male touching is less common in North American cultures than male-female touching. Similar to culture effects, we do not control for gender pairings. As described in Section 1.6.6.4, the main measure of "crossings" is difficult to programmatically assign to one person or another. Therefore, although we collect the gender pairings, it is not possible to use these pairings to group participants for use in statistical tests. For example, we cannot test whether males are less likely to touch other males than they are females, as male-female pairings include both male-to-female and female-to-male touches collected as a single measure.

Lastly, the group's relationship may affect people's willingness to physically touch the other person. Intimate couples are less likely to avoid touching their partner than strangers. In all studies, the demographics questionnaire collects a group's relationship through the following questions: Do you know your partner; how long have you known your partner; and how often do you interact each week with your partner. In addition, Study 1 studies *relationship* as an experimental factor: strangers have never met, friends and co-workers must interact at least once a week, and intimate couples self-identify as an intimate couple (note that all intimate couple pairings were male-female, though this was not deliberately controlled). The other studies all choose a sub-set of relationship types, as described in each study's section.

1.6.6.4 Measures

To better understand people's reaching behaviour, we collect four main measures.

Number of crossings (as a proxy of touch avoidance). Physical reaching behaviour is guided partly by people's aversion to touching another person's physical body (that is, touch avoidance (Andersen 1978)). The main measure of touch avoidance in our studies is how many times people cross embodiments (both for physical arms and digital embodiments). This is collected automatically by the system and the log files produced by the system are used in statistical analyses. As shown in Figure 18, mouse-based crossings are measured as when the lines running through the embodiments (from the shoulder to the finger tip) cross, and touch-based embodiment crossings are measured as when the embodiment blobs intersect. Due to the side-by-side seated location of the participants (see Figure 2), the person sitting on the right was more likely to cross over the person sitting on the left. In the physical world, it is typically clear who is responsible for a violation of this social protocol; however, this is difficult to attribute programmatically to one person or the other. Therefore, the main measure of crossings is collected as a group measure.

Questionnaires. The constructs investigated are highly personal behaviours (e.g., personal space), so we also collect people's perceptions of the different embodiments through subjective questionnaires. We collect people's feelings of invasion and awkwardness. In the final study, we also collect questionnaire responses of their feelings of co-presence in the distributed system. These subjective responses are used in non-parametric statistical analyses.

Video analyses. All experimental sessions are also recorded from an angle enabling observation of both people's physical bodies and their interactions on the tabletop. The videos are not coded for statistical measures, but instead are used as exploratory and explanatory analyses of a group's behaviours. The videos also collect audio, which may provide some additional insight into the group's behaviour.

Interviews. In addition to the above measures, we also ask groups about their experiences through semi-structured interviews at the end of each session (see Appendix E for interview scripts). These interviews help better understand the observations gathered from video analyses and during the sessions, and provide an opportunity to ask questions specific to behaviours observed for this particular group.

1.6.7 Summary

In this section, we outlined why an understanding of group reaching behaviour over tabletops is important for designers and researchers. This behaviour is both common and complex, guided by social protocols built up over years of interacting around other people's physical bodies. In the remainder of this dissertation, we describe the steps we took to better understand group reaching behaviour, both as a physical and a digital behaviour, and how the design of digital arm embodiments affects this fundamental group behaviour. These steps are organized by fundamental research questions that are answered through controlled laboratory experiments using the task and measures previously described.

CHAPTER 2

THE VISUAL DESIGN OF DIGITAL ARM EMBODIMENTS[4]

2.1 Introduction to Manuscript A

To begin investigating group reaching behaviour with digital arm embodiments, it is important to first have a basic understanding of how groups reach over traditional tabletops and whether this is different than physical reaching in a digital system. With this baseline behaviour in mind, we can investigate group reaching behaviour with digital arm embodiments, and how the visual design of a digital arm embodiment can change group reaching behaviour.

2.1.1 Initial Pilot Study Problem and Motivation

The first problem investigated in this manuscript is that researchers and designers have little understanding of how physical reaching in digital systems is similar or different to physical reaching over a traditional tabletop.

People may behave differently in a digital system than they would in a face-to-face environment. For example, the perceived anonymity of the Internet allows people to interact with others without consequence (e.g., see the recent surge in awareness for cyber bullying). Over the years, an etiquette of online behaviour (*netiquette*) has evolved

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[4] The manuscript in this chapter, reproduced with permission from ACM, was published as:

Doucette, A., Gutwin, C., Mandryk, R.L., Nacenta, M., & Sharma, S. (2013). Sometimes when we touch: how arm embodiments change reaching and collaboration on digital tables. In *Proceedings of the 2013 conference on Computer supported cooperative work* (CSCW '13). ACM, New York, NY, USA, 193-202.

to help guide some people's behaviour. The fact that people behave differently in digital and traditional environments suggests that reaching behaviour may also be different.

2.1.2 Solution and Steps to Solution

To investigate this problem, we compare physical reaching behaviour on a traditional tabletop (an initial pilot study with pieces of paper) to physical reaching in the same task in a digital system. This analysis is observational, as this initial pilot study does not include a mechanism to collect quantitative behavioural measures.

2.1.2.1 Research Questions

1. How do groups coordinate access to shared paper artifacts at a physical tabletop?
2. How do these coordinative mechanisms change at a digital tabletop?

2.1.3 Lessons from Traditional Tabletop Pilot Study

As shown later in this Chapter, physical reaching behaviour is the same in digital systems as it is in traditional, paper-based environments, likely because both involve physical interactions that are governed by the same social protocols. With this baseline understanding, we can begin investigating digital group reaching, and how the visual design of arm embodiments may change a group's reaching behaviour.

2.1.4 Embodiment Visual Design Problem and Motivation

The second problem investigated in this manuscript is that researchers and designers have little understanding of how the visual design of digital arm embodiments affects group reaching behaviour.

Physical reaching is useful for group work: it is natural and enables group members to quickly coordinate access to shared objects. However, the physical world can be limiting for group interactions. For example, people can only interact with items that are within their physical reach.

Digital interactions are not necessarily limited by the constraints of the physical world. For example, with indirect input (e.g., through the use of a mouse), people can interact with items anywhere on a digital tabletop. However, when interacting digitally, people are no longer physically embodied during their reaching gestures. Instead, most systems embody digital interactions through a *digital embodiment*, the simplest being a cursor.

Researchers have shown that cursors are difficult for group interactions, as it is difficult to track multiple cursors, and cursors are difficult to design to ensure adequate differentiability and identifiability. Thus, researchers suggested *arm embodiments*, that is, embodiments visually extending from the person's seated location (Nacenta 2007). Arm embodiments are easier to track (due to being visually larger than cursors), and clearly demarcate who is controlling each embodiment (due to the visual link between the person and the embodiment) (Nacenta 2007).

Previous work investigated four factors of tabletop embodiment design: size, occlusion, presence of a connecting line, and realism (Pinelle 2008a). Researchers suggested that the design of digital arm embodiments may affect people's willingness to cross embodiments, based on attributes of social distance (Pinelle 2008a). This initial exploratory study was useful to inform our work, though they did not compare the digital interactions to traditional tabletop interactions, and the large size of the table may have caused the low level of physical arm conflicts. In addition, the "realistic" embodiments in (Pinelle 2008a) were single-colour cartoon arms. These remove the intricate shape of physical arms (such as the wrist and elbow) and the realistic texture of physical arms.

2.1.5 Solution and Steps to Solution

Our solution is to provide empirical evidence showing how four factors of digital arm embodiments affect group reaching behaviour. Based on the exploratory results from (Pinelle 2008a), we designed four arm embodiments based on four main visual factors: physicality, transparency, size, and realism. The empirical evidence stems from a lab study evaluating how group reaching behaviour changes with each of these visual factors.

2.2 Manuscript A – Sometimes When We Touch: How Arm Embodiments Change Reaching and Coordination on Digital Tables

Abstract. In tabletop work with direct input, people avoid crossing each others' arms. This natural touch avoidance has important consequences for coordination: for example, people rarely grab the same item simultaneously, and negotiate access to the workspace via turn-taking. At digital tables, however, some situations require the use of indirect input (e.g., large tables or remote participants), and in these cases, people are often represented with virtual arm embodiments. There is little information about what happens to coordination and reaching when we move from physical to digital arm embodiments. To gather this information, we carried out a controlled study of tabletop behaviour with different embodiments. We found dramatic differences in moving to a digital embodiment: people touch and cross with virtual arms far more than they do with real arms, which removes a natural coordination mechanism in tabletop work. We also show that increasing the visual realism of the embodiment does not change behaviour, but that changing the thickness has a minor effect. Our study identifies important design principles for virtual embodiments in tabletop groupware, and adds to our understanding of embodied interaction in small groups.

2.3 Introduction

The way that people are embodied in tabletop groupware is determined in part by the interaction mechanism used for the system. Direct input implies that people are embodied with their real arms and hands, whereas indirect input (e.g., when using a mouse) means that a virtual embodiment must be used, such as a telepointer or a 'pantograph' line connecting their cursor to their location at the table.

Direct and indirect input techniques have been studied frequently, and both have advantages and disadvantages for tabletop work. Direct input is natural and easy for novices to learn, and works well when artifacts are within arms' reach. However, direct input is problematic when tables are large and objects are farther away. Indirect input, in contrast, makes it easy for people to reach all areas of the table; studies have shown indirect input to be faster, more precise, and more efficient when targets are far away (Ha 2006).

Less is known, however, about other effects of the user embodiments that arise from different input types. Direct input uses people's real arms and hands, and so provides obvious awareness cues for others around the table. Indirect input uses a virtual embodiment on the table surface, and this embodiment can take a wide variety of visual forms. Understanding how things change when systems move from real to virtual embodiments is critically important for the design of tabletop groupware, because of the strong interaction patterns that people exhibit with physical bodies. In particular, people working at a table with their real arms and hands almost never touch or cross one another's arms. This behaviour on tables may stem from the natural touch avoidance (Andersen 1978) that affects our spatial interactions with others, or it may be an attempt to avoid disrupting another person's activities (for example, getting in their way or occluding their view of the workspace).

People's unwillingness to touch or cross arms provides an implicit coordination mechanism for tabletop work – that is, people are careful to negotiate access to shared areas of the table, and rarely reach for the same object. In addition, people use the mechanism in other ways, such as protecting objects by laying an arm around an area of the table. What happens to this natural coordination mechanism, however, when tabletop groupware moves to indirect input and virtual embodiments? Previous research provides conflicting views: work in VR suggests that social protocols are preserved when people are represented with digital avatars, but other research suggests that people may be more likely to break social rules at digital tables. An exploratory study (Pinelle 2008a) looked at several different arm embodiments on tables, and suggested that there are differences between real and virtual arms – but did not look at these differences in a controlled fashion.

To gather stronger empirical evidence about the differences between physical and virtual embodiments on digital tables, we carried out two studies. First, we examined social protocols for arm crossing at physical tables, and found that crossing and touching are extremely rare. Second, we carried out a large controlled study to look specifically at the effects of four factors – physicality of the embodiment, visual realism of a virtual representation, embodiment transparency, and embodiment size – on crossing and touching behaviour at a digital table. In addition, we investigated whether participants' relationship (strangers, acquaintances, romantic couples) affected crossing and touching behaviour with the different embodiment types.

The study showed four main results:

- There are dramatic differences in all measures of social behaviour between physical and digital embodiments;
- Increasing visual realism had no effect – people were just as likely to cross arms with a realistic picture arm as with a simple line embodiment;
- The occlusion resulting from the embodiment type did have a small effect on crossing behaviour;
- Relationship had a strong overall effect on the number of crossings, but did not interact with the other factors.

Our study provides new evidence about the effects of embodiment type on coordination over digital tables, and provides new insights about the principles underlying these findings. In particular, our results indicate that an actual tactile sensation is much more important than the visual arm representation in the phenomena of touch avoidance and the ensuing coordination mechanism for tabletop work. In addition, our results about size and occlusion suggest that people's desire to avoid inconveniencing others also affects their behaviour on shared tables. The findings from our study provide new design implications for supporting space management issues in digital table environments, and add new empirical results to our understanding of embodied interaction in small groups.

2.4 Related Work

Our work draws from previous research into physical touch, personal space in the physical and digital worlds, and tabletop embodiment and input design.

2.4.1 Touch and Personal Space

Touch is the most intimate interpersonal communication channel. It is "…the most carefully monitored and guarded, the most vigorously proscribed and infrequently used, and the most primitive, immediate and intense of all communicative behaviours." (Thayer 1986, p.24). Touch has many social functions – for example, it can demonstrate dominance or increase compliance – see (Thayer 1986) for a review.

Body-accessibility research has shown that people's comfort level with being touched on different parts of their body depends on who is doing the touching, where the touch occurs, and the type of touch (Jourard 1966, Rosenfeld 1976). Studies have shown that people are comfortable with touches on their arms and hands, regardless of gender (Nguyen 1973) or relationship (Heslin 1983); however, other principles of social interaction – such as touch avoidance (Andersen 1978) or inter-personal distance norms (Hall 1966) – are likely to reduce the frequency of incidental arm and hand contact in work environments. Personal space is moderated by many factors, including age, relationship, culture, and gender (Hayduk 1983). Although invasions of personal space are generally avoided, people can accommodate these situations when necessary (e.g., in crowded elevators) (Hayduk 1983).

2.4.2 Personal Space in Digital Environments

Researchers have shown that personal space does exist in digital environments. For example, in immersive virtual environments, people stand farther away from virtual humans that engage them in mutual gaze (Bailenson 2003) (similar to the real world). People also assign personal space to avatars. For example, research has found that people treat their avatar's personal space as they would their own (Jeffrey 2003), that they are uncomfortable with invasions of their avatar's personal space (e.g., Jeffrey 2003, Slater 2002, Smith 2000), and that they use gaze avoidance to compensate for these invasions (Yee 2007). In addition, people avoid actions that could cause others to be uncomfortable (e.g., walking though another's avatar) (Slater 2002).

Previous literature looks primarily at avatars, and less is known about the physical social norms governing other embodiments. Previous researchers assumed that social protocols would be enough to guide users' behaviour (e.g., Greenberg 1994); however, other researchers reported this is not always the case (Izadi 2003, Morris 2004). In a magnetic poetry task over a touch table, users violated each other's personal space by reaching through private workspaces to reach an item, even stealing words from other users (Morris 2004). This may be because the digital world does not have the same social norms as the physical world. For example, in a remote task, people had little issue sitting "in each others' laps" (Tang 2010).

2.4.3 Co-located and Distributed Multi-user Collaboration

Personal space and the digital representation of users were identified early on as important issues in the design of distributed collaborative spaces. For example, ClearBoard showed a remote collaborator as if she was on the other side of the same surface (Ishii 1993). Other remote collaboration systems have used varying degrees of realism in representations of people's arms (Tang 2006, Tuddenham 2007, Tang 2010). Most research on distributed groupware suggests that embodiments aid collaboration by increasing awareness and reducing potential conflict.

In contrast, co-located collaboration naturally provides more information about the positions and postures of collaborators; however, digital tools may disrupt conventional coordination mechanisms that rely on the physicality of action, such as those described by Tang (Tang 1991). Prior research in this area focused on comparing direct and indirect input and the effects on performance (Ha 2006), coordination and conflict (Nacenta 2007, Hornecker 2008, Pinelle 2008a), and spatial interference (Tse 2004, Tang 2006). Some evidence suggests that indirect input changes natural collaborative behaviours such as territoriality (Scott 2004), and leads to an increase in coordination problems (Nacenta 2010).

Pinelle et al. (Pinelle 2008a) carried out a broad exploratory study that is the closest previous work to ours. Pinelle looked at ways that different arm embodiments affected behaviours in a tabletop game. Their observations suggested several hypotheses, which we use as starting points for our investigations. First, they found differences between physical and digital arms (although the low level of interaction they observed between physical arms may have been caused by the large size of the table used in the study and the resulting distance between collaborators). Second, they saw only small differences between different types of digital embodiments, but found that people preferred more realistic representations, and were less comfortable reaching with larger embodiments (Pinelle 2008a).

Overall, the results of previous research (including those of Pinelle et al.) provide conflicting messages about the effects of moving from real to virtual embodiments; we still do not clearly understand the factors that change group behaviour on digital tabletops. For example, it is unclear whether changes in people's behaviour arise from physical touch (and people's attempts to avoid it), or from an awareness of others and a desire to avoid disrupting their work. Similarly, it is unclear whether people will respect others' personal work areas on tables with different kinds of embodiments, and in what situations they will avoid interfering with each others' activities. Answering these questions is important because it is difficult to design appropriate representations of people's bodies in collaborative systems unless we know which factors are likely to influence behaviour, and how.

To address these issues in a controlled fashion, we carried out two empirical studies, focusing on reaching and coordination behaviours. In our first study, we examined these behaviours in a real-world activity at a physical table. In the second study (a controlled experiment), we investigated the effects of four specific factors – the physicality, visual realism, transparency, and size of an embodiment – on crossings, coordination, and awareness.

2.5 Physical-Table Observational Study

Our first study examined how the behaviours and social protocols discussed in previous work occur in the specific setting of tabletop artifact-based work. We observed and interviewed people working with paper artifacts at a physical table, and focused on the behaviour of arm crossing to look at coordination and touch avoidance.

2.5.1 Participants and Tasks

Ten dyads (1 female pair, 6 male pairs, 3 mixed pairs) were recruited from a local university. Participants were instructed to build a haiku (a three-line poem) by arranging words cut from a sheet of paper and placed on the table (Figure 2, left). The two participants built their haikus at the same time, each on a different topic, and assembled the words on the table in front of where they were sitting.

Words were scattered around the table and were available to either of the participants; however, the words related to the left participant's topic were on the right side of the table, and vice versa. Participants had to reach to the other side of the table to retrieve the most appropriate words for their haiku (e.g., see Figure 2, right), which created the potential for many reaching conflicts in a short session.

Users sat side-by-side – a common way for pairs to locate themselves at real-world tables, and a necessary arrangement when working with textual artifacts. It is much easier to read text when it is oriented towards you, and previous work has shown that orientation is often used to imply ownership (Kruger 2003). Our setup ensured that all words were equally available to both people.

Figure 2 - Study setup (left), and word distribution (right).

This task is interesting for CSCW because several of its attributes are common in real work tasks. First, the area is split into territories (see Figure 2), which is common for tabletop work (Scott 2004). Second, the haiku task is a mixed-focus collaborative task (Gutwin 1998), in which users often switch between individual work and group work. The group work in the haiku task is the need to coordinate access to the shared resource (the words) in the public space of the table.

2.5.2 Observed Behaviours

We observed two clear behaviours in the study – touch avoidance, and territoriality – both of which led to specific kinds of space management strategies on the tabletop.

2.5.2.1 Touch Avoidance

It was very clear that people avoided touching the other person's arm or hand. Over ten sessions, with hundreds of reaching events, we observed only three crossings (i.e., where one person reached over or under the other person's arm). In informal, post-experiment interviews, people repeatedly stated that it was rude to reach over or under another person's arm, and that they avoided doing so. When we asked the three people who had been crossed how it felt, all said that they noticed the cross and felt uncomfortable.

Touch avoidance led to two mechanisms for managing table access: implicit coordination, and accommodation.

Implicit Coordination. We observed nascent reaching conflicts where both people simultaneously began reaching to the same area; however, these never became selection conflicts (where both people grabbed the same object) as groups used coordination techniques to avoid selection conflicts. The most common was the 'hallway passing' coordination technique, where both people move their arms in and out until one conceded to the other (see Figure 3). This behaviour was also observed in (Hornecker 2008).

Figure 3 - The hallway passing technique.

Accommodation. People consistently leaned back slightly when the other person reached in front of them; this subtle behaviour was observed in all groups. People reported that they moved away not because the closeness of the other's arm made them uncomfortable, but because doing so would let the other person work without feeling uncomfortable about reaching into their personal space. This accommodation technique provides a subtle and low-effort means for giving permission to reach into personal space.

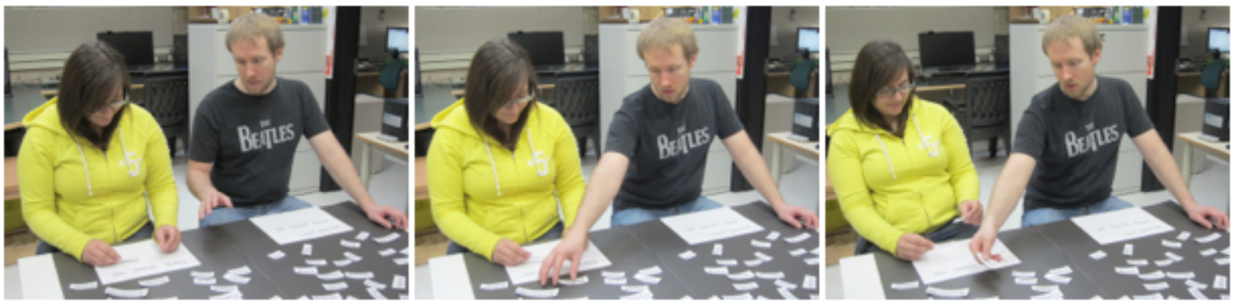

Figure 4 – Accommodation.

2.5.3 Territoriality

The second obvious behaviour that we observed was territoriality (Scott 2004). People immediately adopted the area in front of them as their personal territory. This organization is normal for tabletop work (Scott 2004), and was also encouraged by the setup of the study; however, we also manipulated the sense of ownership in the public space of the main table, by reversing the arrangement of topic words (described above). The main way in which territoriality seemed to affect people's behaviour in the task was in protection of the personal region of the table. Over all sessions, there were no episodes where people reached into the other person's personal territory (defined by the sheet of paper where they built their haiku), even though they needed to reach in front of the other person to retrieve words for their own task.

Both touch avoidance and territoriality provided results in terms of crossing and intrusion events, and we use these concepts as the basis for the design of the digital-table study described below.

2.6 Digital Table Study

We replicated the haiku-building task used in our physical-table study on a digital tabletop. We were interested in two main research questions: first, what changes occur when moving from physical to digital arm embodiments, and what happens to the touch-based coordination mechanism observed in the physical-table study; and second, how does the visual design of a digital embodiment affect behaviour.

2.6.1 Visual Factors of Arm Embodiment Design

Previous work in embodiment design has shown that cursors provide only low levels of awareness in group work (Pinelle 2008a), and that arm embodiments (which maintain a visual link between the cursor and the user's seated location) provide better awareness (Nacenta 2007).

To determine which embodiments to study, we conducted small pilot studies of different digital embodiments based on Pinelle et al.'s exploratory study (Pinelle 2008a). We tested cursors, lines, cartoon arms, transparent thick arms, and realistic-looking picture arms (a picture of the user's actual arm). In contrast to our physical table study and the observational results in (Pinelle 2008a), we observed that in many cases, people had little issue touching the digital embodiments.

Based on these results, we varied three factors of digital embodiment design: *size*, *transparency*, and *realism*. The thicker an embodiment (size), the more likely others are to notice it; however, it also occludes more of the workspace. The more transparent an embodiment, the less prominent it is, and the less it might affect a collaborator's actions. Realistic-looking embodiments may cause people to treat them more like digital extensions of a user.

2.6.2 Study Procedure

To investigate the role of visual embodiment design on coordination, we asked dyads to create five sets of individual haikus using the digital tabletop system. People sat side-by-side, as in the physical-table study, with their mouse to the right of their digital haiku papers.

2.6.2.1 System and Task Descriptions

Dyads used a 125cm x 88cm, top-projected tabletop system, with resolution of 1280 x 960. Participants were able to physically reach any digital word on the table, although this sometimes required them to stand to reach distant words. The size of the digital words was similar to the paper cutouts used in the physical-table study.

Participants built their haikus by moving the words on the table to the digital haiku paper in front of them – the papers measured 400x175 pixels and were positioned directly in front of each user. Each of the five haiku tasks used a different set of words belonging to a topic pair. Each participant was given one topic in the pair for their haiku. The five topic pairs were: Clothing/Book, Coffee/Cat, Car/Tree, Student/Dog, Lake/Chair. Topics were paired so that words from one topic would be less useful to the other topic (e.g., 'lumbar' is more useful for a chair haiku than a lake haiku); however, participants were told they could use any of the words on the table.

There were 36 words from each topic, plus the same 102 joiner words (e.g., 'the', 'and', 'of') as in the physical-table study, for a total of 174 words available for each haiku set. Words were split in a similar way to the physical-table study: the 'tree' words were on the opposite side of the table as the 'tree' haiku. Joiner words were distributed over the entire table. Initial locations of the words were saved, so that all groups saw the same words in the same locations.

2.6.2.2 Procedure

When dyads arrived, we took a picture of each person's right arm to be used as the base image for their virtual embodiment. Virtual arms were anchored at the right side of each haiku paper and were controlled by the mouse (the arm image stretched as users reached farther onto the table).

Participants completed five haikus, one for each topic set and embodiment (described next). During piloting, we found that groups quickly learned how to use the system and build their haikus, so no explicit training was required. Order of presentation of the embodiments was balanced using a Latin Square design. Topic pairs were presented in a single order, thus topic pairs were equally distributed across embodiment conditions over the study. We wanted to ensure we did not bias participants into thinking about personal space and awkwardness, so participants completed questionnaires only after the last haiku.

2.6.2.3 Embodiment Conditions

We tested one physical embodiment and four digital embodiments that varied in the previously identified visual factors of embodiment design. People used a mouse to control the cursor location when using digital embodiments. By using an image of the participant's arm for all digital embodiments, shape was kept constant for all conditions. The display width of the embodiment image was approximately the same as people's actual arm width.

Pens (real arms). In this condition, people moved words using direct touch on the tabletop - a cursor appeared below the tip of a pen and the embodiment was simply their physical arm. Pen location was tracked using a Polhemus Liberty tracker, and selection occurred via a button at the tip of the pen controlled by a Phidget interface board. Polhemus pens were used instead of a touch table to track hand locations at all times, not just during object selection.

Thin. The embodiment image was scaled to 5 pixels wide, and filled in with purple or green to differentiate users.

Solid. The unscaled embodiment image (approx. 200 pixels wide; everyone's arm is a different size and shape) was filled in with purple or green, and was opaque.

Transparent. The unscaled embodiment was filled with purple or green and made semi-transparent (60% opacity), so users could see the words through the embodiments.

Picture. The unchanged image of the user's arm (same size as the transparent and solid conditions).

These five embodiment conditions each varied only one visual factor of embodiment design. Solid, Transparent, and Picture embodiments all have the same size (thickness), because they use the unscaled arm image. *Physicality* was investigated by comparing Solid to Pens*; Size* by comparing Solid to Thin; *Transparency* by comparing Solid to Transparent; and *Realism* by comparing Solid to Picture.

2.6.2.4 Participants and Demographic Factors

Personal space, and people's willingness to invade or be invaded by another, is dependent on a variety of factors (e.g., culture, sex), but is highly dependent on relationship type (Hall 1966, Hayduk 1983). To ensure that our results take the nature of relationship into account, we gathered data from three dyad types: strangers, acquainted pairs, and romantic couples.

Strangers had never met previously; acquainted pairs were dyads that interacted at least once a week and included friends and co-workers; romantic couples included dating and married couples. The median length of relationship for acquainted pairs was 1.00 years (1 month to 20 years), and 3.75 years (9 months to 10 years) for romantic couples.

Sixty people (28 female, mean age 24.1) participated – ten dyads per relationship type. Twenty-four participants had never heard of digital tables; 23 had heard of them but never used one; and 13 had used a digital table before. 42 participants reported English as their first language; 7 dyads had different first languages.

We did not control the distribution of sex in our dyads. All romantic dyads were male-female; 3 acquainted dyads were male-male, 3 were male-female, and 4 were female-female; 4 stranger dyads were male-male, 5 were male-female, and 1 was female-female.

2.6.2.5 Measures and Data Analyses

We collected a variety of objective and subjective measures that we group in three themes relevant to coordination: touch avoidance, territoriality and awareness. Subjective measures used standard 7-point Likert scales.

Touch Avoidance. We counted the number of crossing events (when embodiments crossed each other) to measure the degree of touch avoidance. We also asked participants to rate their feelings of awkwardness when crossing.

Territoriality. Previous work in territoriality (e.g., Scott 2004, Hornecker 2008) showed that people's reaching behaviour is mediated by the location of items on the table. To measure this, we counted the number of events (word pick up and drop) taking place on the other participant's side of the table. To measure how an embodiment's occlusion affected reaching behaviour, we collected the percent of time embodiments occluded the other person's haiku. In addition, we asked participants to rate how awkward it felt to reach to the other side of the table, and their feelings of invasions of personal space, with each embodiment type. Last, we asked them to rate their sense of ownership over various tabletop objects.

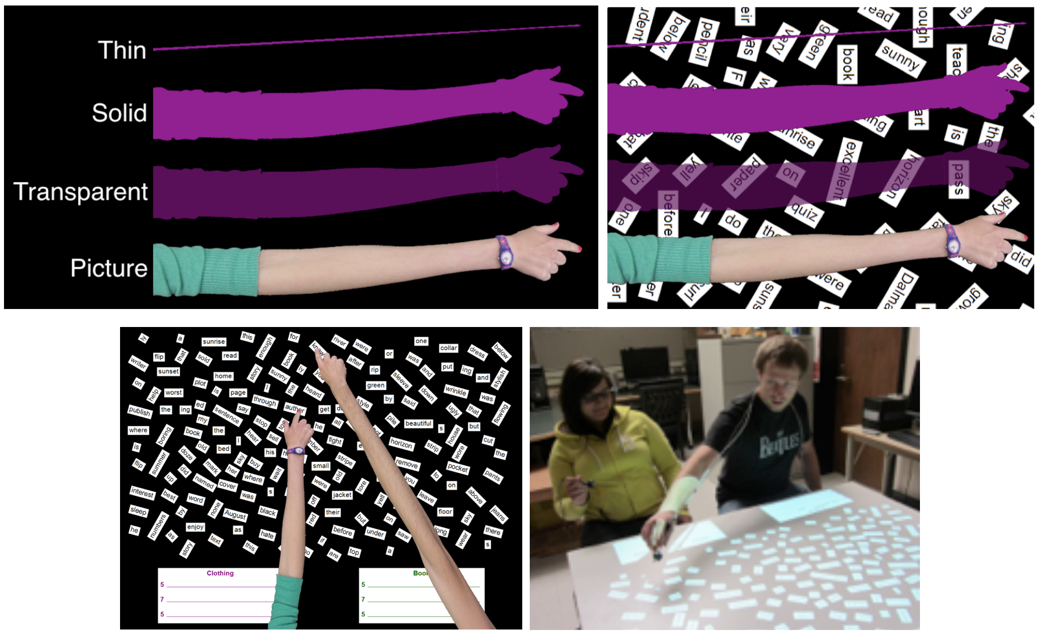

Figure 5 –The four arm embodiments (top left), different levels of occlusion (top right), Picture arms in the system (bottom left), and Pen embodiments (bottom right).

Awareness. We asked participants to rate their level of awareness of their partner's embodiment table position.

Visual inspection of the distribution of the objective counts indicate that parametric analyses were adequate; therefore we run repeated measures ANOVAs with α=0.05. When main effects were found, we performed planned post-hoc comparisons between selected techniques, motivated by four factors: Physicality (Pens to Solid), Size (Thin to Solid), Transparency (Transparent to Solid), and Realism (Picture to Solid). Post-hoc tests were adjusted for multiple comparisons by adjusting α according to the Holm-Bonferroni method.

Due to the ordinal nature of subjective measures we applied more-conservative non-parametric tests to these ratings. Post-hoc tests in subjective measures were also corrected for multiple comparisons. All results are reported for individuals, except for crossings. These are difficult to attribute to one or other participant, so we report by dyad.

2.7 Results

We present analysis for the themes presented in the previous section: touch avoidance, territoriality, and awareness. Relationship effects are included in each theme. Table 1 shows the post-hoc pairwise comparison results.

2.7.1 Touch Avoidance

There was a main effect of embodiment on the number of crossing events ($F_{(4,116)}$=30.02, p≈0.000, η^2=0.53). The pairwise comparisons in Table 1 show that there were significant effects of physicality and size on the number of crossings, but not of transparency or realism. Figure 6 shows that physicality was the dominant factor affecting touch avoidance as measured by crossings.

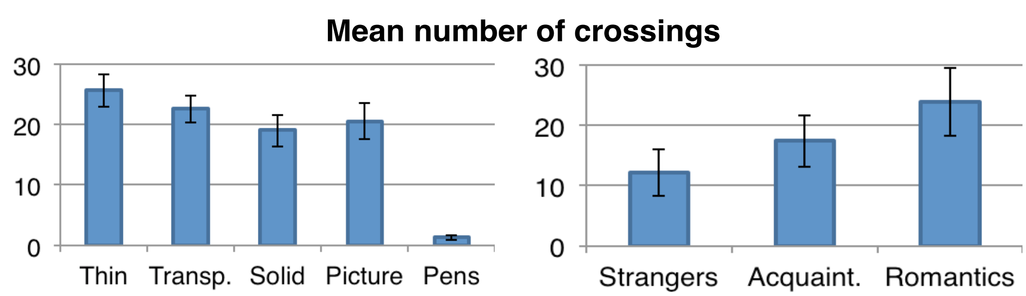

Figure 6 - Mean (±SE) number of crosses, by embodiment (left) and by relationship (right).

Although there was a main effect of relationship on the number of crosses ($F_{(2,27)}$=4.45 p=0.021, η^2=0.25), there was no interaction with embodiment ($F_{(8,108)}$=1.27, p>0.05, η^2=0.09). As Figure 6 shows, Strangers crossed fewer times than Romantics (p=0.016), and Acquaintances did not significantly differ from Strangers or Romantics (p>0.05).

We asked participants to rate their agreement with the statement: "It felt awkward to cross embodiments with this embodiment"; results are shown in Figure 7 (left). A Friedman test showed a main effect of embodiment on participants' feelings of awkwardness when crossing embodiments ($\chi^2(58)=58.69$, $p\approx0.000$). As Table 1 shows, there were significant effects of physicality, size, and transparency, but not realism. A Kruskal-Wallis test showed no main effect of relationship on any ratings of awkwardness of crossing embodiments (all $\chi^2(2)<3.53$, $p>0.17$).

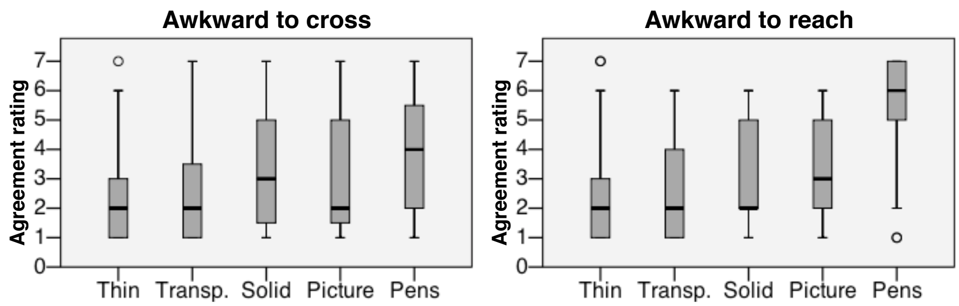

Figure 7 - Subjective feelings of awkwardness.

2.7.2 Territoriality

Figure 7 (right) shows agreement with the statement "It felt awkward to reach to the other side of the table with this embodiment." A Friedman test showed a main effect of embodiment on participants' feelings of awkwardness reaching to the opposite side ($\chi^2(58)=114.16$, $p\approx0.000$). Table 1 shows that physicality and size increased awkwardness, and transparency reduced it.

There was a main effect of embodiment on the percentage of time people spent occluding the other person's haiku ($F_{(4,130.87)}=6.254$, $p=0.002$, $\eta^2=0.086$, Greenhouse-Geisser). Pairwise comparisons showed that Pens occluded less often than all digital embodiments, with no differences between the digital embodiments (see Figure 8).

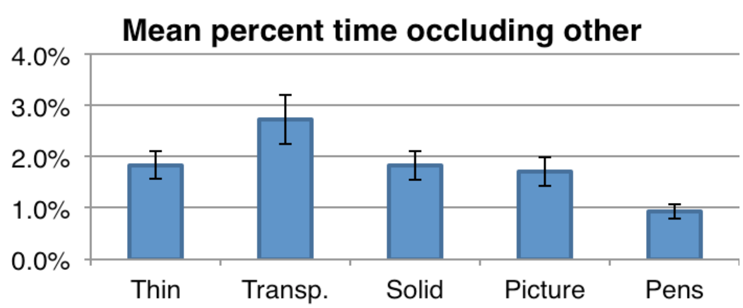

Figure 8 - Mean (±SE) percent time occluding other's haiku.

There was a main effect of embodiment on the proportion of words picked up from the other side of the table ($F_{(4,200.68)}$=5.578 p=0.001, η^2=0.086, Greenhouse-Geisser). There were no significant pairwise comparisons after adjusting for multiple comparisons.

Table 1 - Pairwise comparisons showing the effect of each factor as compared to Solid (e.g., for Physicality, Pens had fewer crosses than Solid). Bolding indicates significant difference (after correction for objective measures).

Theme	Measure	**Physicality** (Pens vs. Solid)	**Size** (Thin vs. Solid)	**Transparency** (Transparent vs. Solid)	**Realism** (Picture vs. Solid)
Touch avoidance	**Number of crosses**	**Fewer crosses** (p≈0.000)	**More crosses** (p=0.016)	No difference (p=0.082)	No difference (p=0.366)
	Feelings of awkwardness	**More awkward** (p=0.017)	**Less awkward** (p≈0.000)	**Less awkward** (p≈0.000)	No difference (p=0.627)
Territoriality	**Proportion of events on opposite side**	No difference (p=0.032)	No difference (p=0.445)	No difference (p=0.019)	No difference (p=0.541)
	Percent time embodiment occludes other's haiku	**Less time occluding** (p=0.002)	No difference (p=0.981)	No difference (p=0.061)	No difference (p=0.592)
	Feelings of awkwardness reaching to other side	**More awkward** (p≈0.000)	**Less awkward** (p=0.001)	**Less awkward** (p≈0.000)	No difference (p=0.268)
	Feeling of being invaded	**More invaded** (p=0.021)	**Less invaded** (p≈0.000)	**Less invaded** (p≈0.000)	No difference (p=0.444)
	Feeling of invading partner's space	No difference (p=0.108)	**Less invading** (p≈0.000)	**Less invading** (p≈0.000)	No difference (p=0.802)
Awareness	**Feeling of awareness**	**More aware** (p=0.018)	**Less aware** (p≈0.000)	**Less aware** (p=0.038)	**More aware** (p=0.010)

We asked participants to rate their agreement with the statements, "I felt like my partner was invading my space" and "I felt like I was invading my partner's space" (see Figure 9). Friedman tests showed a main effect of embodiment on participants' feelings of being invaded by their partner (χ^2(58)=52.66, p≈0.000) and of invading their partner's space (χ^2(58)=63.69, p≈0.000). As Table 1 shows, participants felt less awkward invading and being invaded with increased transparency and decreased size. Participants felt more awkward being invaded with a physical embodiment (Pens), but there was no effect of physicality on the feeling of invading space. Realism did not affect the awkwardness of invading or being invaded.

A Kruskal-Wallis test showed no effect of relationship on feelings of being invaded with all embodiments (all $\chi^2(2)<0.695$, $p>0.17$) except Picture ($\chi^2(2)=8.00$, $p=0.018$). Acquaintances were different than Strangers and Romantics (both $p<0.02$). A Kruskal-Wallis test showed no main effect of relationship on the ratings of invading partner's space (all $\chi^2(2)<2.35$, $p>0.309$).

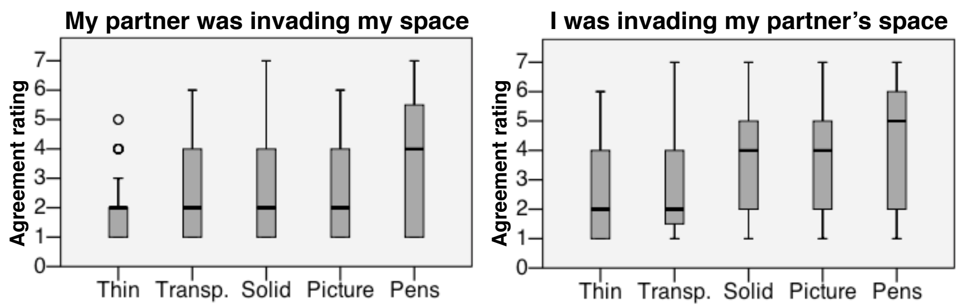

Figure 9 - Feelings of being invaded, and of invading partner.

Participants had complete freedom constructing their haikus and we did not provide instructions about whether they were allowed to reach onto another user's paper. Only 15 of the 30 groups ever accessed words on their partner's paper (3 Strangers, 6 Acquaintances, 6 Romantics), and there were large variations in the amount of this activity in the dyads. Strangers invaded their partner's paper sparingly (1-2 times), Acquaintances did so more often (1-11 times), and Romantic couples invaded most of all (3-96 times). Half of the groups did not invade their partner's paper; many stated they did not realize that they would be able to do so.

On average, invasions represented only 1% of pick and drop events. There was no main effect of embodiment on invasion ($F_{(4,236)}=0.72$, $p>0.05$, $\eta^2= 0.01$).

We also asked people to report their level of ownership over table items on a 5-point scale (1="no ownership", 5="complete ownership"). Although people felt more ownership over their paper (mean=4.07) and the words on their paper (3.75) than over their partner's paper (1.97) or words on their partner's paper (2.05), people did not differentiate ownership of words on the opposite side of the table (2.71) from words on their side of the table (2.9). There were no main effects of embodiment on these ratings.

2.7.3 Awareness

Figure 10 shows agreement ratings to the statement “I was aware of my partner’s position on the table while using this embodiment”. A Friedman test showed a main effect of embodiment on participants’ feelings of awareness ($\chi^2(58)=63.69$, $p \approx 0.000$). As Table 1 shows, increases in size, physicality, and realism increased awareness, while transparency reduced awareness.

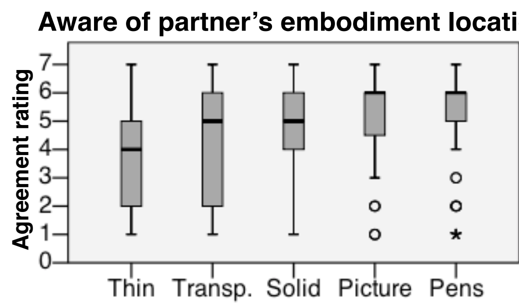

Figure 10 - Subjective awareness of partner's embodiment location.

2.7.4 Open-Text Questions and Observed Behaviours

In addition to finding out how participants behaved with and felt about visual embodiments, we asked two open-text questions about crossing embodiments. We grouped participant responses into categories based on the words used (one response can appear in multiple categories).

When responding to the question “briefly describe why you avoid crossing over (or under) someone’s physical arm”, people reported that it is rude, impolite, uncomfortable, or awkward (33 times), it is an invasion of personal space (19 times), and it causes a performance cost to the partner – occlusion, interruption, and distraction (19 times). For the question “briefly describe how crossing over (or under) someone’s physical arm is different than crossing someone’s digital embodiment”, people reported that embodiments can’t “feel” (26 times), the embodiment is not “me” or “them” (18 times), and the embodiments don’t have or invade personal space (14 times).

2.7.4.1 Observations of Coordination with Physical Embodiments

In addition to clear evidence of touch avoidance (as described above), we also observed instances of implicit coordination and accommodation (e.g., see Figure 5). Another coordination policy we observed with the pens was that some people planned out the words they wanted, then quickly reached for the words, making a pile on their paper, and then organized them into sentences.

2.8 Discussion

The user study shows five main results.

- All measures showed large differences between physical and digital embodiments: crossings with physical arms were rare (fewer than two per session), but were very common with all digital embodiments (twenty or more); in addition, subjective perceptions of awkwardness and invasion of space were strongly different between physical and digital embodiments.
- Increased realism of the embodiment – even photos of people's actual arms – had no effect on behaviour, but did increase subjective ratings of awareness.
- The size of the digital embodiments had the largest effect on behaviour.
- Relationship had a strong overall effect on the number of crossings, but did not interact with the other factors;
- Perception of awareness differs for physical and digital embodiments and is also affected by all visual factors.

2.8.1 Interpretation of Results

2.8.1.1 Differences Between Physical and Digital Embodiments

People rarely crossed physical arms, but had little issue crossing digital embodiments (even when they looked like their own physical arms). The main reasons for this dramatic difference lie in the way people felt about the arms' connection to the real bodies, and the lack of any touch sensation. First, most participants reported that they did not associate the digital embodiments with their own, or their partner's, actual body:

several people said that the embodiments were “not me” and “not my partner;” others stated that the digital embodiments did not have personal space. We saw further evidence in the lack of proprioception with the digital embodiments – people often left their digital arms ‘laying out on the table,’ something that would likely never happen with real arms. Second, participants stated that the digital embodiments cannot “physically touch,” and that they have no sense of feeling, and so the awkwardness of crossing was removed.

These statements imply that people perceive physical touch differently than a visual representation of touch, even if that visual representation is dynamic and realistic, contrary to some VR work (e.g., Jeffrey 2003, Smith 2000, Slater 2002). The touch avoidance first seen in the physical-table study appears to be dependent on a true sensation of touch rather than a visual representation. This is in part because representations of arm crossing are not subject to social norms; it is possible, however, that other representations of touch (e.g., touching while holding hands) might not be seen as being as neutral as crossing.

Nevertheless, in our tabletop systems, the lack of true touch in digital arm embodiments appears to remove most touch-avoidance behaviour. This has strong design implications, because people may perform actions in the digital world that they would strongly avoid in the physical world (e.g., crossing over an outstretched arm to steal an item).

2.8.1.2 Territoriality

People did not extend their private territories in front of them beyond their pieces of paper. This may be because we swapped the word locations, which forced people to reach into what otherwise might be the other person’s territory. We also did not allow people to create their own territories in the public workspace. The system automatically moved words back to their original location when they were dropped anywhere outside of pieces of paper.

Our territoriality results also suggest there is an effect of dyad relationship on territorial behaviour (which has not been reported before). The more intimate the relationship, the more likely people are to invade personal territories. In addition, although people’s public-workspace territorial behaviour was different than reported in other research (e.g., Ha 2006, Scott 2004), people's subjective ratings matched previous work (e.g., people are uncomfortable reaching to the other side of the table (Hornecker 2008)).

2.8.1.3 Occlusion and Digital Embodiment Size

Although not nearly so strong as the effect of physicality, we also saw an effect of embodiment size on crossings and awareness. Figure 10 and Table 1 show the same trend: the thicker an embodiment is, the more aware people feel of their partner, and the less they cross. In addition, increased thickness was paired with more feelings of awkwardness reaching to the other side of the table (Figure 7, right).

These effects are likely due to both the increased visual prominence of the thicker embodiments, and the increased likelihood that the arm will occlude artifacts on the table and disrupt the partner's activities. Many of the open-text responses stated that people were concerned about disrupting their partner's work, both with physical and digital embodiments. We speculate that the cause of the differences was directly related to the level of occlusion caused by that embodiment. The lack of effect for Realism (the Picture to Solid comparison) provides additional evidence for this hypothesis, because both Picture and Solid occluded the workspace to the same degree.

2.8.2 Implications for Design

There are five issues from this research that designers should consider when developing tabletop systems.

2.8.2.1 Touch Input (real arms) vs. Indirect (digital embodiments)

When designing tabletop systems, designers must choose the way that people will interact with the table. In some cases, indirect touch (and digital embodiment) are advantageous, but our study shows that this decision can greatly impact the way that people use the system. As a result, designers should think carefully about the ramifications of different choices. For example, designers might use only real-arm touch input when selection conflicts could lead to severe errors; with real touch, people will be more aware of their partner and less likely to come into conflict over the table.

2.8.2.2 Visual Realism does not Reproduce Social Protocols

The study showed that no purely visual design reproduced the degree of touch avoidance seen with physical arms. This means that designers will not be able to re-introduce social control mechanisms simply through appearance (although several participants found the picture arms ‘creepy’, this did not produce additional touch avoidance). As a result, systems that use digital embodiments may need to build in explicit access control to prevent uncontrolled access.

2.8.2.3 Lack of Awkwardness Could be Useful

In some situations, such as fast-paced tasks or games, people may be able to complete their work faster when they do not have to worry about making others uncomfortable. In these cases, designers could choose digital embodiments to allow for comfortable crossings, and narrow embodiments to avoid occlusion. However, this decision also means that actions will be less obvious, decreasing awareness.

2.8.2.4 Relationships Change Behaviour

Reaching and territoriality behaviour is strongly dependent on the relationship of the users. This is important for public digital tabletop installations (e.g., museums), where the system may be used by anyone. Designers who know the relationship of their users may need more than simple embodiments – for example, if users are more familiar with one another, access control mechanisms might be required.

2.8.2.5 Occlusion is an Important Factor in Embodiment Design

Of the visual factors we investigated, size was the only one that had an effect on behaviour. In general, people did not want to disrupt others (this was true even for intimate couples). Transparency is easy to build into arm embodiments, and provides a reasonable combination of visual salience (for awareness) and low occlusion.

2.8.3 Directions for Future Research

2.8.3.1 Replacing Coordination Mechanisms on Tables

Touch avoidance provides people with a natural way of avoiding conflict, but without true touch, alternate means of managing access to the table will be needed. First, access could be controlled at the system level through roles or permissions. Previous CSCW work on explicit roles and access provides the control required and provides solutions to conflicts, but these methods are often too heavy-weight to be used in practice. We plan to explore new possibilities for light-weight access controls for tabletops (e.g., touching an object to reserve it for a short time).

Alternatively, new social protocols may appear as people become more experienced with digital embodiments. The changes that we saw may have occurred because people have so little exposure to these techniques. With more experience, groups may develop new coordination methods – for example, they may start to associate digital touching with the negative implications of physical touching, or may develop other mechanisms that do not depend on touch avoidance (e.g., more explicit turn-taking behaviours).

2.8.3.2 Mixed Input Ecologies

Our results suggest it will be important to know more about systems that allow multiple types of input and embodiment. For example, systems that combine direct and indirect input will have the two embodiments mixed together. We speculate people would have little issue crossing an arm embodiment over a physical arm, but more study is needed. Remote collaboration over distributed tables is another mixed setting: both people interact with direct touch, but are represented remotely via an arm embodiment (e.g., VideoArms (Tang 2006)). It is not known whether the real-arm origin of a remote representation would change behaviour.

2.8.3.3 Other Instantiations of Social Protocols

Our work looked at the change of embodiment from a physical form to a representational form, and how this changes behaviour. We chose arm embodiments as our representation and touch avoidance as the behaviour. Although we lose touch avoidance with this representation, feelings of awkwardness and invasion are still present, so other protocols may also remain. For example, touching certain parts of another's avatar with your avatar's arm may still be considered rude, even though neither person can "feel" that touch.

2.9 Conclusion

In this paper, we presented two studies of tabletop reaching behaviour: a physical table study, demonstrating that people rarely cross arms, and a digital table study, demonstrating the marked difference between reaching with physical and different digital arm embodiments. We showed that the most important factor in the visual design of embodiments is the level of occlusion caused by the embodiment: the lower the occlusion, the less people are aware of each other's actions, the less awkward it is to interact in shared spaces, and the more people cross embodiments. This research is an important step in understanding the differences between physical and digital group interactions, opening up many new questions on what factors tabletop designers should manipulate to ensure that groups are able to work as naturally as they do over physical tables.

2.10 Summary of Manuscript A

Physical group reaching behaviour is similar in digital systems as it is in traditional, paper-based environments, likely because both involve physical interactions that are governed by the same social protocols. This baseline behaviour is important to ground work on digital reaching, as investigated next.

The main contribution of this work is empirical evidence showing that group reaching behaviour is radically different with physical and digital reaching. While reaching physically, people avoid reaching over or under the other person's arm, in an intricate dance of coordinative turn-taking. While reaching digitally, regardless of the visual design, people have little need or desire to avoid colliding with others' embodiments and occluding the other's workspace. This complete free-for-all means that people are less aware of what the other person is doing, with no coordinative turn-taking.

Secondary contributions of this work include empirical evidence that the group's relationship changes their level of collisions: the more intimate the relationship, the more likely people are to cross arms (both physical and digital). People also tended to cross more with less occluding embodiments, though they still crossed almost 20 times more with even the most occluding embodiment over physical reaching with Pens.

CHAPTER 3

EFFECTS OF EMBODIMENT AUGMENTATIONS[5]

3.1 Introduction to Manuscript B

The previous work demonstrated empirically that group reaching gestures are different with physical and digital reaching, regardless of the visual design of digital embodiments. Specifically, people are less concerned about interfering with others' work, freely colliding with the other person's embodiment. As shown in Manuscript A, avoiding interfering with others is an integral part of coordinative reaching behaviour with physical arms, so we wonder whether we can design digital arm embodiments that re-introduce the coordinative benefits of physical reaching gestures.

3.1.1 Problem and Motivation

The problem investigated in this manuscript is that digital arm embodiments do not support the automatic reaching coordination mechanisms of real arms.

This is a problem because the free-for-all behaviour of digital arm embodiments means that people are less aware of what others are doing in the workspace – an integral part of successful collaboration. It also means that the coordinative benefits of physical interactions (turn-taking, the ability to block off sections of the workspace by placing an

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[5] The manuscript in this chapter, reproduced with permission from ACM, was published at:

Doucette, A., Mandryk, R.L., Gutwin, C., Nacenta, M., & Pavlovych, A. (2013b). The effects of tactile feedback and movement alteration on interaction and awareness with digital embodiments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 1891-1900.

arm down on the table, and the lack of simultaneously grabbing the same object) are missing from digital arm embodiments.

This lack of coordinative benefits of digital arm embodiments may be because arm embodiments do not behave as physical arms: there is no sense of "touching" another's arm embodiment, and digital arm embodiments can freely cross through one another. To gain coordinative benefits, digital arm embodiments may require the addition of constraints.

3.1.2 Solution and Steps to Solution

The solution is to design digital arm embodiments with constraints based on attributes of physical arms, and to evaluate their effectiveness. We provide empirical evidence through a laboratory study of the effectiveness of arm embodiment augmentations.

3.1.2.1 Research Questions

1. Can arm embodiment augmentations shape people's collaborative interactions over digital tables?
2. How do our two mechanisms, tactile feedback and movement alteration, affect group reaching behaviour?

3.2 Manuscript B – The Effects of Tactile Feedback and Movement Alteration on Interaction and Awareness with Digital Embodiments

Abstract. Collaborative tabletop systems can employ direct touch, where people's real arms and hands manipulate objects, or indirect input, where people are represented on the table with digital embodiments. The input type and the resulting embodiment dramatically influence tabletop interaction: in particular, the touch avoidance that naturally governs people's touching and crossing behavior with physical arms is lost with digital embodiments. One result of this loss is that people are less aware of each others' arms, and less able to coordinate actions and protect personal territories. To determine whether there are strategies that can influence group interaction on shared digital tabletops, we studied augmented digital arm embodiments that provide tactile feedback or movement alterations when people touched or crossed arms. The study showed that both augmentation types changed people's behavior (people crossed less than half as often) and also changed their perception (people felt more aware of the other person's arm, and felt more awkward when touching). This work shows how groupware designers can influence people's interaction, awareness, and coordination abilities when physical constraints are absent.

3.3 Introduction

Digital tables provide large workspaces where people can share and manipulate computational artifacts. Digital tables are natural sites for collaboration: they allow rich verbal and non-verbal communication, and they let people use well-practiced coordination mechanisms from everyday experience with physical tables and surfaces (Morris 2006, Nacenta 2007, Scott 2004).

The shift from physical to digital environments, however, can also change the way that people interact with objects and with each other. Designers of tabletop groupware systems must take these changes into consideration to effectively support group work – but little is currently known about how the move from physical to digital can affect behavior. One issue that has strong ramifications for groupware design is how the table's input technique, and the embodiment type that results from that input, affects coordination and awareness in tabletop activity.

Digital table systems can employ two main types of input: *direct touch*, in which people use their real arms and hands to manipulate objects on the table, or *indirect input*, in which people use an input device like a mouse, and where people are represented on the table through a virtual embodiment such as a pointer, a line, or an arm drawn on the surface. Indirect input is valuable (and sometimes the only option) when tables are large and items out of people's physical reach require them to move around the table (Pinelle 2008a).

The type of input, and the resulting embodiment type, can dramatically influence tabletop interaction. Recent research shows that one basic interaction – touching or crossing another person's arm – is very rare with direct touch and physical arms, but is common with indirect input and virtual arms (Doucette 2013a). This difference is not just a curiosity, because the strong avoidance of touching and crossing with physical arms is one of the awareness mechanisms that helps people understand and manage shared access to public space. Touch avoidance is evident in several complex behaviors in tabletop work: for example, it plays a role in people's fine-grained awareness of others' locations, in dynamic negotiation of access to shared objects, in people's ability to protect areas of the workspace, and in accommodation behavior, where people move out of the way when someone needs to reach past them (Doucette 2013a).

When tables use indirect input instead of direct touch, this strong mechanism underlying awareness and coordination disappears from the environment, leading to dramatically different crossing and touching behavior with virtual arm embodiments (Doucette 2013a). Although this loss of a constraint can be useful in some situations, in others it can cause interaction problems: people are less aware of others, less able to avoid access conflicts, and less able to protect objects and maintain control over their personal work territory (Doucette 2013a).

Designers of tabletop groupware systems need to better understand the factors that govern and shape interaction behavior over tables – not to replace touch avoidance, and not to simply replicate the physical world, but to determine whether some of the valuable aspects of physical interaction can be added to the designer's toolbox. It is not immediately clear what these factors might be; for example, an earlier study showed that increasing the visual fidelity of an arm embodiment did not reduce people's crossing and touching behavior (Doucette 2013a). However, this study also suggested two factors for further study: *tactile feedback*, which is one of the foundations of touch avoidance in the physical world; and *movement alteration*, which can prescribe the difficulty of interacting in the same table space as another person.

In this paper, we investigate embodiment augmentations through a tabletop study designed to test the effects of tactile feedback and movement alterations on group reaching behavior and awareness. To test tactile feedback, we attached vibration outputs to either the participant's mouse or to their thigh. To test movement alteration, we changed the cursor's movement speed when embodiments touched (either slowing it or stopping it altogether). Participants carried out tabletop tasks with all augmentations types, as well as a control condition with no augmentations. Our study provides three main results:

- Both augmentation types significantly changed tabletop behavior: tactile feedback reduced crossings by as much as one-half; movement alterations reduced crossings by as much as 75%;
- Both augmentation types also significantly changed people's feelings of awareness, awkwardness, and intrusion; augmentations were rated significantly higher than the control; the ratings for augmentations are similar to those reported for physical arms (Doucette 2013a).
- Participants reported that the addition of tactile feedback and movement alteration was more annoying to use than an un-augmented embodiment; they also reported that having to coordinate was not very frustrating overall.

Our study is the first investigation of using embodiment augmentations to shape people's collaborative interactions over digital tables, and the first to show how tactile feedback and movement alteration can modulate people's behaviour in co-located collaborative situations. Our research provides a first step towards a richer set of design capabilities for designers of tabletop groupware to enable a broader range of group tabletop applications.

3.4 Related work

Our work draws from previous research into physical touch, personal space in the physical and digital worlds, tabletop embodiment and input, and access control to shared items.

3.4.1 Physical Touch

Touch is the most intimate interpersonal communication channel (Thayer 1986). Work in body-accessibility shows that the location of a touch, and the intimacy of the touched area, are central to people's comfort level in being touched (Jourard 1966). Hands and arms are the least intimate touch locations, and the thighs are one of the most intimate and guarded (Heslin 1983, Jourard 1966, Nguyen 1973). The social rules of touch, including who can do the touching (Heslin 1983), manifest themselves in the well-studied phenomenon of touch avoidance (Andersen 1978). Touch avoidance research focuses on the circumstances that cause people to avoid tactile contact with each other. People's natural ability and inclination to avoid touching others is particularly prominent during tabletop work, where people avoid crossing over or under another person's arm; instead, people take turns interacting in the workspace (Doucette 2013a). Previous work showed that touch avoidance does not transfer when physical arms are replaced by digital embodiments (Doucette 2013a).

HCI researchers have studied several aspects of touch that are peripherally related to our research. For example, research into mediated social touch attempts to support touch over a distance through tactile or kinesthetic feedback (see Haans 2006 for a review). Other researchers created haptic or tactile feedback systems for a variety of purposes, ranging from increasing presence (Oakley 2001), expressing and interpreting emotion (Bailensen 2007), providing spatial information to blind users (Owen 2009), and encouraging users to take breaks (de Korte 2008).

3.4.2 Personal Space in Digital Environments

People vary in their willingness and comfort letting others into the space surrounding them (i.e., personal space) (Hall 1966). Work on VR suggests that personal space also applies to digital avatars – researchers showed that invasions of avatar personal space make people uncomfortable (Jeffrey 2003, Slater 2002, Smith 1998). People also avoid making others uncomfortable (e.g., by not walking through their avatar) (Slater 2002).

There is little previous work investigating personal space in tabletop or other groupware systems. Previous researchers assumed that social protocols would be enough to guide users' behaviour (e.g., Greenberg 1994). Other researchers reported that users reached through each other's personal workspaces, even stealing words from others (Morris 2004), suggesting that the digital world does not have the same social protocols as the physical world. For example, in a remote task, people had little issue sitting "in each others' laps" (Tang 2010).

Territoriality research (Scott 2004) showed that people partition tabletop workspaces into personal and public workspaces. Personal workspaces are often directly in front of each user, simulating a version of personal space. Some evidence suggests that indirect input affects natural collaborative behaviours such as territoriality (Scott 2004), and leads to an increase in coordination problems (Nacenta 2010).

3.4.3 Tabletop Embodiments

Embodiments represent users in the workspace. They allow users to interact with the workspace, and allow others to track a user's actions. Previous work in CSCW has studied several kinds of embodiments, such as avatars, telepointers, and video embodiments.

Tabletop embodiments can be either physical (people use their arms and hands to interact in the workspace) or digital (a visual representation of the user, with a form of indirect input, like a mouse). There are many advantages of digital embodiments over physical embodiments (e.g., ability to reach (Nacenta 2010)). Tabletop embodiments can be cursors, pantographs (a line connecting cursor and user), arm embodiments (pantographs with more “arm-like” visuals) (Pinelle 2008a), or video of physical arms for distributed tables (Tang 2006).

The choice of embodiment can affect several aspects of group interaction. Prior research in this area focused on comparing direct and indirect input and the effects on performance (Ha 2006), coordination and conflict (Nacenta 2007, Hornecker 2008, Pinelle 2008a), and spatial interference (Tse 2004, Tang 2006).

3.4.4 Coordination and Access Control in Groupware

Access to shared resources is an important issue for groupware designers. Early groupware researchers examined role-based access and distributed-systems approaches such as locking and serialization (Greenberg 1994). Recently, researchers have started investigating different possible techniques to enable collaboration, and how these interact with social protocols and affect behaviour (Morris 2004, Tsandilas 2005, Morris 2006).

Researchers identified that social protocols were often enough to support coordination and turn taking without needing more explicit access control, as long as there was adequate awareness information about others’ locations and activities (Greenberg 1994). What happens to social protocols when moving from physical to digital is still not well understood, with some researchers suggesting that physical protocols do not transfer directly to digital (Izadi 2003, Morris 2004). Only a few researchers have investigated adding dynamic rather than role-based or explicit access control; for example, (Pinelle 2009) investigated how competitive behaviour in a game was affected by rules and policies that control who can manipulate which objects and when. An alternative approach to access control is to introduce a cost to the behaviour. Previous researchers have shown that there are benefits to making a task more difficult to complete. For example, performance costs can aid spatial learning (Cockburn 2007) and can improve planning on a task without impairing the final result (O’Hara 1999); and adding visual difficulties can induce deeper learning strategies in information visualizations (Hullman 2011).

To our knowledge, there has not been any substantial study addressing the relationship between interpersonal physical touch, coordination, and how digital environments can replicate or substitute this fundamental proxemic behaviour.

3.5 Digital Tabletop Study

People avoid touching and crossing physical arms when working at a table. In many situations (e.g., when working remotely, or on large tables), indirect input is more appropriate; however, previous work has shown that people have little issue crossing digital embodiments, regardless of the visual design (Doucette 2013a). The lack of awkwardness of touching embodiments means that people may not maintain awareness of others' embodiment locations and actions, in stark contrast to the continuous, rich, and up-to-date information people collect of others' physical arms.

We introduce two augmentations to affect interaction (i.e., embodiment crossing) and to increase awareness in co-located tabletop collaboration. Our augmentation types are designed to bring attention to crossing behaviour through various levels of feedback. With physical arms, this feedback comes naturally through the social awkwardness of touching another person (Andersen 1978, Hall 1966) and also through the time it takes to reach around another person's arm. This suggests two styles of embodiment augmentations: introducing awkwardness and affecting movement.

3.5.1 Embodiment Augmentations

Based on our observations of physical arms in multiple pilot studies, we created two embodiment augmentation types: tactile feedback and movement alteration. Within these two types, we created both low and high levels.

Table 2 - Embodiment augmentation types

	Low	**High**
Tactile Feedback	Mouse Vibration	Pocket Vibration
Movement Alteration	Slowed Interaction	Blocked Interaction

- In **Mouse Vibration**, a small vibrotactile motor buzzes inside of a custom-built mouse.
- In **Pocket Vibration**, a small vibrating box is placed on the front of each user's thigh.
- In **Slowed Interaction**, a control-display (C/D) gain decrease slows both embodiments when they cross.
- In **Blocked Interaction**, the embodiments cannot cross.

The tactile feedback replicates the social awkwardness of touching arms in the digital domain. Mouse vibration is the lower level of feedback because it is applied to a device that is held in the hand – the location considered least awkward to be touched (Nguyen 1973). The pocket places the feedback on the thigh, one of the most awkward locations to be touched (Nguyen 1973). Although participants are aware that they are not "touching" their partner, we believe control over producing vibration by touching embodiments would follow the same pattern of awkwardness from physical touching.

The movement alteration approach introduces feedback through performance by affecting people's ability to work quickly. The slowed interaction is the lower level because it only delays interaction using a C/D gain, creating a feeling of stickiness (Mandryk 2008). The blocked level is the high level because it prevents interaction (implemented through setting the C/D gain to zero – as the cursor moves, there is no corresponding movement of the embodiment).

3.5.1.1 Implementation of Augmentations

The mice and pocket vibrating boxes each contained two cylindrical button-type vibrators, either wrapped in polymer foam and formed into a sturdy package using hot glue and adhesive tape (for the pocket devices), or placed into a desktop mouse. The individual motors inside each device were wired in parallel and were computer-controlled via a *Phidgets* analog board. As the board outputs only 20 mA per channel, and the motors required about 300 mA, we added a transistor stage to each channel as a voltage buffer (also known as an *emitter follower*). The setup allowed us to reliably control the vibration strength of the devices. The vibrators ran continuously at the same frequency (approximately 150 Hz, according to the manufacturer's specs) while embodiments were crossed.

The C/D gain slowdown for slowed interaction was determined through pilot studies. We scaled all mouse movements down by a factor of 17 – a mid-level range that still allows movement, but is "sticky" enough to be noticeable. As noted above, to prevent embodiments from crossing, the factor for blocked was set to infinity.

3.5.2 Study Setup

To investigate how groups would respond to the augmented embodiments, we asked dyads to create six sets of individual haikus using a digital tabletop system.

3.5.2.1 System and Task Descriptions

We replicated the system and task used in (Doucette 2013a). Dyads were asked to build six individual haiku sets by dragging words from the shared center part of the table to their haiku paper in front of them (see Figure 11), where they assembled their haikus. The digital haiku papers measured 400 x 175 pixels. The digital words were large enough to be easily read by both participants from their seated location.

Dyads used a 125cm x 88cm top-projected tabletop system, with resolution of 1280 x 960. People sat side by side, and interacted with the tabletop with their mouse to the right of their digital haiku papers. It is common for pairs to sit side-by-side at real-world tables. This arrangement is also necessary when working with textual artifacts, given how much easier it is to read text oriented towards you. In addition, previous work showed that people associate orientation with ownership (Kruger 2003). Our setup ensured people felt they could use any of the shared words on the table.

The attributes of the haiku building task are common in real world tasks. First, the tabletop is split into territories, common in tabletop work (Scott 2004). Second, the haiku task is a mixed-focus collaborative task (Gutwin 1998), where users switch between individual and group work. The coordinated access to the shared words in the public space is the group work.

The six haiku building tasks used a different set of words from six topic pairs: Planet/Horse, Clothing/Book, Coffee/Cat, Car/Tree, Student/Dog, Lake/Chair. Topics were paired so that words from one topic were less useful to the other topic (e.g., 'flower' is more useful for a tree haiku than a car haiku). There were 174 shared words available for each haiku task: 36 words from each topic, plus 102 joiner words (e.g., 'the', 'and', 'of').

We arranged the words such that the words for each topic were on the opposite side of the table; for example, the 'tree' words were on the opposite side of the table to the 'tree' haiku (see Figure 11). This distribution encouraged people to reach to the other side of the table, increasing the chance of an arm crossing. We randomly distributed the words on the appropriate sides of the table, with joiner words distributed over the entire table. The distribution of words was stored such that each group saw the same words in the same location. Groups were told they could use any word in the shared space.

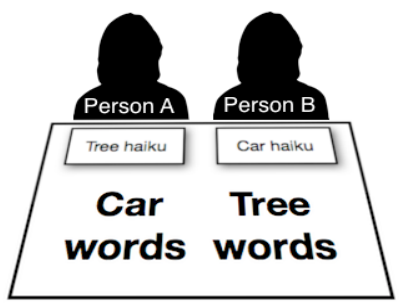

Figure 11 - Distribution of words relative to haiku papers.

3.5.2.2 Procedure

During pilot testing, we found that groups quickly learned how to use the system to build their haikus, so no explicit training was required.

Participants completed the task using a baseline (un-augmented) embodiment, and the four augmented embodiments. The visual embodiment was based on the *Transparent* embodiment from (Doucette 2013a), which had the best balance between interruption and noticeability. It is shaped like a real arm, and has 70% opacity. All embodiments were controlled with the mouse; the tip of the embodiment corresponded to the cursor location, and the embodiment created a straight line between the cursor location and the right side of the participant's haiku paper.

Participants all started the experiment by completing one haiku set using the baseline (non-augmented) embodiment. Following this baseline trial, participants were informed that they would receive feedback when they crossed their arms. A blank screen with the embodiments appeared, and groups were instructed to cross once to experience the feedback. The next haiku task was started immediately after, because we wanted to see how groups would adapt to the feedback and did not want all the adaption to happen in the training stage, where we were not logging interactions.

Augmented embodiments were presented in four orders to balance potential effects of presentation order. Half of the participants started with the tactile feedback augmentations and half with the movement alteration augmentations. Within those groups, the initial condition was balanced between the high and low levels. The order of the last two augmentations mirrored the order of the first two. Haiku topic pairs were presented in a single order.

We were interested in whether changes to behaviour from augmented embodiments lasts after the augmentation is removed. To investigate this 'permanence', we included a second baseline condition following the first augmentation. This allowed us to compare augmentation types in a within-subjects design and compare the effect of permanence in a between-subjects design. Thus, the four orders were:

Baseline1-Blocked-Baseline2-Slowed-Pocket-Mouse

Baseline1-Slowed-Baseline2-Blocked-Mouse-Pocket

Baseline1-Mouse-Baseline2-Pocket-Slowed-Blocked

Baseline1-Pocket-Baseline2-Mouse-Blocked-Slowed

Following the six haikus, dyads completed a post-experiment questionnaire to collect subjective responses. To ensure we did not bias participants into thinking about personal space and awkwardness, participants completed the questionnaire only after the last haiku.

3.5.2.3 Participants

Participants were asked to bring a friend or co-worker for the study. Users of tabletops in real work settings will likely work mostly with co-workers whom they know. We focus our research on work settings, so we tested this type of dyad. The median length of relationship for dyads was 30 months (2 months to 17 years). Ten dyads reported being friends, and six were class- or lab-mates. Dyads reported they interacted on average 3.75 times per week.

There were 32 participants (15 female, mean age 26.4). None participated in previous haiku-building studies. Twelve participants had never heard of digital tables; 12 had heard of them but never used one; and 8 had used a digital table before. Ten participants reported a Chinese language as their first language; 9 reported English; 5 dyads had other first languages.

Because people brought a partner, we did not control the distribution of sex in our dyads; yet, this balanced with 5 male-female, 6 male-male and 5 female-female dyads.

3.5.2.4 Measures

The system recorded the number of times people crossed embodiments. The number of crossings relates to people's willingness to touch each other. For Blocked, the system restricts people's ability to cross. Because our measure (crossings) is also the manipulation (i.e., we do not allow crossings), we only record new crossing events if people are blocked, move 50 pixels away (half the width of the embodiment), and then try to cross again.

Following the experiment we collected subjective responses to 7-point Likert scale questions about participants' awareness of their partner's embodiment, their feelings of awkwardness reaching and crossing, and their feelings of invasion of personal space. In addition, we also had a semi-structured interview with dyads following the session.

3.5.2.5 Data Analyses

Visual inspection of the distribution of crossing counts indicate that parametric analyses were adequate; therefore we ran RM-ANOVAs with α=0.05. Crossings are difficult to attribute to one or the other participant, so we report these per dyad. We determined that order of presentation of augmentations had no effect on the number of crossings through a RM-ANOVA with order as a between-subjects factor. There was no main effect of order on the number of crossings ($F_{(3,12)}$=0.3, p=0.369, η^2=0.07), and no interaction of order with augmentation type ($F_{(12,48)}$=1.1, p=0.368, η^2=0.22). Subsequent tests do not include order as a factor.

We planned six comparisons. If a main effect of technique was found, we first compare Baseline results to each augmentation type. We also compare Mouse to Pocket, and Slowed to Blocked, to investigate the effect of level. Post-hoc tests in subjective measures were corrected for multiple comparisons. Subjective results are reported per individual. Due to the ordinal nature of subjective ratings, we applied more-conservative non-parametric tests to these responses.

3.6 Results

We first present the effects of our augmentations on crossing behaviour; we follow with how they influenced participants' subjective reports.

3.6.1 Crossing Events

We first wanted to determine whether the augmentations changed baseline behaviour. We ran a RM-ANOVA with the first Baseline and the four augmented embodiments (Slowed, Blocked, Mouse, and Pocket), and 4 planned contrasts (comparing each augmented embodiment with the baseline). There was a main effect of embodiment on the number of crossings ($F_{(4,60)}$=13.3, p≈0.000, η^2=0.47).

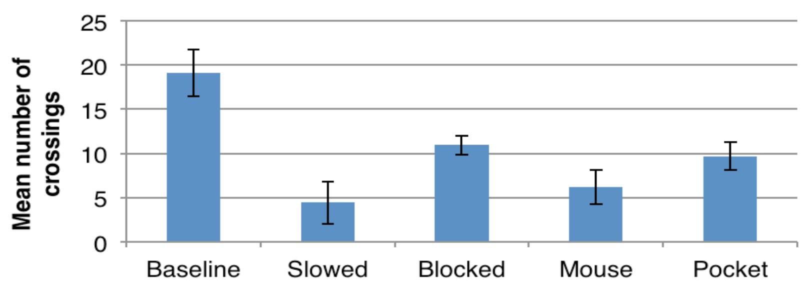

Figure 12 - Mean crossings (±SE) by augmentation type.

Planned contrasts show that people crossed more with no augmentation (Baseline) than with all augmentation types (all p<0.015). See Figure 12.

We next wanted to determine whether the approach to augmentation (tactile feedback or movement alteration) and the level of augmentation (high or low) had an effect on crossing behaviour. We conducted a 2 (approach) x 2 (level) RM-ANOVA on the number of crossings. There was no main effect of approach ($F_{(1,15)}$=0.07, p=0.798, η^2=0.00), showing no difference between the tactile feedback approach and the movement alteration approach. However, there was a main effect of level ($F_{(1,15)}$=10.0, p=0.006, η^2=0.40), showing that people crossed more with high level of augmentations than with the low level (see Figure 12).

3.6.1.1 Permanence Effects

We included a second baseline trial with an embodiment with no augmentations immediately after the first augmentation type. We did this to determine whether introducing an augmentation would have a lasting effect on crossing behaviour after the augmentation was removed. To answer this question, we conducted a RM-ANOVA with repetition of the two baselines as within-subjects data, and first augmentation type as a between-subjects factor. There was no main effect of repetition on crossing behaviour ($F_{(1,3)}$=1.84, p=0.200, η^2=0.13), and no interaction of repetition with starting condition ($F_{(3,12)}$=0.69, p=0.578, η^2=0.15). Thus, people did not cross fewer times in the second baseline test, and this lack of difference was consistent across the four augmentations (see Figure 13). We interpret these results to mean there was no permanence effect: people resume behaving as they did before having experienced any augmentation.

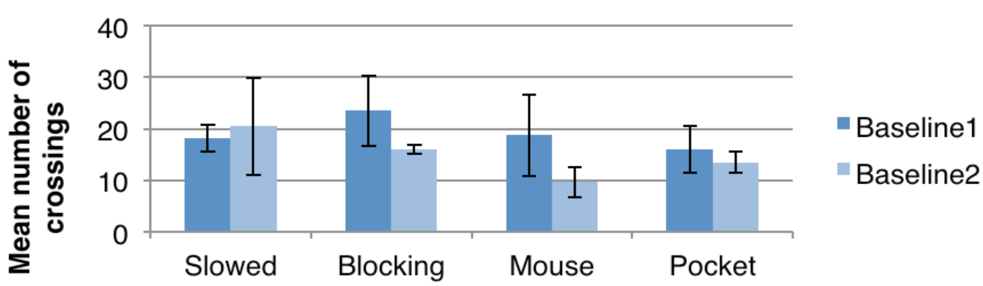

Figure 13 - Mean crossings (±SE) between the Baseline trials

3.6.2 Subjective Responses

We asked participants eight questions to gather their perceptions of the augmentations. A RM-MANOVA with order as a between-subjects factor shows no effect of order for any of the subjective measures, except for awareness of partner's position ($F_{(3,25)}$=4.4, p=0.012, η^2=0.347).

For each subjective response, we test for effects of augmentation type using a Friedman test. Pairwise comparisons (between Baseline and all conditions, between Mouse and Pocket, and between Slowed and Blocked) are investigated through Wilcoxon Signed Ranks Tests.

3.6.2.1 Awareness

People rated their agreement to the statement: I was aware of my partner's *position* on the table (see Figure 14). There was a main effect of augmentation type ($\chi^2_{(4)}$=40.4,p≈0.000). Pairwise comparisons showed that awareness was lower for the Baseline than every augmentation type (Slowed Z=−3.6, Blocked Z=−3.8, Mouse Z=−4.1, Pocket Z=−3.8, all p≈0.000). Blocked produced more awareness than Slowed (Z=−2.3, p=0.020). There was no difference in awareness between the Mouse and Pocket augmentations (Z=−0.7, p=0.498).

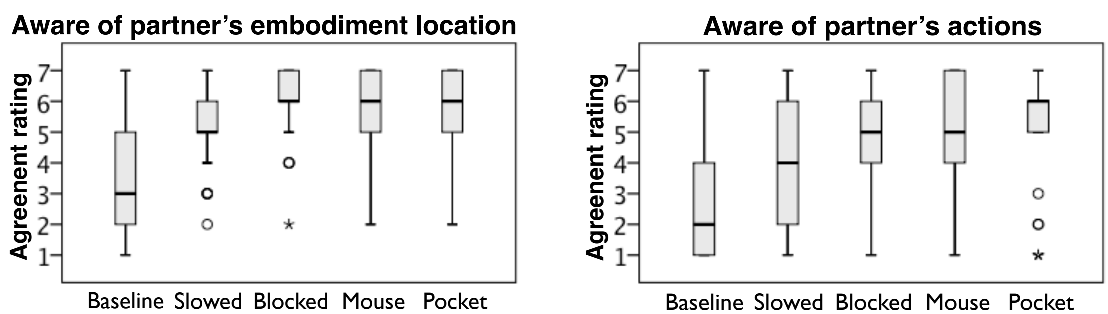

Figure 14 - Subjective ratings of awareness

People rated their agreement to the statement: I was aware of my partner's *actions* on the table (see Figure 14). There was a main effect of augmentation type ($\chi^2_{(4)}$=33.0, p≈0.000). Pairwise comparisons showed that people were less aware in Baseline than every augmentation type (Slowed Z=−2.4, Blocked Z=−2.8, Mouse Z=−3.2, Pocket Z=−3.2, all p<0.017). People were more aware when using Blocked than Slowed (Z=−2.1, p=0.040). There was no difference between Mouse and Pocket (Z=−0.4, p=0.725).

3.6.2.2 Awkwardness

People rated their agreement to the statement: It felt awkward to *cross* my partner's embodiment (see Figure 15). There was a main effect of augmentation type ($\chi^2_{(4)}$=47.7, $p\approx 0.000$). Pairwise comparisons showed that people felt less awkward crossing in the Baseline condition than with every augmentation type (Slowed $Z=-3.9$, Blocked $Z=-3.9$, Mouse $Z=-4.1$, Pocket $Z=-4.2$, all $p\approx 0.000$). People felt more awkward crossing embodiments when using Blocked than Slowed ($Z=-2.0$, $p=0.042$). There was no difference between Mouse and Pocket ($Z=-1.3$, $p=0.178$).

People rated their agreement to the statement: It felt awkward to *reach* to the other side of the table (see Figure 15). There was a main effect of augmentation ($\chi^2_{(4)}$=30.0, $p\approx 0.000$). Pairwise comparisons showed that people felt less awkward reaching in the Baseline condition than with every augmentation type (Slowed $Z=-3.3$, Blocked $Z=-3.4$, Mouse $Z=-3.3$, Pocket $Z=-3.7$, all $p<0.001$). There was no difference between Blocked and Slowed ($Z=-1.9$, $p=0.056$) or between Mouse and Pocket ($Z=-1.6$, $p=0.104$).

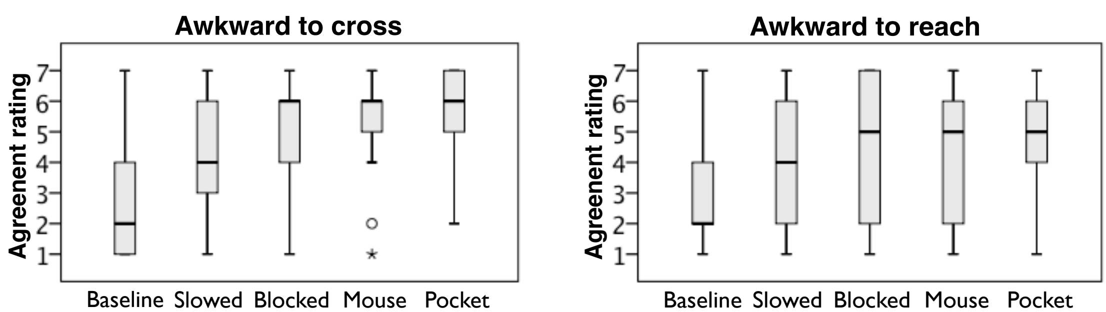

Figure 15 - Subjective ratings of awkwardness

3.6.2.3 Feelings of Invasion

People rated their agreement to the statement: I felt like my partner was invading my space (see Figure 16). There was a main effect of augmentation type ($\chi^2_{(4)}$=29.1, $p\approx 0.000$). Pairwise comparisons showed that people felt less invaded in the Baseline condition than in every augmentation type (Slowed $Z=-2.9$, Blocked $Z=-3.3$, Mouse $Z=-3.2$, Pocket $Z=-3.4$, all $p<0.004$). People felt more invaded with Blocked than with Slowed ($Z=-2.2$, $p=0.028$), and more invaded with Pocket than with Mouse ($Z=-2.3$, $p=0.024$).

People rated their agreement to the statement: I felt like I was invading my partner's space (see Figure 16). There was a main effect of augmentation type ($\chi^2_{(4)}$=38.9, p≈0.000). Pairwise comparisons showed that people felt less invading in the Baseline condition than in every augmentation type (Slowed Z=−3.1, Blocked Z=−3.1, Mouse Z=−3.5, Pocket Z=−3.8, all p<0.002). People also felt more invading with Blocked than Slowed (Z=−2.0, p=0.043), and more invading with Pocket than Mouse (Z=−2.4, p=0.017).

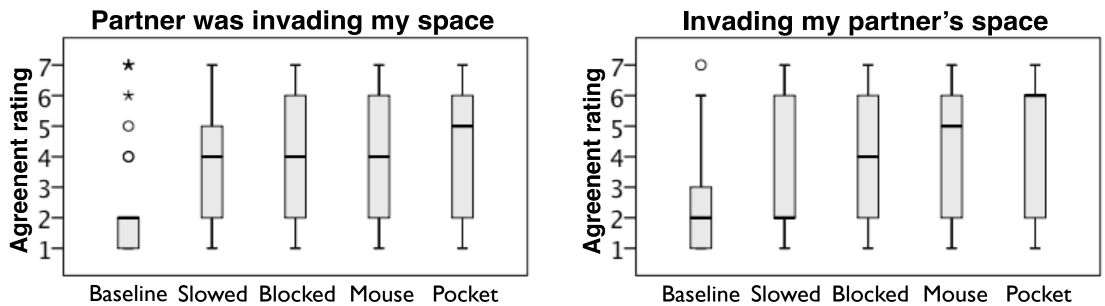

Figure 16 - Subjective ratings of invasion

3.6.2.4 Frustration and Annoyance

People rated their agreement to the statement: This embodiment was annoying to use (see Figure 17). There was a main effect of augmentation type ($\chi^2_{(4)}$=36.1, p≈0.000). Pairwise comparisons showed that it was less annoying in the Baseline condition than in every augmentation type (Slowed Z=−3.3, Blocked Z=−3.8, Mouse Z=−3.8, Pocket Z=−3.9, all p<0.001). There was no difference between Blocked and Slowed (Z=−1.3, p=0.185), or between Mouse and Pocket (Z=−1.2, p=0.212).

People rated their agreement to the statement: It was frustrating to coordinate with my partner to avoid touching (see Figure 17). There was a main effect of augmentation type ($\chi^2_{(4)}$=40.4, p≈0.000). Pairwise comparisons showed that it was less frustrating in the Baseline condition than in every augmentation type (Slowed Z=−3.0, Blocked Z=−3.1, Mouse Z=−3.7, Pocket Z=−3.6, all p<0.003). There was no difference between Blocked and Slowed (Z=−1.3, p=0.195), or between Mouse and Pocket (Z=0.0, p=1.000).

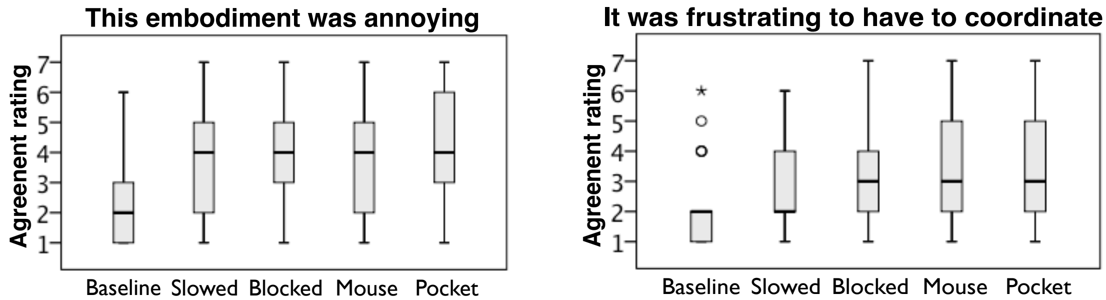

Figure 17 - Subjective ratings of annoyance and frustration

3.6.2.5 Interview Responses

Frustration. 12 groups explicitly stated that it was not frustrating to have to coordinate with the other person. 4 stated it may be frustrating if there was a time limit, evaluation of haiku quality, or if they were strangers.

Cell phone. 3 groups stated that Pocket was like a cell phone in their pocket, a feeling they are accustomed to. 1 stated the Mouse was like a game controller.

Mouse noise. 7 groups stated that the loudness of the Mouse vibration increased the disruption of the Mouse.

Slowed. 9 groups reported that Slowed was frustrating and annoying because it was slow to recover from the cross. Most preferred Blocked, because it prevents crossing, whereas Slowed suggests you still can, but punishes you.

3.6.3 Observed Episodes

We observed clear behaviour change and an increase in coordinative, turn-taking behaviour. The following episodes describe situations observed during the study.

Scanning. Many people moved their embodiments around the table as a pointing aid while searching for words. This is common behaviour with physical arms (e.g., while reading a book), but rarely occurs on physical tabletops. We observed scanning behaviour change with augmentations. Most people stopped scanning, and kept their cursors near to their haiku to avoid crossing; however, this was not true for all groups. One group (211) scanned during the entire experiment, causing many crossings in all haiku tasks.

Alternating. Many groups quickly formed a turn-taking strategy. A common strategy was alternating, where each person takes one turn in quick succession. Alternating behaviour is a clear and effective turn-taking technique that requires good awareness of the other's actions. An obvious instance of alternating behaviour was from group 9. Person **A** (Figure 11) has her embodiment on her haiku. **B** reaches in front of **A**'s haiku and grabs a word. **B** waits until **A** moves out of the way, and then reaches in front of **A**'s haiku. **B** waits her turn, and then reaches to the other side of the table. This alternating continues until each person picked three words each in quick succession. This occurred with Blocked, which forces groups to take turns; however, not all groups had good alternating behaviour, reaching when the other person was in the way, and causing a collision.

False starts. As part of turn-taking, we observed numerous false starts – when one person is in the way, the second person begins to move but realizes there will be a collision, and so stops and waits. False starts are a clear indication that people had good awareness of the other person's embodiment location, because they were able to prevent the collision from happening. A good example of a false start was in group 6. **B** is in his haiku. **A** reaches to the top of **B**'s side. **B** looks to the other side of the table and starts to move, but sees that **A** is in the way. He pauses, and waits. **A** tries to grab a word, and begins to move her embodiment, but missed the word, so reaches forward again. **B** waits and watches her embodiment as she selects the word. When she pulls back, **B** grabs a word that was under her embodiment.

3.7 Discussion

Our study shows that both tactile feedback and movement alteration can change interaction in tabletop tasks, can make people more aware of another person's digital embodiment, and can make people more sensitive to feelings of intrusion and awkwardness. These changes were also accompanied, however, by increased feelings of annoyance and frustration at having to coordinate with the augmented embodiments. In the following sections, we provide explanations for these main results, and consider how our findings can be used by researchers and designers of tabletop systems.

3.7.1 Interpretation of Main Results

Our primary result is that when tactile feedback and movement alteration were present, people's behaviour with, and perception of, the digital embodiments changed substantially. The next paragraphs summarize and explain the effects for each of the augmentations in turn.

3.7.1.1 Slowed Movement

People crossed least with the Slowed embodiments overall, and significantly less often than with the Blocked embodiment. This latter result is the opposite of what we expected, because Blocked incurs a larger movement penalty than Slowed. However, interview results suggest that this was not how groups interpreted these augmentations. Groups reported that Slowed punished performance in both directions; that is, it required that people move slowly to perform a crossing action, and also move slowly to recover from the cross. In contrast, even though Blocked was more restrictive, it did not reduce the local responsiveness of the embodiment. This difference seems to have caused greater interaction avoidance than with any other embodiment.

3.7.1.2 Blocked Movement

People crossed more with Blocked than with Slowed, but reported being more aware with Blocked, and reported that Blocked was more invasive. These results seem contradictory: if Blocked is more invasive and causes better awareness, why did people cross more? We see three reasons. First, people knew they had to change their behaviour, because Blocked completely prevents people from crossing; however, there was no interaction penalty to recover from the cross (unlike Slowed), so people felt free to collide or bump into the other Blocked embodiment. Second, people often poked at the other person's embodiment to signal them to move out of the way, leading to an increased number of crossing events (even though these were not intended as crosses). Third, the lack of a real performance cost may have caused people to be sloppier with their actions, preferring to simply interact and then recover (which was quick and easy) from collisions.

3.7.1.3 Mouse Tactile Feedback

People crossed less with Mouse than with Pocket, and reported Mouse as less invasive than Pocket. The crossing result is again the opposite of what we expected, but the invasiveness result matches expectations. On the intimacy scale, a touch on the thigh is much more intimate than a touch on the hand; however, people crossed less with tactile feedback on their hands than on their thighs. It appears that the reduction in crossing was not due to the increased intimacy of the location. Instead, people reported that it was the increased perceptual intrusiveness of the Mouse that caused them to avoid crossing. The Mouse vibration was more obvious than the Pocket vibration, partly because it was louder (i.e., the mouse buzzed against the table); as a result, people reported that it was more distracting and it broke their concentration.

3.7.1.4 Pocket Tactile Feedback

People crossed more with Pocket than Mouse, and reported Pocket to be more invasive than Mouse. The subjective results show that the intimacy scale on which we based the tactile augmentations was correct, and that tactile sensations and body location do have some governing effect on behaviour. However, the results suggest that pocket vibrations are not overly intimate for some people. Several participants reported that this condition "felt like a cell phone", although others stated that it was uncomfortable. This suggests there is a familiarity effect: people who are used to having a cell phone vibrate in their pocket interpreted this tactile feeling as less invasive than those that are not accustomed to the feeling.

3.7.2 Using the Findings in Tabletop Design

Our study showed that even in the absence of true physicality, designers of tabletop groupware can find ways of influencing and shaping interaction and awareness. An obvious question, however, that arises from these findings is whether, and when, it is useful for designers to add constraints to interaction. We address several issues that surround this question, including the design goal of the augmentation, the tension between discomfort and utility, and the use of public actions as a basis for social protocols.

3.7.2.1 The Design Goal of Adding Artificial Constraints

First, it is important to note that the goal of our exploration is *not* to simply try and replicate the constraints of the physical world – i.e., to duplicate the behaviours that arise with physical arms and hands. It is clear that this did not happen in our study: even though interaction changed, it was clear that the behaviour was different in many ways from what has been observed with physical arms in past work (Doucette 2013a). For example, people reacted to the obviousness and interruption of the tactile feedback as much as they did to the intimacy of the feedback; similarly, the movement-based manipulations led to people calculating the penalty to their own work rather than recreating a notion of touch.

There are two goals in adding artificial augmentations to embodiment interaction: first, to better understand what governs and shapes shared behaviours like awareness, coordination, and territoriality; and second, to make use of those factors to increase the range of experiences that designers can provide in a tabletop groupware system. We hypothesize a 'continuum of control' in group interactions, where at one end there are no constraints on behaviour, and at the other end there are rigid structures and regulations that affect people's every move. In previous CSCW research, these structures have often been built into the task interface itself (e.g., floor control); in this research we are instead exploring implicit forms of control that arise from characteristics of embodiments, awareness, and interaction.

In the space of tabletop systems, there are several valuable points along the continuum of control. There are situations toward the 'unconstrained' end of the spectrum where the lack of awkwardness in interactions may be beneficial. For example, in time-critical systems, users can work faster knowing their interactions will not inconvenience others. There are other situations (e.g., safety-critical applications) that demand that coordination conflicts be minimized. Systems to support these situations could benefit from the addition of artificial (but still implicit) constraints.

3.7.2.2 Tension Between Discomfort and Usefulness

Causing discomfort for people around the table – that is, adding factors that increase awkwardness and intrusion, and that increase people's annoyance and frustration as a result – may seem like a strange design strategy. However, recent research in CHI and CSCW has shown that there are legitimate reasons to use discomfort as a design principle: for example, Benford *et al.* suggest that 'uncomfortable interactions' can provide potential benefits in several areas such as entertainment, enlightenment, and sociality (Benford 2012). In the case of tabletop interaction, it is clear that discomfort underlying touch avoidance leads to obvious benefits for the group in terms of their ability to operate successfully and smoothly in a constrained space.

As previous researchers have noted, there are always tradeoffs between designing for the individual and designing for the group in shared-workspace systems (Gutwin 1998). It may be that the uncomfortable interaction of close physical contact is a fundamental part of people's natural coordination abilities around tables; therefore, it is not so strange to expect increases in individual feelings of awkwardness or annoyance when attempting to improve group awareness. In addition, in situations like the safety-critical scenario mentioned above, group members may be willing to give up some degree of individual control in order to have a better sense of the group's location and activity, and to reduce errors and conflicts.

3.7.2.3 Making Actions Public

One of the main properties of both augmentation types studied here is that they make embodiment interactions much more obvious – when crossings occurred, people received tactile, auditory, and movement-based feedback. The obviousness of this feedback can play a role in the development of rules for social behaviour. For example, people may have been more reluctant to cross with the noisy Mouse vibration because the feedback was clearly obvious to both parties; similarly, the Slowed condition was an effect that was particularly public (in that it slowed down both people, not just the person crossing).

Several researchers have noted that when actions are public, people change their behaviour (for example, people are much less likely to watch another person if the watching behaviour is made public) (Birnholtz 2007). We are interested to see how social protocols may evolve around different kinds of public signals that are produced when embodiments interact – we wonder whether the obviousness of the signal will provide a stronger impetus to form new social protocols.

3.7.3 Generalization and Limitations

Our study involved a large sample and well-controlled conditions, so we are confident that our effects can be replicated for two-person work in other tasks and scenarios. However, there are also limitations to the work. We did not collect an objective measure of awareness; instead, we collected crossing events, which we use as a proxy for awareness (i.e., you need to know where the other person is to avoid touching them). Second, we do not know how the augmented embodiments would scale to larger groups. As the number of embodiments increase, there are more opportunities for conflicts, meaning that people may be constantly receiving feedback (and thus start to ignore it). However, we note that in the physical world, we are still able to avoid touching others even when there are more than two people interacting over the table.

3.8 Conclusion and Future Work

Digital embodiments support coordination and awareness far less well than physical arms, partly due to the loss of touch avoidance that occurs naturally in the physical world. There is little understanding of other factors that may guide and govern tabletop interactions, leaving designers with few options as they attempt to provide a wide range of collaborative tabletop experiences. To add to this understanding, we carried out a study that demonstrated the effectiveness of tactile feedback and movement alteration in changing behaviour and improving group awareness. Our work provides designers with new understanding of group interaction, and provides tools and strategies for creating richer and more complex behaviour in tabletop groupware.

In future work, we plan to explore these findings in more detail. We will address the limitations noted above (objective measures of awareness and coordination, and studies with larger groups). In addition, we are interested in replicating our effects in distributed settings: both for networked tables, and possibly even for standard desktop-based groupware. Finally, we are interested in studying the possibility that new social protocols may develop over time that adapt to the new artificial constraints.

3.9 Summary of Manuscript B

The main contribution of this work is that embodiment augmentations change group reaching behaviour, causing people to cross embodiments up to 75% less than without augmentations. Reducing crossings in and of itself may not be an important contribution, but the coordinative behaviours stemming from the aversion to touch others are. We observed groups reverting to automatic turn-taking, thereby increasing people's awareness of what the other is doing. This suggests that the addition of constraints to arm embodiments may enable groups to coordinate access to shared items on the tabletop.

CHAPTER 4

DISTRIBUTED ARM EMBODIMENTS[6]

4.1 Introduction to Manuscript C

The previous work showed that digital reaching is inherently different than physical reaching. The question of *why* people behave differently with digital and physical reaching was first investigated through augmented embodiments: the fact that arm embodiments lack attributes of physical arms may cause people to reach differently. An alternative answer is that the digital reaching itself, instead of how the embodiments interact with each other, causes changes in behaviour. That is, it may be the indirect nature of mouse-based input causing people to behave differently with digital arm embodiments than with their physical arms.

4.1.1 Problem and Motivation

Researchers and designers know little of how physical reaching with arm embodiments changes group reaching behaviour.

In Chapter 2, we showed that people behave differently with mouse-based embodiments than when physically reaching into the shared tabletop space. Specifically, people no longer care about crossing over the other's embodiment with mouse-based input, regardless of the visual design of the embodiment. Other researchers have shown that direct and indirect input affects group behaviour (e.g., the type of input changes people's level of awareness of the other's actions (Ha 2006)). However, these results show only that the change in visual embodiments has an effect (e.g., from physical arms to a cursor), and not that the change in input type has an effect (that is, from indirect

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[6] At the time of publication, the manuscript in this chapter was in submission to ITS 2014.

mouse-based input to direct physical touch input). The question remains whether the change of input (from physical touch to mice), while keeping the visual embodiment the same, will affect group reaching behaviour.

There is an inherent problem investigating this question using the experimental procedures from previous studies. Specifically, if people are physically reaching into the shared space to control their arm embodiment, both co-located people would be reaching into the shared physical space, and thus people interact with each other using their physical arms instead of with each other's digital arm embodiments. One way to investigate this question is to use a distributed system, so that people are reaching into separate physical spaces (over different tables). With a distributed setup, we can now investigate the difference between mouse and physical interaction while controlling for the effects of different visual embodiments.

There is another benefit to a distributed setting. In previous studies, we used a picture of people's arms as a "realistic" arm embodiment, but this isn't a truly realistic embodiment, as it cannot articulate (fingers, wrist, elbow), cannot demonstrate height (to cross "over" another embodiment), and cannot rotate (to turn over, showing the bottom of the arm). A truly realistic arm embodiment is a live video stream, as demonstrated in VideoArms (Tang 2006), which only makes sense in a distributed environment (otherwise, both people are physically reaching into the shared physical space above the table).

4.1.2 Solution and Steps to Solution

The solution is to provide empirical evidence comparing physical reaching in co-located and distributed settings.

4.1.2.1 Research Questions

1. How are physical reaching gestures different with and without a physical co-present body?
2. How is physical reaching with arm embodiments different than digital reaching with arm embodiments?

3. How do live video arm embodiments affect group reaching behaviour?

4.1.2.2 Changes to System and Experimental Protocols for this Study

In the previous studies, people were co-located, interacting on the same table. To investigate the effects of distribution, the system was modified to enable distributed tables, such that each person interacts on their own table in two different rooms. Distribution also enables us to study fully realistic embodiments using live video (video does not work in a co-located setting, because people are then physically embodied again); however, the previous study apparatus used a top-projected table, meaning there is a feedback loop of projection-video (projecting the other's physical arm on top of the space where the video is taken). Thus, this study used two touch-enabled tabletops (60" TVs with touch overlays). To enable generalizability to the other studies presented in this dissertation work, people sat on the short side of the table, and the system used only the half of the display closest to their seated location (see Figure 23).

Due to the nature of how VideoArms work, the main measure of "crossing" required a minor adjustment. In the previous studies, arm embodiments could not bend (e.g., at the elbow), and thus a crossing event was triggered when the straight lines connecting the embodiment origins (fixed to the right of their haiku paper) and the tip of their embodiment finger crossed (see Figure 23 left, crossing lines denoted in red). VideoArms no longer have a fixed origin, and people naturally bend their arms during reaching gestures, so the connecting line between the finger tip and the origin may no longer even be within the arm embodiment (see Figure 23 right). Thus, in this study, a crossing event with VideoArms is triggered when any part of the two arm embodiments intersect. In principle, this mechanism of detecting crossing events is an over-count as compared to the mouse-based arm embodiments, as there are "touches" of VideoArms counted as crossings that would not be a "crossing" with mouse-based arm embodiments (e.g., see Figure 23 right, fingers are touching, but lines are not crossed).

Lastly, this study added another set of questionnaires between each trial to gather measures of co-presence. In co-located settings, measures of co-presence are meaningless, because people are physically co-located.

4.2 Manuscript C – How Arm Embodiments Affect Coordination, Co-Presence, and Awareness on Distributed Digital Tabletops

Abstract. People interact naturally and fluidly over traditional tables, and one reason for their expertise is that people have years of experience interacting around other physical bodies. This experience provides mechanisms for quick and effective coordination. At distributed digital tabletops, however, the lack of a physical co-present body provides an impoverished environment as compared with a co-located setting. To compensate for the lack of a physical co-present body, distributed system designers often use digital embodiments to provide feedback about actions occurring in the shared space. Digital arm embodiments are particularly useful for tables because people interact with objects on the table by reaching over the surface, and arm embodiments have been shown to be useful for co-located group work. However, we still know little about how digital arm embodiments affect group behaviour for distributed tables. To provide this information, we carried out an empirical study of how four factors of arm embodiment design (transparency, input technique, visual fidelity, and tactile feedback) affected coordination, awareness, and co-presence. Our study showed that video arm embodiments are subjectively preferred to more basic visual designs, but do little to change people's coordinative behaviours. We also show that in a loosely-coupled task, people can and do easily ignore the remote person, and that touch-based embodiments may better support coordinative behaviours than mouse-based embodiments.

4.3 Introduction

Traditional tables are natural settings for coordination and communication, due in large part to their support for people's physical interactions over and around the table. People interact naturally and fluidly using their arms and hands over tables – they are able to coordinate actions and maintain awareness of others' activities, simply by gathering information produced by people's bodies.

Part of our expertise in physical interaction arises from the many social rules that govern and guide touch and close-proximity interactions, learned through years of experience interacting around other people's physical bodies. The rules of personal space reduce behaviours such as stealing items from others, or interfering with other people by occluding their workspace or physically bumping into them. These rules are also useful for guiding a group's close-proximity behaviour, providing an avenue for automatic coordination.

When people interact together from different locations at distributed tables, however, the other person's physical body is not in the same room, and so there is no foundation for the awareness, coordination, and social protocols that we take for granted in a co-located setting. Without the information produced by the other person's body in the shared space, it becomes more difficult to stay aware of what others are doing, and more difficult to coordinate actions and access to shared items – leading to wasted effort on duplicated tasks and more potential conflicts (such as two people grabbing the same item).

In an attempt to replace the missing co-present body, designers of distributed tabletop systems typically represent remote participants through digital embodiments, such as cursors, avatars, or virtual arms. These embodiments are much better than nothing at all, since they convey some level of information about the remote collaborator's actions in the shared space. However, digital embodiments are poor replacements for physical co-present bodies, because the social protocols that govern and shape bodily interaction often do not work with these virtual representations. For example, researchers have shown that digital embodiments are much less noticeable than real bodies (Pinelle 2008a), and that rules about touch avoidance do not hold with digital arm embodiments, even in co-located settings (Doucette 2013a).

If distributed tabletop systems are to re-enable people's expertise in physical bodily interaction, designers need to understand how different embodiments affect qualities such as awareness, coordination, and co-presence. There are several factors in an embodiment that could change the representation's effect on these qualities – whether the embodiment uses touch or mouse input, the visual fidelity of the embodiment compared to real arms, whether the embodiment provides tactile feedback, and the degree to which the embodiment occludes the workspace (Doucette 2013a, Doucette 2013b).

Tabletop arm embodiments have been studied in co-located scenarios (Pinelle 2008a, Doucette 2013a), but little is known of how people interact with arm embodiments in distributed systems. To provide designers with initial information about the effects of arm embodiment design on distributed tabletop collaboration, we studied four embodiment design factors (visual fidelity, occlusion, input technique, and tactile feedback) in a controlled study. We had pairs of people carry out parallel tasks in a shared space, but located at two networked tables in two different rooms. Participants were represented on the other table with several different arm embodiments. Visual representations were: a picture of the participant's arm, a translucent picture arm, and a video arm that showed live video of arm movements. Participants controlled these embodiments using either direct touch or a mouse. In addition, we included one co-located condition where participants worked at the same table, and manipulated artifacts with their physical arms through touch input.

We gathered several measures to investigate how the design of the embodiment affected participants' coordination in reaching over the table (e.g., the number of times that people reached over one another), the level of awareness that participants were able to maintain (e.g., self-reports of noticing the other person's embodiment), and the level of co-presence that people felt (i.e., the degree to which people felt that the other person was in the same room).

We found surprising differences between the distributed arm embodiments, including:

- People felt that embodiments with higher visual fidelity (i.e., video arms) increased co-presence, but higher fidelity did not change any behavioral measures;
- Regardless of embodiment design, people behaved as if there is no other person in the space – freely crossing embodiments, occluding the other person's workspace, and physically leaning over the remote person.
- Tactile feedback did not lead people to be more careful in managing access to the shared space (contrasting results seen in co-located studies (Doucette 2013b)). In our study, people often ignored the tactile feedback, although it may still be useful as a reminder that there is another person in the space.

Our work makes three main contributions. First, ours is the first study to collect empirical evidence about the effects of arm embodiment type on collaboration at distributed tables. Second, we provide design information about how to maximize the value of digital embodiments for distributed settings. Third, we provide foundational results about the difficulty of replicating the advantages of a co-located environment – even with live video and tactile feedback.

4.4 Related Work

There are three areas of previous work that inform our current study.

4.4.1 Distributed Embodiments

When people are physically distributed, their physical bodies do not occupy the same space. Distributed shared digital spaces can connect remote users, providing a shared visual space that helps groups coordinate their actions by making the state of the task and others' actions visible (Gergle 2006, Kraut 2002). It is common for distributed systems to represent the other person through a digital embodiment, a visual representation of remote people (Benford 1995). A long line of research in distributed embodiments focused on the transmission and interpretation of gestures as a means of communication (e.g., Fraser 2007, Gaver 1992, Genest 2013, Heath 1991, Kirk 2005, Kirk 2006). We are more interested in interactions in the shared space, where digital embodiments not only represent people's communicative gestures, but also their interactions within the shared space.

Researchers have investigated different kinds of digital embodiments. Telepointers, the simplest embodiments, represent other people's locations with shapes and colours (Greenberg 1996, Gutwin 2002), and can be augmented with additional user information (Stach 2007). Though researchers identified that video loses much of the information of 3D interactions because it is projected onto a flat 2D display (Gaver 1992), many systems have provided richer embodiment visualizations with video (Ishii 1992, Izadi 2007, Kirk 2006, Tang 1991), typically overlaying the remote user's video stream over the local workspace. A more recent technique uses digital video and masking to remove the background, leaving just the digital arms (Gutwin 2002, Tang 2006, Tang 2010, Yamashita 2011). We know little of how people actually use and interpret these video arm embodiments when co-interacting in a shared spaces.

4.4.2 Digital Personal Space and Mediated Touch

Research in avatar-based systems suggests that people extend their own personal space (Hall 1966) to surround their avatars (e.g., Jeffrey 2003, Slater 2002, Smith 2000), and avoid invading the personal space of other's avatars. Researchers have shown that other embodiments do not necessarily convey the same social rules as physical bodies. For example, in a collocated system, people touch and cross digital arm embodiments, regardless of their visual design (Doucette 2013a), something avoided when interacting with their physical arms. By augmenting the digital arm embodiments with touching feedback, researchers have shown that augmentations can cause people to treat digital arm embodiments more like physical arms by avoiding touching others (Doucette 2013b); however, little is known of how people interpret digital arm embodiments in distributed systems. Researchers have shown that distributed arm embodiments may provide a mechanism for communicating love and closeness through metaphorical touch (Yarosh 2013), though other researchers have shown that distribution may change physical social protocols (e.g., people sit "in each other's lap" without issue (Tang 2010)).

4.4.3 Social Presence and SoE in Distributed Systems

Distributed systems are more impoverished than collocated systems due to the lack of physically co-present bodies. First, the distance changes people's interactions and their feelings of sharing the same space (Olson 2000). Second, people miss simple physical cues that help inform others' actions because they are represented through an impoverished digital embodiment instead of their physical bodies (Olson 2000).

Researchers have striven to increase people's feelings of social presence (co-presence) – the sense of being with another in a mediated system (Biocca 2013, Garau 2005). Co-presence has been evaluated using questionnaires (Biocca 2013, Garau 2005) (e.g., to assess people's awareness of the other).

A separate issue is whether the digital embodiments *are* the person. The Sense of Embodiment (SoE) is when "…some properties of [an embodiment] are processed in the same way as the properties of one's body" (de Vignemont 2010,p3). It encompasses the sensations of "being inside, having, and controlling a body" (Kilteni 2012,p374), and is made up of three components: sense of self-location (I'm *inside* the embodiment), sense of agency (I'm *controlling* the embodiment), and a sense of body ownership (the embodiment *is part* of my body) (Kilteni 2012). The components of SoE are often evaluated using subjective reports in questionnaires, though some behavioural measures also exist. For example, in the digital version of the rubber hand illusion (RHI) (IJsselsteijn 2006) and its full-body counterpart (Lenggenhager 2007), people estimate the location of their physical bodies after a tactile manipulation. Researchers have shown their manipulation causes proprioceptive drift, where people estimate their physical body's location to be outside of their actual body, *in* the virtual embodiment. This theoretical knowledge is interesting, but the RHI takes minutes to induce, and lasts for a short time. We are primarily interested in practical applications, initially using only digital arm embodiment design.

4.5 The Study

To better understand how the design of distributed arm embodiments affect coordination, people's sense of co-presence, and their awareness of the other person, we carried out a controlled experiment.

Based on previous work on co-located arm embodiments (Doucette 2013a, Doucette 2013b, Pinelle 2008a), we investigated four embodiment design factors.

1. *Occlusion:* the degree to which an arm embodiment blocks the view of objects underneath it.
2. *Input:* the input technique (e.g., direct touch or mouse) used to control the embodiment.
3. *Visual fidelity:* the degree to which the embodiment conveys the appearance and behavior of the real arm.

4. *Tactile feedback:* whether touching an arm embodiment provides a tactile sensation (e.g., through vibration).

4.5.1 Task

The task used in the study was the poem-building task used by Doucette et al. (Doucette 2013a, Doucette 2013b) for earlier arm embodiment research. Dyads (groups of two) sat side-by-side at a tabletop and created haiku poems about an assigned topic from a set of shared words on the tabletop. There were two "haiku papers" on which the poems were built – one in front of each person. Topic word locations were switched, such that the words on each side of the table were more appropriate for the haiku on the other side of the table (see Figure 2) this meant that people had to reach to the other side of the table, and were therefore required to manage access to the shared space.

4.5.2 Study System

We developed a distributed table system for the study that linked two tables in different rooms across a network. The tables used 60" Sony HDTVs with PQ Labs multi-touch overlays, and the system allowed either direct touch input or mouse-based input. To ensure that all words were reachable while seated, people sat on the short side of the table, and the system used only the half of the display closest to their seated location (see Figure 23). The two tables were connected via a Skype voice connection.

4.5.3 Conditions

We designed and evaluated five digital arm embodiments that instantiated our four design factors. We compared these distributed arm embodiments to each other, and also to a co-located touch-input condition. The embodiments were:

- *Transparent*: Showed an outline of the participant's actual physical arm, filled with purple or green and set at 70% opacity. The mouse controlled the tip of the embodiment's finger.

- *PictureMouse*: Showed the same outline as *Transparent*, but with the actual visual image of the participant's arm, at full opacity. This embodiment was also controlled with the mouse.
- *PictureArm*: Showed the same visual representation as PictureMouse, but was controlled using direct touch: the tip of a person's physical arm (tracked using a Kinect) controls the tip of the embodiment finger. The "base" of the embodiment was fixed to the right side of their haiku paper.
- *VideoArm*: Showed live video of the participant's arm (which is more visually realistic than a static picture, as people can articulate their fingers, wrist, and elbow). We implemented a version of VideoArms (Tang 2006) using KinectArms (Genest 2013). The embodiment's base moved with the participant's physical body, adding to the sense of realism.
- *VideoArmVibe*: Showed the same visual representation as the VideoArm, but added tactile feedback when people touched embodiments. The effect was implemented using a vibrating box placed in each person's front pants pocket, following (Doucette 2013b).
- *Co-located*: At the end of the study, groups completed one additional haiku while co-located and using touch input, providing a baseline measure of physical reaching behaviour for each group.

4.5.3.1 Embodiment Latency

The KinectArms toolkit introduces latency in the display of the video image, due to processing delays in the Kinect hardware, the video-manipulation software, and the network transmission. We calculated end-to-end latency through video analysis of a reciprocal movement task (i.e., people at each end moved as soon as they saw the other person move), and local latency was recorded as the time between a finger-down event to the moment when the embodiment arrived at the down location.

As shown in Table 3, the VideoArm embodiment has the largest local latency (500ms), which is well above the threshold of noticeability (Gutwin 2001). The video processing for VideoArms also adds network lag of around a second. The PictureArm embodiment added a fifth of a second of local latency, and no additional network lag as compared to mouse-based techniques.

Table 3 - Approximate system latency times

	Transparent	PictureMouse	PictureArm	VideoArm
End-to-end latency	1050ms	1000ms	950ms	1300ms
Local latency	No apparent lag	No apparent lag	200ms	500ms

4.5.4 Measures and Statistics

We use both quantitative and qualitative analyses to answer our research questions. We investigated people's explicit coordination in the table’s shared space by recording the number of times their arms crossed. In previous work, arm crossing has been shown to indicate the degree to which people are explicitly managing access to the shared space of the tabletop (e.g., taking turns or backing off when another person reaches into the space) (Doucette 2013a, Doucette 2013b). People’s ability to avoid crossing embodiments also demonstrates an increase in people’s awareness of the other person’s actions (Doucette 2013b).

In addition to this data collected automatically through log files produced by the system, we also investigated how embodiment design affects the sense of co-presence and subjective awareness of action through questionnaires. Questionnaires are a standard mechanism to collect these subjective measures (Doucette 2013a, Garau 2005).

4.5.4.1 Planned Comparisons

We investigate the four design factors by comparing one pair of embodiments for each factor:

1. *Occlusion*: Transparent (partial occlusion of objects under the arm) vs. PictureMouse (complete occlusion)
2. *Input*: PictureMouse (mouse input) vs. PictureArm (touch input);
3. *Visual fidelity*: PictureArm (static picture) vs. VideoArm (live video);

4. *Tactile feedback*: VideoArm (no vibration) to VideoArmVibe (vibration when embodiments touch).

4.5.4.2 Quantitative Analyses

The system recorded the number of times people crossed embodiments, which we use as a proxy of people's explicit coordination. The number of crossings is analysed through an RM-ANOVA (α=.05), using the Greenhouse-Geisser method to compensate for sphericity violations.

The mouse-input arm embodiments cannot bend (e.g., at the elbow), and thus a crossing event was triggered when the straight lines running through each embodiment crossed (see Figure 18 left, crossing lines denoted in red). The VideoArm embodiments allow people to move their shoulders (where the crossing line begins), as well as bend their elbows, wrist, or fingers. Thus, the crossing line may no longer even be within the arm embodiment (see Figure 18 right). A crossing event with VideoArms is triggered when any part of the two arm embodiments overlap. In principle, this is an over-count as compared to the mouse-based arm embodiments, as there are "touches" of VideoArms counted as crossings that would not be a "crossing" with mouse-based arm embodiments (e.g., see Figure 18 right). In summary, with touch-input embodiments, we count the number of times the visual embodiments intersect as a crossing, whereas with mouse-based embodiments, we count the number of times the lines running through the embodiments intersect as a crossing.

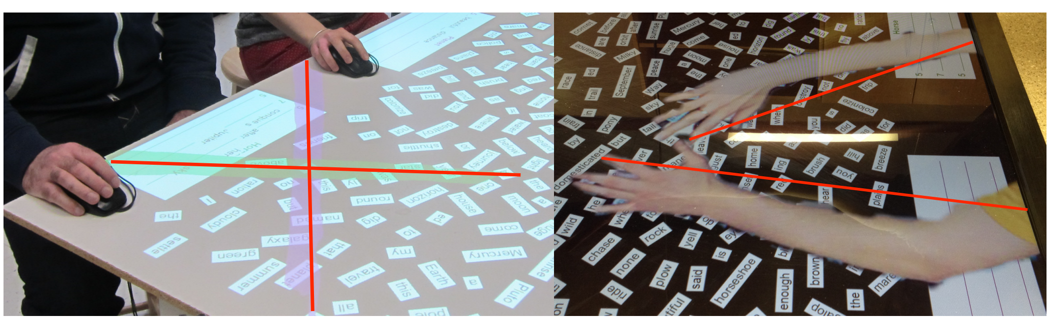

Figure 18 - Crossings with arm embodiments. A crossing with Transparent embodiments (left), and a crossing of VideoArms without crossing lines (right).

We also collected subjective responses to questionnaires through 7-point Likert-style questions (from Strongly Disagree to Strongly Agree). The responses were analyzed using non-parametric analyses. We used Friedman tests to establish main effects, and use Wilcoxon Signed Ranks for our planned pairwise comparisons. There were two surveys:

- A *between-conditions questionnaire* collected people's feelings of co-presence; we asked questions about sharing the same space and questions related to the sense of embodiment (control of the arm and the sense of being *in* the arm).
- A *post-experiment questionnaire* collected people's feelings of awkwardness, their subjective awareness of positions and actions, and the subjective similarity to interacting with a collaborator at the same table.

4.5.4.3 Qualitative Analyses

We video recorded each session and finished each session with a semi-structured interview. The videos were not coded for statistical measures, but were used as exploratory and explanatory analyses of a group's behaviours. Post-experiment, semi-structured interviews were used to follow up on observations from the sessions. Interview questions asked people to directly compare embodiments (e.g., picture to video and touch-based to mouse-based interaction), and to describe their sense of embodiment. Groups were asked, "*Did it seem like the other person's embodiment was _them_?*" and "*What about your own embodiment? Did it seem like it was you?*"

4.5.4.4 Co-located Condition

We include the co-located condition to provide a benchmark for the reader to compare the distributed conditions against. The results from the co-located condition are not used in any statistical analyses, as this condition is not included in any planned comparisons to answer our research questions. We also use the video from the co-located condition for video analyses.

4.5.5 Participants

We tested 17 pairs, removing two outlier groups because these groups did not complete the task as instructed. Of the 30 remaining participants, 18 were men, the median age was 24 years, 27 were students, and 16 reported English as their first language. Participants were paired randomly – this meant that they were interacting with a stranger, which was intentional since previous work has shown that explicit management of a shared space is more pronounced with strangers (Doucette 2013a). Gender pairings were: 5 male-male, 8 female-male, and 2 female-female.

4.6 Results

We report on our analyses of the effects of the four factors (occlusion, input, visual fidelity, and tactile feedback), grouped by coordination, co-presence, and awareness.

4.6.1 Coordination

We studied the effects of arm embodiment design on coordination by looking at people's willingness to cross embodiments (originally studied in Doucette 2013a), coupled with observation of coordinated actions and people's subjective responses to questionnaires.

4.6.1.1 Crossings Analysis

There was a main effect of embodiment on the number of crossing events ($F_{(2.25,31.45)}$=6.680, p=0.003, η^2=0.323, adjusted for sphericity using Greenhouse-Geisser). The pairwise comparisons in Figure 19 show there was an effect of *Input* (p=0.014): people cross less with touch input than with mouse input. All other comparisons showed no significant difference (all p>0.05).

Figure 19 shows a split between touch input and mouse input. People seem to cross more with the mouse than when interacting with direct touch. We observed little evidence of people coordinating more to avoid crossing with touch than mouse input, so we investigated whether the difference between touch and mouse input can been explained by different reaching behaviours, as crosses typically only occur during the reaching gestures.

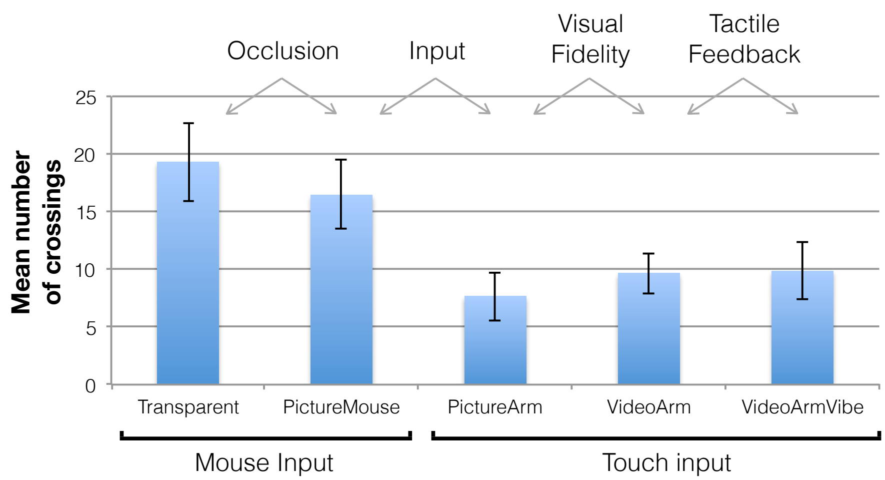

Figure 19 - Mean number of crossings, with conditions grouped by input type (below) and question (above)

4.6.1.2 Follow-up Reaching Analysis

To explain the difference between touch and mouse input, we performed follow-up analyses on reaching behaviour.

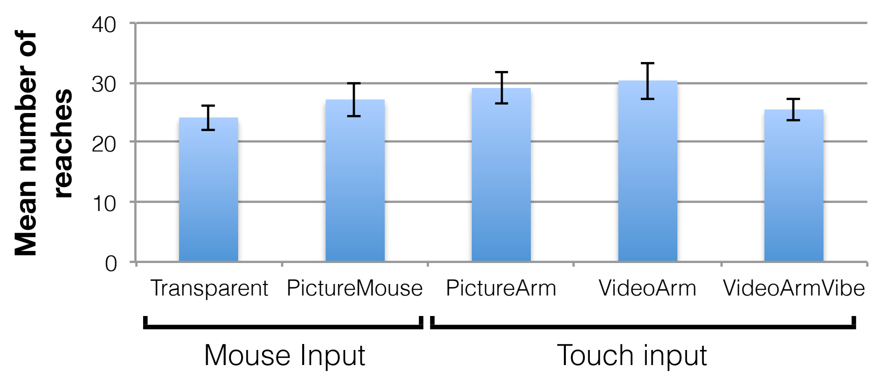

Figure 20 - Mean number of reaches passed haiku papers

One reason people cross less with touch input may be that there are fewer opportunities to cross. For example, if people reach fewer times, there will be fewer opportunities to cross. We performed a follow-up RM-ANOVA on the number of reaches and found there was no main effect of embodiment on the number of times people reached past their haiku papers (p>0.05). As shown in Figure 20, there was no overall effect of input on the simple number of times people reached for words. As the frequency of reaches does not explain the difference in crossings, we performed a second analysis on the reach durations.

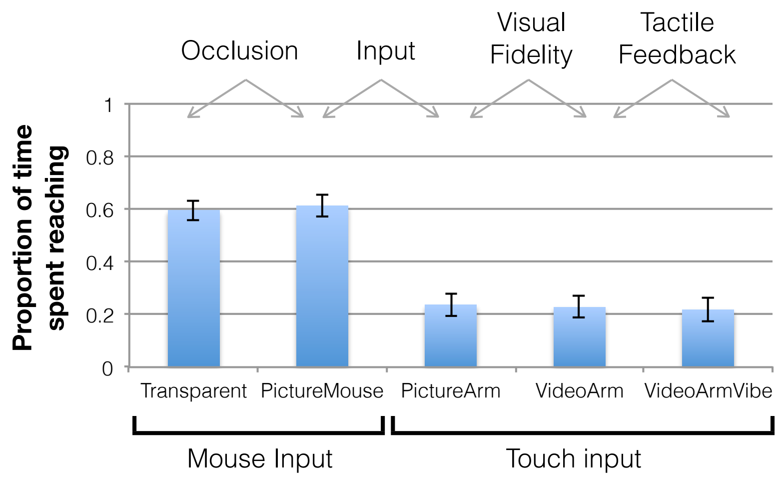

Figure 21 - Proportion of time reaching into the table's public space

There was a main effect of embodiment on the proportion of time spent reaching past the haiku papers ($F_{(4,56)}$=68.853, p≈0.000, η^2=0.831). The pairwise comparisons in Figure 21 show that there was a significant difference for the *Input* factor (p≈0.000), but no significant difference for the other factors (all p>0.05). As shown in Figure 21, people spent a larger proportion of time with their cursor (i.e., their embodiment's fingertip) past the haiku papers (that is, in the public tabletop space) with mouse input than with touch input. We discuss potential explanations of this effect next.

4.6.1.3 Physical Resting Position (video analysis)

When using touch input, people generally did not leave their arms extended on the table, except when reaching for words. With mouse input, people often scanned the surface with their arm embodiment while looking for words (Doucette 2013a); this behaviour was observed only once with touch input. In addition, when they were done building their haiku, people sometimes flicked their mouse out, leaving their embodiment stretched out while the other person finished.

With physical arms, people had a natural arm resting position on the bezel near their haiku paper. We suspect this resting position, as well as scanning and flicked out behaviours when using mice, explain why people spent more time reaching into the public space with mouse input embodiments than with touch input embodiments (Figure 21), and contributed to the difference in the number of crossings (Figure 19).

4.6.1.4 Observations of Coordination (video analysis)

In general, we observed very little evidence of people explicitly coordinating their reaching gestures: people just reached for the object they wanted. This mirrors previously reported results (Doucette 2013a). We observed participants appearing to consider the other person's location in the vibration condition, but often this coordination seemed to be as a reaction to the vibrations, not to prevent the cross or vibration. People would respond to the vibration by pulling their arms back and monitoring what the other person was doing, but did little to predict when the initial vibration may occur. This is in contrast to previous research on vibration-enhanced co-located reaching (Doucette 2013b).

4.6.1.5 Summary of Coordination Results

People cross more often with mouse-based embodiments than when physically reaching (touch input), likely because there are fewer opportunities to cross with physical input. In all conditions, people reached for words with the same frequency, but there is a substantial difference in the proportion of total time people spent reached out. With mouse-based input, people often scanned the surface of the table with their embodiment while searching for words and flicked their mouse out after finishing their haiku, leaving their embodiment stretched out over the tabletop. We believe these behaviours contributed to the differences in the number of crosses between mouse and touch input.

4.6.2 Co-presence

We study the effect of arm embodiment design on co-presence by people's subjective questionnaire responses, coupled with observations of their body movements.

4.6.2.1 Sense of Being in the Same Space (questionnaire)

Figure 22 shows agreement ratings to the statement "*I had a sense that I was in the same space as my partner*" from the between-conditions questionnaire. A Friedman test showed a main effect of embodiment on participants' sense of sharing the space (χ^2_4=29.26, p≈0.000). Wilcoxon Signed Ranks tests showed an effect of *Visual fidelity*

(Z=-2.63, *p*=0.009) and *Tactile Feedback* (Z=-2.96, p=0.003): people had a greater sense of sharing the same space with video and with vibrations. There was a marginal effect of *Occlusion* (Z=-1.86, p=0.063): people had an elevated sense of sharing the same space with more occluding embodiments. There was no effect of *Input* (*p*>0.05).

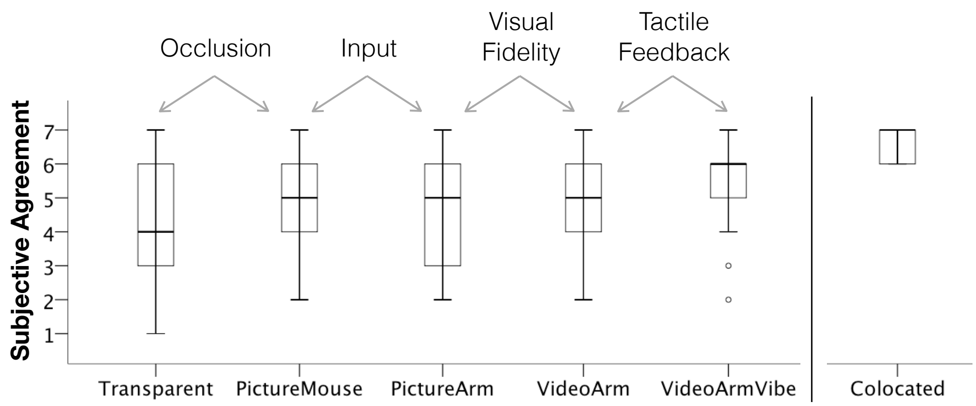

Figure 22 - Subjective sense of being in the same space (dots are outliers, box bounds are upper and lower quartile with median as cross bar, and whiskers are min and max non-outliers)

4.6.2.2 "No other person there" (video analysis)

Overall, there was only a single vocalization that was intended for the other person over the 15 sessions (people sometimes spoke to the co-located researcher). During an occlusion incident, the person being occluded was trying to see under the other's embodiment, and vocalized an "umm" to get the other's attention (audible to the other person through Skype). The person occluding had no reaction, and continued with their interaction as if nothing was wrong.

4.6.2.3 Use of Horizontal Space (video analysis)

When collocated, each person used about half the horizontal bezel space to avoid encroaching on the other person's personal space (see Figure 23, bottom). When distributed, people on the right stretched out on the bezel, suggesting people had little feeling that the other person's personal space extended to the remote situation (see Figure 23, top) – note that people on the left stretched less because they used their mouse with their right hand. This behaviour is similar to previous work showing people had little issue sitting "in each others' laps" (Tang 2010).

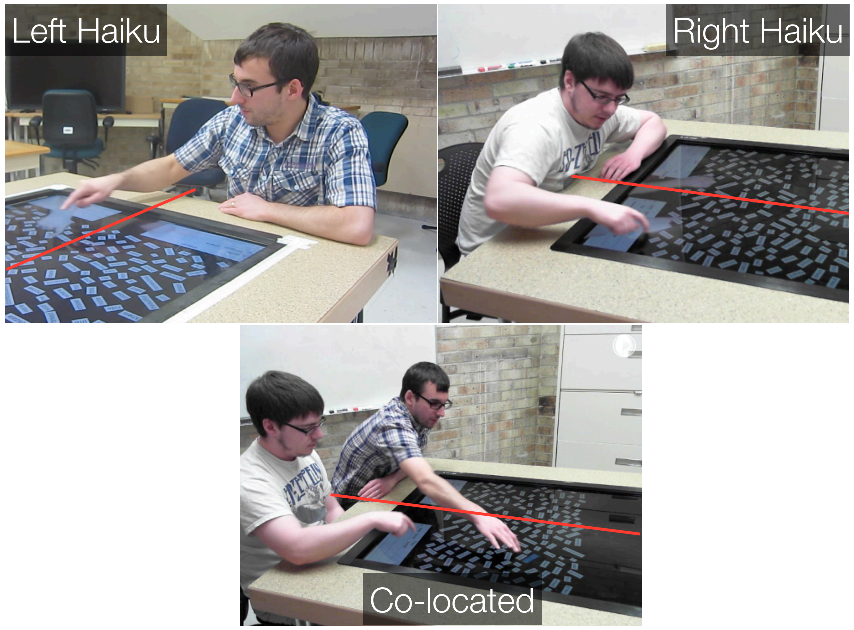

Figure 23 - People's horizontal size when distributed (top) and when collocated (bottom). Lines split the table in half, showing how people stretch to the other side when distributed

4.6.2.4 Similarity to Interacting at the Same Table

Figure 24 shows agreement ratings to the statement "*This embodiment was similar to interacting at the same table*" from the post-experiment questionnaire. A Friedman test showed a main effect of embodiment (χ^2_4=69.94, *p*≈0.000). Wilcoxon Signed Ranks tests showed an effect of *Input* (Z=-2.38, *p*=0.017), *Visual fidelity* (Z=-2.96, *p*=0.003), and *Tactile feedback* (Z=-4.05, *p*≈0.000): people felt that the distributed embodiments were more similar to interacting at the same table with physical input, video, and vibrations.

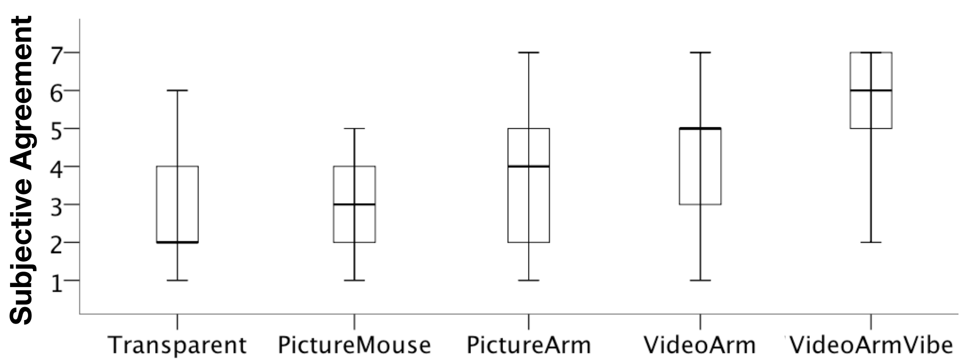

Figure 24 - Subjective responses to "similar to interacting at the same table"

4.6.2.5 Realness of VideoArms (interviews)

Nine people reported that the video embodiments (VideoArms) were the most realistic and the most like the participants' real bodies. For example, one person stated, "The video, it seemed more real, I thought about using my second arm as well." Another participant said: "It's better with live video than pictures. It is much more normal, more comfortable."

Subjectively, people reported that VideoArms were the most real and they treated them the most like physical arms. This suggests that people have a higher sense of embodiment (de Vignemont 2010, Kilteni 2012) with video than with lower fidelity embodiments; however, people ignored their partner, and acted as if the other person was not even there. People freely crossed the other's embodiment, and occluded areas where the other person was interacting, suggesting the other person was not embodied in their remote arm embodiment.

4.6.2.6 Vibration Reminded me of the Other Person (interviews)

Doucette et al. showed that, in a co-located system, tactile feedback typically caused groups to begin coordinating in order to avoid crossing embodiments (Doucette 2013b). In the distributed system, it appears that people do not actively try to avoid crossing, and only coordinate when *reminded* of the other person, through the tactile vibrations.

As one participant said, "Before the vibrating thing, I didn't even notice you're there; I just do my own work." Similarly, one group stated, "The vibrating one, you kind of noticed where their arm was" and "Yeah, other than the vibrating one, I didn't even pay attention to where her arm was."

4.6.2.7 Summary of Co-presence Results

People reported they had a greater sense of sharing the same space with video and with vibrations, but this space may not be the physical space where the remote person "is". People completely ignored their partner, physically occupying the space where the other person would be.

People felt the distributed embodiments were more similar to interacting at the same table with physical input and video. They reported higher feelings of "realness" of the VideoArms, but there are no substantial differences in behaviour by adding video.

The vibrations were interpreted very differently than in previous work (Doucette 2013b). People still ignored the other person, and made little effort to coordinate reaching. People reacted to the vibrations, often pulling back their arms; however, they made no effort to track the other person to avoid a cross – rather, the vibrations reminded them of the other person.

Overall, people reported higher feelings of co-presence with video and with vibrations. This co-presence did not extend to the local physical space where the body represented by the arm embodiment would be. In the digital world, there was little evidence that people thought they were co-interacting with another person.

4.6.3 Group Awareness

4.6.3.1 Subjective Awareness of Partner's Actions

Figure 25 shows agreement ratings to the statement "*I was aware of my partner's actions on the table*" from the post-experiment questionnaire. A Friedman test showed a main effect of embodiment on participants' feelings of awareness of action (χ^2_4=39.75, p≈0.000). Wilcoxon tests showed that people felt more aware with *Visual fidelity* (Z=-2.31, p=0.021) and *Tactile feedback* (Z=-3.17, p=0.002).

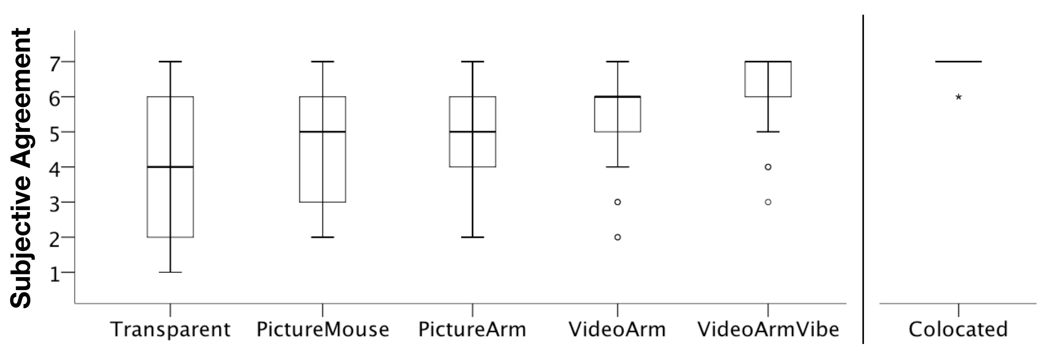

Figure 25 - Subjective awareness of partner's action

4.6.3.2 Awkwardness of Crossing

Figure 26 shows agreement ratings to the statement "*It was awkward to cross my partner's embodiment*" from the post-experiment questionnaire. A Friedman test showed a main effect of embodiment on participants' feelings of crossing awkwardness (χ^2_4=49.25, p≈0.000). Wilcoxon tests showed that people felt more awkward with *Visual fidelity* (Z=-2.72, p=0.007) and *Tactile feedback* (Z=-4.35, p≈0.000).

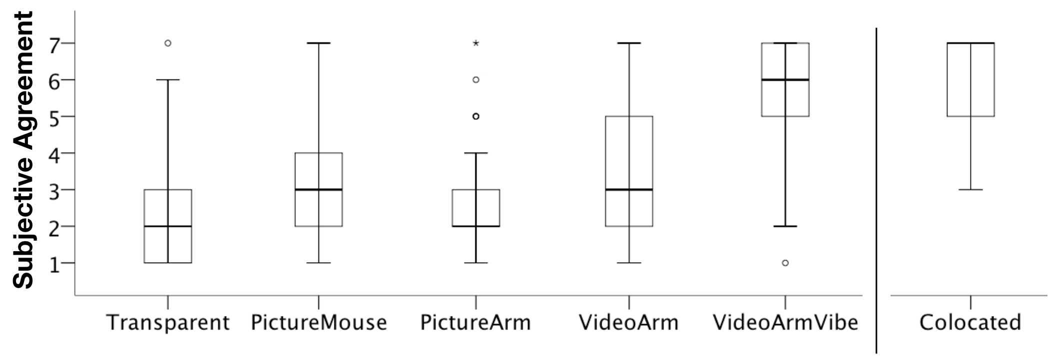

Figure 26 - Subjective feelings of awkwardness to cross embodiments

4.7 Discussion

4.7.1 Summary of Results

We found that video embodiments are subjectively preferred over simpler visual embodiments and increased people's sense of co-presence, but that this had little effect on people's coordinative behaviours. We also found that people generally ignored the remote person, freely occluding their personal workspace and crossing their embodiments. Last, we found that there are substantial differences in how people interact with touch- and mouse- based embodiments, spending less time reached out into the public space with touch-based input.

4.7.2 Interpretation of Results

Although people reported feeling that visual fidelity and tactile feedback increased their sense of a collaborator, people did not coordinate to avoid crossing distributed mouse-based arm embodiments: people reached as guided by their individual need, regardless of the location of the other person's embodiment. This follows results previously shown for co-located mouse-based arm embodiments (Doucette 2013a). However, distributed tactile feedback did not mimic results previous shown for co-located arm embodiments (Doucette 2013b). In general, we observed little effort to coordinate reaching, regardless of visual embodiment or input type.

There are potentially some benefits of VideoArms, at least on subjective measures of awareness and realism, but the added complexity (e.g., hanging a Kinect above the table and the live processing and distribution of video) does little to change behavioural measures.

4.7.3 Physical Reaching versus Mouse Reaching

There are large differences between mouse and touch input on the time spent reaching. It is physically tiring to keep an arm extended over a table, so most people keep their arms in a resting position near their seated location. This means there are fewer opportunities to cross: people spend less time reached out, and thus cross less.

Overall, this behaviour may have a substantial effect on distributed tabletop interactions. People are tuned to track changes in the environment, so the higher number of mouse-based actions in the public tabletop space means that people may start to ignore them. The large and less frequent physical reaches are more noticeable than the often quick and jerky gestures of mouse-based input. In addition, physical reaching is a more purposeful act than mouse-based reaching; people typically do not spend any more time with their physical arm reached out than they have to. Video embodiments are also subjectively reported to provide more awareness of action. Together, these results suggest that touch-based distributed tabletops may provide better awareness of the other person's actions than their mouse-based counterparts.

4.7.4 Predicting the Other Person's Actions

It is difficult to predict what other people are about to do in distributed environments. In our system, reaching gestures are only captured and transmitted once they are over the table's surface, removing the subtle preparatory gestures that precede a reach. For example, people move their gaze towards where they are going to reach, they rotate their torso to orient themselves towards the target, and lean in to begin the reaching gesture. Visual cues, such as display trajectories (Fraser 2007), may alleviate some of these issues.

In addition, VideoArms require a lot of processing power, and introduced lag into both the local and remote embodiments due to the Kinect and the LAN connection. Visual lag has been shown to affect coordinative behaviours (Gergle 2006), which may help explain people's behaviours with VideoArms. The video quality of our VideoArms is not perfect due to the technical limitations of the Kinect. There are visual noise artifacts around the embodiments and blur during movement, giving them a ghosted appearance. These issues may also reduce people's sense of embodiment. In the rubber hand illusion (IJsselsteijn 2006), it is the temporal correspondence of the tactile and visual feedback that is key in created the sense of embodiment. Removing the temporal correspondence of input and feedback may contribute to a lower sense of embodiment.

Overall, these effects lead people to ignore the other person's interactions in the shared space. This may increase the perceived distance between remote groups (Olson 2000), and potentially increase people's separation of in- and out-groups (Bos 2004), breaking the collaborative experience.

4.7.5 Distributed Tactile Feedback

Why did tactile feedback work so well in a co-located setting (Doucette 2013b), but have little effect in a distributed setting? We suspect there are at least two reasons.

First, the latency of the VideoArms may make it harder to predict when other people will be reaching (see previous section). The difficulty of predicting when a crossing might happen may have caused people to simply give up trying to avoid the tactile feedback.

Second, even though people report that crossing with tactile feedback is more awkward than without tactile feedback, in practice it seems that tactile feedback is less awkward when the other person is not physically co-present. When people are co-located, the vibrations are a shared experience, with both people reacting and generally trying to avoid it. In a distributed setting, the vibrations become individual experiences, with most people ignoring them and being indifferent to causing the other person to feel the tactile feedback. There seems to be something about seeing another's actions directly causing the tactile sensation that is lost when people are distributed.

4.7.6 What it Means to be Embodied with Arm Embodiments

To be truly embodied (a sense of being *inside* the embodiment, a sense of *controlling* the embodiment, and a sense the embodiment *is part* of physical body (Kilteni 2012)), it is going to take more than just visual representations. The visual representation alone is not strong enough to cause people to treat arm embodiments as they treat physical arms, and augmented embodiments lose some of their power to promote awareness and coordination when deployed in distributed environments. Vibrations increase the feeling of sharing the same space, though they do not change people's willingness to touch the other embodiment. In the end, our results suggest that people do not extend their personal space to surround their arm embodiments. They do not avoid reaching near or through others' arm embodiments.

One reason we wanted to study distributed embodiments was because we were under the "most real thing in the room" hypothesis. When co-located and physically reaching, people's physical bodies are the most real representations of others (Doucette 2013a); however, when augmentations are added in co-located a setting, the arm embodiments become more "real". People's actions have consequences in the physical world, and so people extend their personal space to encompass the digital arm embodiment.

Distribution removes the physical co-present body, so the most real thing in the room should be the other's arm embodiment; however, people were generally oblivious to the other person's embodiment and even their personal workspace (see occluding example in video analysis). Instead of becoming more real without a co-present body, the embodiments became less real. Even the tactile feedback did not really cause the distributed VideoArms to encapsulate people's personal space.

The best remote embodiment may end up being a physical device, such as the workplace robots (e.g., Paepcke 2011) or physical remote arms used in surgical systems; however, we still know little of how people would treat the personal space of these physical representations.

4.7.7 Future Work

The task studied in this work includes only symmetric interaction, as people are performing the same task and interact at the same time (symmetric and synchronous interactions). In everyday tasks, people can interact at different times (asynchronously) and can work on different tasks (e.g., gatherer and assembler). We believe arm embodiments may be useful as asynchronous visual traces (Gutwin 2002), even sped up or aggregated (Roy 2012).

At a higher level, this exploratory work leaves us with many questions. How would people's interactions be different in a cooperative (instead of parallel) task? Groups created a playful environment with the augmentations, poking at each other jokingly, opening up questions about the meaning of digital touch. Will digital touch one day have similar social norms as physical arms? Will augmentations be required to induce behaviour change, or will a new medium or embodiment induce a higher SoE?

4.8 Conclusion

We expect digital embodiments to be an important component of distributed tabletop systems, as groups require system support to replace the missing co-present body. We investigated how the design of distributed digital arm embodiments affects group behaviour by answering questions on Occlusion, Input, Visual Fidelity, and Tactile Feedback. We showed that video embodiments are subjectively preferred over simpler visual designs, but provide no additional coordinative benefits over simpler visual designs. We also showed that when tasks are loosely-coupled, people can and do ignore the remote person, even when interacting with the other person causes tactile feedback. Last, we show how people interact differently with touch- and mouse- based input, suggesting that touch input may better support coordinative behaviours because they are less frequent and more purposeful than mouse-based input. Our results inform the design of digital systems, and add to our understanding of what it means to be digitally embodied.

4.9 Summary of Manuscript C

The main contribution of this work is that video embodiments are subjectively preferred over simpler visual embodiments; they increase people's sense of co-presence and sense of embodiment. However, this increase in subjective feelings had little effect on people's coordinative behaviours, with people freely occluding the remote person's personal workspace and embodiment. We also found that people interact quite differently with mouse- and touch- based embodiments, spending less time reached out into the public space with touch-based input than with mouse-based input. This has important consequences for the design of distributed systems, because over time, the jerky mouse-based movements may be ignored, whereas the purposeful touch-based interactions may better support group awareness and coordination.

CHAPTER 5

OVERALL DISCUSSION

5.1 Review of Work in this Dissertation

5.1.1 Goals of the Research

The main goal of this research was to provide an exploration of how the design of digital arm embodiments affects group interactions over digital tabletops. Digital systems are becoming more and more important to our daily interpersonal interactions, so we want to inform the design of digital systems to support group interactions (both co-located and distributed) for both task work and team work. This research directly informs the design of digital systems by evaluating how the design of arm embodiments affects a group's interactions, and provides additional foundational work on what it means to be embodied in digital systems.

5.1.2 The Studies

To address the goals of this research, we performed four user studies.

5.1.2.1 Paper-based Pilot

The first step to this research was to ensure our task demonstrates the main construct we are interested in: people's close-proximity physical coordination, as shown through people's aversion to crossing over or under another person's physical arm. We created a mixed-focus task of building individual haikus. To maximize the number of potential physical reaching conflicts, we switched the locations of the topic words on the table in front of the two people. We piloted this task with ten groups of various demographic pairings.

5.1.2.2 Study 1 – Visual Design

With a task that reliably produced the physical behaviour we wanted to study (people's aversion to reaching over and under another's physical arm), we began exploring how people interact with mouse-based embodiments. We focused on the visual design of arm embodiments and evaluated the effects of four visual factors identified in previous work (Pinelle 2008a): physicality, occlusion, size, and realism. We compared four digital arm embodiments to interacting with physical touch input: a thin line, a colour-filled picture of their arms, a semi-transparent colour-filled picture of their arms, and the picture of their arms with the original texture (showing rings, watches, and sleeves).

5.1.2.3 Study 2 – Embodiment Augmentations

The results from Study 1 suggested that visual design had little effect on people's coordinative behaviours as contrasted with the differences between reaching physically (touch input) or digitally (mouse-based input). We explored ways of providing feedback of embodiment crossings, comparing tactile and movement alteration augmentations (each augmentation type was evaluated at two different strengths). We compared a vibrating mouse, a vibrating box in people's front pant pocket, embodiments that slow down when crossing (as if going through molasses), and embodiments that cannot cross (they bump against each other).

5.1.2.4 Study 3 – Distributed Environment

Aiming for generalizability of this work, we explored how our findings from Study 1 and Study 2 generalized to a distributed environment. The distributed environment allowed us to study touch-based digital arm embodiments (which make little sense when co-located as they are always "under" the physical arm), as well as live video. We evaluated the effects of four factors of embodiment design: occlusion, physical input, live video, and tactile feedback. We compared the mouse-based transparent and picture arm embodiments to three touch-input embodiments: the Picture arm embodiment controlled with touch input, live video, and live video with Pocket vibration.

5.1.3 Summary of Overall Results

In traditional tabletop tasks, people generally avoid crossing over or under another person's physical arm. We found that this same behaviour exists in co-located digital systems, but only when people are physically reaching. When reaching digitally with mouse-based arm embodiments, people freely crossed embodiments, regardless of the embodiments' visual design. People had little incentive to avoid colliding with others' arm embodiments because there were no consequences to their actions.

We found that providing feedback of crossing events changed people's behaviour, causing them to avoid crossing the other person's embodiment. Groups reverted to automatic coordination mechanisms, like the hallway passing effect and false starts, by increasing their awareness of what the other person was doing. This came at little cost, requiring no training and minimal overhead.

In a distributed environment, we found that video embodiments were subjectively preferred over simpler visual embodiments. Video embodiments increased people's sense of co-presence and sense of embodiment, but that this had little effect on people's coordinative behaviours, with people freely occluding the remote person's personal workspace and embodiment. We also found that people interacted quite differently with mouse- and touch- based embodiments, spending less time reached out into the public space with touch-based input than with mouse-based input.

5.2 Lessons Learned

This work provides new understanding about what it means to be digitally embodied by arm embodiments. These lessons are useful for designers of multi-user systems where it is important to track what others are doing in the shared space.

5.2.1 Occlusion

We found that the degree to which an embodiment occludes the objects underneath has a strong effect on group work. People's physical arms are opaque, and thus people cannot see through arms to see the tabletop below. They are also physically solid, so people cannot reach through them. These cause both visual and physical occlusion of the workspace. In general, people are very aware of when their physical limbs occlude where another person is interacting, and often avoid reaching when it will cause occlusion.

When interacting with mouse-based digital embodiments, physical occlusion is no longer an issue (people can easily reach through other embodiments), but visual occlusion is still a problem. When co-located, people are aware of visual occlusion caused by their embodiment and typically avoid occluding the other person's personal workspace. Distributed touch input changes how people react to the occlusion of their embodiments; when interacting with strangers, people seem to ignore the other person and occlude their workspace with little regard of the interruption they are causing.

5.2.2 Constraints

We found that the constraints imposed by physical bodies can be a benefit or a detriment, and so the removal of these constraints with virtual embodiments can also be beneficial or detrimental.

The removal of constraints is often considered a benefit of digital interactions. For digital embodiments, the removal of the physical constraints (reach limitations, physical occlusion, and social rules) can be a boon for high-speed interactions: people no longer have to worry about interfering with other people, and thus can interact faster.

On the other hand, the work in this dissertation suggests that artificially constraining digital behaviour through embodiment design can be useful in shared environments. Constraints enable people to predict what other people are going to do, and help to guide a group's behaviour by enabling simple and automatic coordination.

5.2.3 Embodiment Resting Position

We found that people have a natural resting position near their physical bodies when interacting with touch input, a behaviour that has no digital analogue with mouse-based embodiments. Physical reaching is much more tiring than digital reaching, so people naturally spend less time extended out into the public tabletop space. With mouse-based input, people scan the table's surface while searching for items, a behaviour only observed once with physical arms (with the VideoArm embodiment). Physical arms have a default resting position on the table bezel near the person's physical seated location. This resting position does not exist for mouse-based digital embodiments, as there is no cost to leaving the digital embodiment stretched out over the surface. Overall, people spend more time with their embodiments in the shared space with mouse-based embodiments than with touch-based embodiments.

5.2.4 Preparatory Gestures

We found that the physical preparatory gestures people produce when reaching are useful for others to interpret what they are about to do. These preparatory gestures are missing in the distributed environment studied in this dissertation.

When co-located, people perform many preparatory physical cues that help others interpret what actions they may take next. People scan the surface of the table with their eyes, searching for items; people re-orient their physical bodies to point towards the target they are reaching for; and the large physical gestures of reaching are easily picked up by our peripheral vision. When interacting with mice, the preparatory gestures are missing, though eye gaze is still present. When distributed, even eye gaze is missing, creating a truly impoverished experience. The removal of preparatory cues seems to have a large effect on people's ability to predict what others are going to do in the shared space.

5.2.5 Input Fidelity

We found that the richness of physical arm input is useful in creating a subjective sense of embodiment, something that will be difficult to reproduce with mouse-based embodiments. People have years of experience interacting around others' physical bodies, and have developed simple rules guiding these close-proximity interactions. For example, to avoid interfering with other people in the shared space, people often reach "around" other people's physical arms. This "reaching around" behaviour means that people perform less-optimal interactions in order to avoid interfering with other people (it takes longer to reach around someone than to reach over them); however, this less-optimal behaviour provides an opportunity for simultaneous interactions, while also acknowledging other people's personal space. These rich reaching behaviours are only possible with fully articulated arms (fingers, wrist, elbow, and shoulder), something not currently possible with mouse-based embodiments. Designing mouse-based embodiments with such large input degrees of freedom will no doubt be difficult problem to solve. This direction may not be worth the effort given how well people's physical arms can efficiently perform these rich interactions.

5.3 Design Guidelines

The lessons we learned throughout this work have informed nine design guidelines.

5.3.1 Visual Design

5.3.1.1 Co-located Occlusion

Occluding embodiments (more opaque and larger size) are disruptive to other people in the shared space. When co-located, people are more aware of interrupting others with occlusion, and generally avoid occluding others' personal workspace. Use more occluding embodiments to increase people's awareness of the other person's workspace. Less occluding embodiments allow people to interact freely, without feeling like they will interrupt others. Use less occluding embodiments when free interaction is needed, such as in high-speed, low-awareness tasks.

5.3.1.2 Distributed Occlusion

In contrast to when co-located, people can and do ignore the other person when using distributed embodiments, at least when tasks are independent. Occlusion is mostly negative when distributed, as people cannot see through opaque embodiments to the workspace below. Use less occluding embodiments paired with augmentations to reduce the interruption while still providing awareness of the remote user's location and actions.

5.3.1.3 Picture Embodiments

The realistic texture of the Picture embodiments had no substantial benefit over simpler, arm-shaped embodiments. Picture embodiments are likely not worth the extra effort of setup (taking the picture) and the additional image processing required.

5.3.1.4 Video Embodiments

For embodying touch-based interaction, video embodiments are subjectively preferred; people report they feel the most real. For strangers, use simpler visual embodiments, as video does little to change how people interact with remote strangers, providing no additional coordinative benefits over simpler visual embodiment designs (e.g., a solid arm-shaped embodiment).

5.3.2 Interaction Design

5.3.2.1 Touch and Mouse Input

For high speed, low awareness, high input-precision tasks, use mouse-based input. Mouse-based embodiments provide less awareness because the actions are so frequent and serve little communicative purpose. To provide better awareness of public workspace interactions, use touch-based input. Touch-based input is less frequent and more purposeful, providing better awareness of actions.

5.3.2.2 Augmentations

Augmented embodiments provide a balance between the high awareness provided by touch input and the lower awareness provided by low-occlusion embodiments. To achieve better awareness with low-occlusion embodiments, augment the embodiments with movement alteration or tactile feedback.

5.3.2.3 Movement Alteration

Small performance penalties can be useful in providing awareness of others. Use movement alterations to increase people's awareness of other people's actions by making certain interactions more difficult (e.g., the Slowed augmentation), or prevent the interactions altogether (e.g., the Blocked augmentation).

5.3.2.4 Co-located Tactile Feedback

Tactile feedback is a simple way to provide immediate feedback of an interaction. For subtle, shared feedback, use less disruptive feedback such as Pocket vibration. Mouse vibration is also effective, but the loud noise of Mouse vibration is more disruptive than the more subtle Pocket vibration.

5.3.2.5 Distributed Tactile Feedback

Tactile feedback provides awareness when distributed, but does not increase people's ability to coordinate. There is something about actually seeing the other person perform the action that causes the tactile sensation that makes co-located tactile feedback effective. It is the temporal and visual correspondence of the action and feedback that is important. Nevertheless, use distributed tactile feedback to increase awareness of the remote person's co-presence.

5.4 Bringing it All Together

Through the work completed in this dissertation, we now know a lot more about how the design of digital arm embodiments affects group reaching behaviour on a tabletop display. We know that the visual design of arm embodiments has subjective effects on reaching behaviour, that augmentations can help support group coordinative behaviours, and that reaching behaviour with physical input is remarkably different than mouse-based input. In this section, we expand on these ideas and explore what these results tell us about being embodied in digital systems.

5.4.1 Visual Design of Arm Embodiments

Throughout this work, we have focused on the visual design of digital arm embodiments. The overarching concept driving this exploration was that the more an embodiment resembles the physical body, the more people will treat the embodiment as a part of their physical body. Our work shows that the visual design of arm embodiments has little effect on how people interact with others through the embodiments.

Though their behaviour was unchanged, people did report different subjective experiences with the visual designs. They reported that more realistic embodiments (i.e., the video embodiments) increased awareness of the other person and that the videos felt more *real*. People reported in interviews that the PictureArms were creepy, suggesting the PictureArm embodiments presented in this dissertation may fall within the uncanny valley (where representations of humans that are almost real, but not quite right, are uncomfortable for many people). The videos also had strange blur and pixilation effects that, coupled with the local and remote lag, made for a less satisfying experience with these embodiments.

Our mixed results provide good guidelines for future designs. There is one additional visual effect we did not investigate: that of caricatures. Caricatures[7] are visual representations of real people with exaggerated physical features (e.g., big ears or nose). Caricatures are somewhat surreal, and sometimes are even more representative of the person than a picture of the actual person. Representing embodiments using exaggerated features (creating, in a sense, a Caricature Embodiment, possibly based on the psychological Homunculus effect[8]) may invoke the supernormal stimulus[9], where people may react to the exaggerated features of the embodiment more strongly than to our Picture and Video embodiments.

Regardless of new potential directions in visual design, it seems that, at least when using touch-input while co-located, the social norms of physical arms will greatly outweigh anything we can do with the visual design of digital arm embodiments.

5.4.2 "Embodied"

What does it mean to be "embodied" with arm embodiments? Does it mean that the embodiment is an extension of the body, or is the embodiment just a tool to perform

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[7] http://en.wikipedia.org/wiki/Caricature.

[8] http://en.wikipedia.org/wiki/Homunculus. We use the definition of homunculus from psychology, which uses the term for a visual representation of the human body with exaggerated features based on the sensory or motor functioning of the limb. For example, the hands and genitalia take a much large proportion of our sensory and motor cortexes as compared to the rest of our bodies.

[9] http://en.wikipedia.org/wiki/Supernormal_stimulus

actions in the digital system? Our work suggests that, although we call them embodiments, arm embodiments have a long way to go to truly embody people.

5.4.2.1 Are Arm Embodiments Tools or an Extension of the Body?

People did not strongly feel like the arm embodiments were “part of me”, or that the partner’s embodiment was part of the partner. Though we caution against drawing statistical conclusions across our studies, the overall effect seems to be that people reported feeling more embodied when distributed (see Figure 27 and Figure 28). We suspect this effect may be due to our “realest thing in the room” hypothesis, which suggests that the physical body overpowers any effect of the arm embodiment design when co-located. In essence, the digital arm cannot be part of the other person, because their body is physically sitting next to you. In the distributed environment, the lack of the partner’s physical co-present body means the arm embodiment is the only representation of the remote person. Thus, people may interpret distributed embodiments to be *more real* than when the other person is physically co-present.

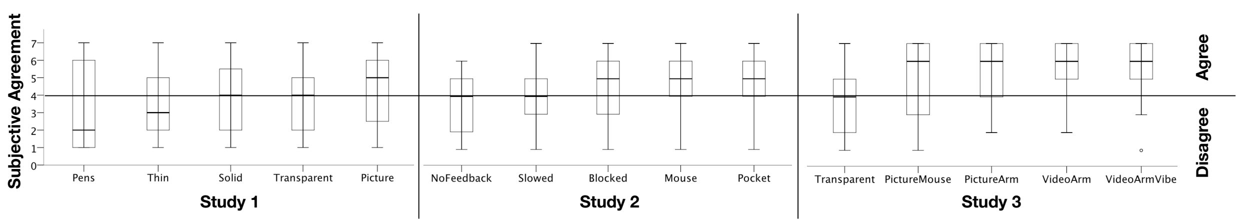

Figure 27 - Subjective response to embodiment is "part of me"

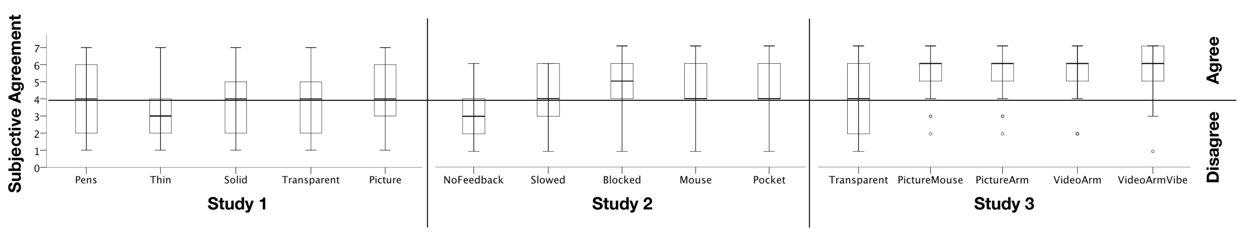

Figure 28 - Subjective response to embodiment is "part of them"

Overall, these results suggest that arm embodiments are typically interpreted as tools when co-located, and potentially more “embodied” when distributed.

5.4.2.2 The Role of Touch

In this work, we have focused on the ‘negative’ side of touch. The overarching concept was to cause people to want to *avoid touching*. Though appropriate as an exploration of the coordinative benefits of touch avoidance (Andersen 1978), this is a limiting view of the role of touch. Physical touch is part of a rich communication medium where touch is the most intimate channel. It is "…the most carefully monitored and guarded, the most vigorously proscribed and infrequently used, and the most primitive, immediate and intense of all communicative behaviours" (Thayer 1986, p.24). Touch is a powerful way to show support, but can also demonstrate dominance and increase compliance (Thayer 1986).

Researchers have created prototype systems for communicating touch and intimacy over distance, starting with social mediated touch (Haans 2006) and extending into physical devices like one for distributed hugging (DiSalvo 2003). This line of research has contributed to the bourgeoning field of teledildonics, where partners can engage in remote mutual masturbation for the ultimate experience in remote intimacy. For example, Zeus and Hera[10] are commercial networked his-and-her sex toys, providing tactile and haptic feedback of the other's intimate interactions with their toy.

Visual digital touch is special though: it is such a new experience that people have not yet developed social rules guiding digital touch behaviours. People do not associate the rules of physical touch with that of digital touch, possibly due to the lack of a physical tactile experience; however, people associate meaning to actions that are otherwise meaningless (e.g., giving someone the finger) and that have no tactile experience. In the digital world, people associate meaning to textual descriptions (e.g., virtual sex over chat), and even to virtual touch. For example, in the ShareTable system, Yarosh *et al* describe how a mother and daughter comforted the sick son who was staying with his father (Yarosh 2013). They "held hands" virtually, through a VideoArm-like system, with family members assigning a comforting meaning to digital touch. A physical parallel of this no-touch touching occurs when physical constraints prevent a tactile touch. People assign meaning to "touching hands" through a pane of glass, such as when interacting with a loved one in prison; even though there is no tactile touch, the gesture still conveys love and intimacy.

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[10] https://www.lovepalz.com/

This discussion suggests that people do not associate digital arm touching with physical arm touching, though this may be due to people's inexperience with digital embodiments. The examples also show that digital touching in general could become an important component of our digital communications, given how people already assign meaning to no-touch touching.

5.4.3 Playful Interactions

Throughout this exploration, we have observed playful interactions with the digital systems and the different arm embodiments. Many groups engaged in playful interactions, poking at each other with the different embodiments. This was a common theme through non-Stranger groups, starting with the Lines embodiments (the "laser beams", as one participant stated) and re-occurring with the Pictures and tactile feedback.

Many people really liked the tactile feedback. Some of this can be attributed to the novelty of the experience, but people seemed to enjoy the simplicity with which they could interact with others on an intimate level. People poked at each other, giggling as the other person jumped each time they purposefully crossed embodiments with them. Some groups played with the movement alteration embodiments as well, with one person cornering another with the Blocked embodiment, completely preventing them from interacting.

We suspect the playful effect may be due to the novelty of digital tabletops. It seems like poking at each other would get old pretty fast, especially when it is coupled with a disruptive augmentation. A surprise Pocket-buzz just to be funny would likely become rude and improper, with people discouraging this behaviour through social costs.

5.4.4 On the Novelty of Digital Tabletops and Arm Embodiments

Digital tabletops have been around for over 20 years, yet they have only found limited niches outside of research labs (with the Microsoft Surface, SmartTable, and DiamondTouch the notable commercial products). Thus people have little to no experience interacting over digital tabletops, but have thousands of years of experience physically interacting over horizontal surfaces. Some of this experience transfers directly to digital tabletops when using touch input: people physically interact with a digital system with similar reaching coordination as when interacting over a traditional tabletop.

Even with the lack of experience, people had little issue using our digital tabletops. There were a few technical issues, such as people's interaction point being offset from their Picture embodiment during set up, making it harder to select words with the mouse, but most participants quickly adapted to the constraints of the technology. The touch-screen input was local and responsive, making it easy to interact in the shared workspace.

It appeared that most people understood the feedback provided by the augmentations. People knew why the feedback was happening, and how they should respond by coordinating with their partner to avoid crossing.

One goal of digital systems should be to provide systems that support people's natural coordination mechanisms; however, due to people's inexperience with digital tabletops, people have not yet formed baselines of behaviour on which to establish new group norms. Over time, groups may form social norms to guide people's interactions in shared digital systems.

5.4.5 Co-located and Distributed Tabletop Territories with Arm Embodiments

Throughout this work, we have investigated how the design of the digital system can affect group behaviour over a tabletop. We have shown that certain manipulations do indeed affect group behaviour, though tabletop territoriality (the way that groups partition a tabletop's surface into private and public workspaces (Scott 2004)) was consistently present. In all studies, the ownership of the haiku papers and the words on them was assumed and upheld: people very rarely interacted inside of their partner's haiku, and tried to avoid occluding it (at least in the co-located case). When people had an existing relationship prior to the study, they sometimes "helped out" the other person by moving words onto and around their partner's haiku paper (this never occurred with strangers). These invasion events were typically accepted as helpful, though some were playful or annoying (e.g., throwing one of their haiku words back onto the table).

5.4.6 Assigning Blame

Many groups told us that they avoided crossing with vibrations because they did not want to make the other person feel awkward. Few people stated they avoided crossing because they themselves did not want to feel weird, and most people made no reference to feeling weird when receiving the vibration. Throughout the work, we have thought about the idea of assigning *blame* to one of the interactors. This would allow for *differential feedback*, where one person would receive the feedback and not the other. It is difficult to design heuristics that capture blame as effectively as people do naturally when physical invasions of personal space are concerned.

5.4.7 Social Protocols

The initial motivation of this work was to better understand the physical social protocol of touch avoidance, and to understand how these kinds of physical social norms may be incorporated into digital systems. We found that the social protocol with physical arms is *don't touch*, whereas with digital embodiments, the protocol is *touching is fine*. Over time, different social protocols may develop as people gain more experience interacting with others in digital environments.

This applies more generally than only in shared workspace environments. The overarching concept is that, traditionally, people's actions in digital environments had no consequences in the physical world. For example, in multiplayer games like a first-person shooter (FPS), the punches, kicks, and shots have little consequence but to vibrate the other player's controller. However, some actions in digital environments have real world consequences people try to ignore. For example, the recent push for cyber-bulling legislation suggests there is a social problem online, where people have few consequences to their actions. It is possible that by adding real world consequences to people's online actions (a new law being the extreme case of a social protocol), people may incorporate this cost into their interactions.

5.4.8 On Our Exploratory Approach

Throughout this work, we have used an evidence-based build-test iteration cycle, running short pilot studies to explore the space of arm embodiment design before forming research questions and completing controlled user studies. This exploratory approach was a good choice because there is little known about this space, with too many interesting avenues to fully cover in a dissertation. To shed some light onto our process, here is how the work actually progressed.

We were interested in investigating group interactions over tabletops based on some previous work from our lab (Nacenta 2007, Pinelle 2008a, Pinelle 2009). We established a situation where a physical protocol guides behaviour in a paper-based task (that is, dyads building haikus with the words switched). We built a system to explore how embodiment design could affect the observed physical behaviour.

With a digital version of the physical task, we started with pilot studies on visual design, testing cursors, lines, thick cartoon-like arms, picture arms, and filled in picture arms. Initial testing suggested the visual design had little effect on people's behaviour: it was a total free-for-all. Why was that? What was missing from digital arm embodiments that would enable people to use them as they do their physical arms? One participant suggested, "These embodiments, they just don't… *feel*". We interpreted this to mean that there was a lack of feedback to interactions with others: when you collide with physical arms, this is a shared tactile experience that you most definitely *feel*.

We began our exploration based on related work, combining the idea that adding constraints to behaviours can be beneficial (Cockburn 2007, Hullman 2011, O'Hara 1999), with work in interaction design (Mandryk 2008), and tactile feedback (Haans 2006) with the intimacy of touch locations (Nguyen 1973). We pilot tested[11] mechanisms for providing feedback. Pilot results were good: people were reacting to the feedback and changing their behaviour.

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[11] Ideas that never made it to user study: increasing the size of embodiment, an alarm sound, a socially awkward sound (think children chanting "oouuuu"), and providing feedback to only one person.

Armed with the results of our pilot studies, we formulated a set of research questions for visual design and augmentations of arm embodiments and performed two controlled user studies to answer our questions. These two studies were well received, and make up Chapter 2 and Chapter 3.

We were left with many questions, leaving us with many options for follow-up work. We decided to pursue generalizability due to two motivating factors. First, we investigated arm embodiments in a co-located setting to ensure as much similarity to the real world experience; however, we know that distributed environments are where embodiments are likely be to the most useful. Second, some participants mentioned that the PictureArms were not very realistic: pictures did not bend, and did not really look like an arm. Video would be a more realistic embodiment, but video made no sense when co-located because then people are reaching physically and so are not really interacting with the digital embodiments. When distributed, however, video arms were an option.

Based on the results from Study 1 and 2, we planned Study 3 to test remote mouse-based and touch-based embodiments. We used the KinectArms (Genest 2013) toolkit to support the video arms, but there was a problem: Studies 1 and 2 used a top-projected tabletop. When coupled with the Kinect, there is a feedback loop when projecting the local workspace (with the remote embodiment displayed) over the remote display. We switched to using a touch-display. Sitting at the short end of the table, the visual size of the workspace was similar to when using the top-projected tabletop, allowing us to generalize some of the results between the three studies (same task and same system in all studies).

The work presented in this dissertation builds up a story about what it means to be embodied by digital arm embodiments: how do people feel about arm embodiments, use them, and interact with others with them? Through the exploration of this space, we identified research questions that could explain what we were observing in our pilot studies. We designed and completed three user studies, answering the research questions identified from the initial exploration.

This exploratory work improved our understanding of what it means to be embodied digitally (or rather, identify there is a lack of embodying). We are left with the large question: what does it mean to be embodied digitally? How do embodiments transition from being tools (as shown in this dissertation) to being a part of you? For example, why do avatars embody people's feelings of personal space (e.g., Jeffrey 2003)? Why do people treat avatars as "people" by avoiding making eye-contact in immersive virtual environments (Bailenson 2003)? What makes these embodiments different than the arm embodiments studied in this dissertation?

Beyond embodiments specifically, designers are likely to continue the move to asynchronous and distributed systems in the next generation of digital tools. How will we ensure they are simple, easy to learn and use, and yes, playful? What will make digital experiences rich, on par with or better than the in-person experience? Will the feeling of being "embodied" in the shared space be the key?

5.5 Limitations of Results

5.5.1 Demographics

Although there was no observational evidence of cultural or gender-based differences, the experimental protocols presented in this dissertation do not allow us to study culture or gender effects directly. We collected a proxy for culture, a person's self-reported first language. After observing the 122 people complete the task with 16 different first languages (see Appendix A), we never directly observed any behavioural differences in the physical social norms described in this dissertation. It seems as though this kind of table manner (not crossing over or under another's physical arm) is universal, though this remains to be determined empirically in a controlled cultural study.

5.5.2 Other Tasks

The particular task studied in this dissertation is an open-ended, mixed-focus task, where there are few tightly-coupled interactions and no correct answer. Though we suspect many of the conclusions will generalize to other tasks, we cannot conclusively state how competitive, tightly-coupled, or time-constrained tasks would change how people interact with digital arm embodiments.

5.5.3 Performance

Participants were instructed that the task was not a race, and that they would not be judged on the quality of their haiku. As such, we cannot measure how different group reaching behaviours ultimately affect the performance of people using digital tabletop systems. Although we believe that improved coordination will also improve performance, future work is needed to establish the effects of embodiments on task performance.

5.6 Future Work

The work presented in this dissertation opens many new avenues for future research.

5.6.1 Beyond Workspace Awareness and Crossings

One overarching theme of this work is in providing feedback of interactions to both the individual and the group. This feedback provides awareness of what the other person is doing, an important component of successful collaboration. This work informs the designs of systems beyond simple real-time workspace awareness.

5.6.1.1 Augmentations as Warnings

In this work, augmentations are a retroactive mechanism to recover after the conflict has already occurred. Augmentations may be useful as a warning mechanism for group-level actions (e.g., someone wants to switch the shared application), potentially preventing conflicts before they occur. Another way to prevent conflicts could be to provide feedback of your own interactions (for example, to warn you that you are approaching the edge of another person's personal workspace).

5.6.1.2 Augmentations as Reminders

Embodiments may also be useful as reminders of recent changes in the digital space. Subtle shared augmentations (such as Pocket vibrations) inform everyone involved that a conflict may occur. For example, people could be notified of global actions such as closing the document without saving, or when someone else is interacting in your personal workspace.

5.6.1.3 Protection of Territory

With physical arms, people can place their arm down on the tabletop in order to partition off a section of the shared space, claiming ownership of the items in this partition. In essence, this is a lightweight way to create personal workspaces. This behaviour will not work with simple arm embodiments (as people have little issue crossing over this digital barrier, thus providing little protection for the items), but may work with embodiment augmentations.

5.6.1.4 Feedback of Asynchronous Changes

Arm embodiments in general may be useful as digital traces (Gutwin 2002) for visualizing non-synchronous interactions. When returning to a shared environment, it is important for people to re-establish the current state of the system, and to know what has happened in their absence (Roy 2012). A sped-up or aggregated replay of embodiment actions would provide a high level overview of where people interacted, what they did with that object, and what they are doing now.

5.6.1.5 Beyond Crossing

What kinds of interactions, beyond crossings, could augmentations be applied to? As discussed in the Role of Touch (Section 5.4.2.2), the concept of digital touch may evolve one day to have meaning. We have shown that digital arm embodiment touching was meaningless in our independent-task workspace; however, other researchers have shown that VideoArm-like touching can be interpreted as intimate comforting touch (Yarosh 2013). How can we create digital experiences that will fulfill basic human needs, such as intimate touch?

5.6.2 Formation of New Group Norms

As alluded to throughout this discussion, the novelty of digital tabletops mean that people have not spent enough time in these environments to develop social norms to guide group behaviour. How will these new norms develop? In general, social norms are created when the cost of not following the new norm is higher than the benefit of performing the original behaviour (Hechter 2001). Will people associate meaning to digital touching, thus necessitating rules to govern how groups should interact digitally?

Will digital touching become a proxy for physical touching after weeks or months of experience? Will these digital norms be different than the norms with physical bodies?

5.6.3 Desktop Systems

This work has focused on digital tabletop systems, but the results may also directly inform the design of desktop groupware systems. Research in shared editors and digital whiteboards have struggled with how to represent users in the shared workspace, and the arm embodiments studied in this work could be useful in these non-tabletop distributed systems; however, there is a problem with *arm* embodiments in non-tabletop distributed systems. Digital arm embodiments require the visual connection to a person's seated location. The visual connection informs everyone of embodiment ownership, and is the essential component that distinguishes *arm* embodiments from other kinds of embodiments. In non-tabletop distributed systems, people lack a natural seating location around the shared workspace. How can we map people around the edge of the workspace? Is the outer edge even the most appropriate place for people to be visually represented? For independent tasks, it may make more sense for everyone to be centered in the middle, pointing away from each other, providing slices of the workspace like pizza slices extending out from the center (see Figure 29).

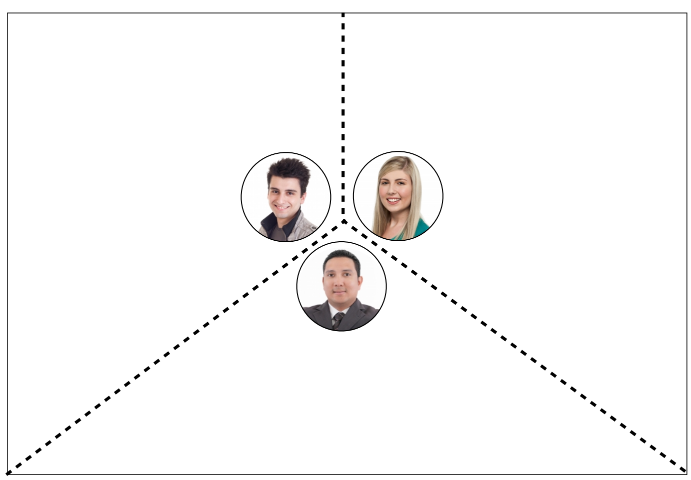

Figure 29 - Personal workspaces without physical seated location, extending from the center of the shared space instead of the edges of the shared space

5.7 CONCLUSION

Tables are a common place for group interaction. We use tables for entertainment, for work, and due to their ability to physically support objects, for everyday activities like adding sugar to our coffees. An essential component to these tasks is group reaching, the intricate coordinative dance groups perform while coordinating access to shared items. It is essential to understand this fundamental group behaviour to inform the design of multi-user digital systems. Through the work presented in this dissertation, we now know more about what it means to be digitally embodied with arm embodiments, and how the design of arm embodiments can change a group's reaching behaviour.

Human group behaviour is a complex phenomenon, constantly adapting to changing pressures and environments. As our lives continue their march towards the digital world, understanding what it means to be embodied in digital systems becomes more and more important. How will systems support our natural understanding of how the world works, of how people should behave while interacting with others, of what is considered appropriate behaviour? This dissertation provides an initial investigation into this area, providing useful guidelines for the design of multi-user digital systems.

5.8 Contributions of this Dissertation

The main contribution of this dissertation work is an initial understanding of how the design of digital tabletop arm embodiments affects a group's reaching behaviour.

This work also has several secondary contributions:

- Understanding of how a group's relationship (strangers, friends/co-workers, and intimate couples) affects group reaching behaviour.
- Design and initial understanding of how embodiment augmentations affect group reaching behaviour.
- Understanding of how distribution changes feelings of working with another person.

- Empirical evidence showing how the visual design of arm embodiments, from simple lines to full live video, affect group reaching behaviour.
- Understanding of how reaching with physical arms (in co-located and distributed settings) affects group reaching behaviour.

At a high level, this dissertation contributes to our understanding of what it means to be embodied in digital systems, and what it means to interact with others embodied in the system. This work provides a baseline on which future designers and researchers can create the next generation of digital tools, with benefits we cannot even begin to imagine.

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APPENDIX A

TABLE OF PARTICIPANT LANGUAGES

Self-reported first language	Study 1	Study 2	Study 3	Totals
English	42	9	16	67
Chinese, Cantonese, and Mandarin	6	10	3	19
Persian and Farsi	5	3	3	11
German	2		1	3
Hindi		1	2	3
Bengali	1	1	1	3
Malayalam		2	1	3
Telugu		2		2
Thai	2			2
Indonesian	1	1		2
Russian			1	1
Konkani			1	1
Urdu			1	1
Tamil		1		1
Polish		1		1
Serbo-Croatian	1			1
			TOTAL	**122**

APPENDIX B

TABLE OF PARTICIPANT GROUPINGS

Dyad relationship	Study 1	Study 2	Study 3	Totals
Strangers	10		15	25
Co-workers or friends	10	16		26
Intimate couple	10			10

Dyad gender distribution	Study 1	Study 2	Study 3	Totals
Male - male	7	6	5	18
Female - male	18	5	8	31
Female - female	5	5	2	12

APPENDIX C

EXPERIMENT CONSENT FORMS

DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF SASKATCHEWAN
INFORMED CONSENT FORM

UNIVERSITY OF SASKATCHEWAN

Research Project: **Social Embodiments**

Investigators: Dr. Carl Gutwin, Department of Computer Science (966-8646)

Andre Doucette, Department of Computer Science

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

This study is concerned with studying how people interact over a tabletop.

This session will take approximately 60 minutes during which you will be asked to build a series of haiku poems.

At the end of the session, you will be given more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (usually within two months). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

Contact email address:____

All personal and identifying data will be kept confidential. If explicit consent has been given, textual excerpts, photographs, or video recordings may be used in the dissemination of research results in scholarly journals or at scholarly conferences. Anonymity will be preserved by using pseudonyms in any presentation of textual data in journals or at conferences. The informed consent form and all research data will be kept in a secure location under confidentiality in accordance with University policy for 5 years post publication. Do you have any questions about this aspect of the study?

You are free to withdraw from the study at any time without penalty and without losing any advertised benefits. Withdrawal from the study will not affect your academic status or your access to services at the university. If you withdraw, your data will be deleted from the study and destroyed.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact:

- Dr. Carl Gutwin, Full Professor, Dept. of Computer Science, (306) 966-8646, gutwin@cs.usask.ca
- Andre Doucette, Department of Computer Science, andre.doucette@usask.ca

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a participant. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. If you have further questions about this study or your rights as a participant, please contact:

- Dr. Carl Gutwin, Full Professor, Dept. of Computer Science, (306) 966-8646, gutwin@cs.usask.ca
- Office of Research Services, University of Saskatchewan, (306) 966-4053

Participant's signature:____

Date:______________________

Investigator's signature:____

Date:______________________

A copy of this consent form has been given to you to keep for your records and reference. This research has the ethical approval of the Office of Research Services at the University of Saskatchewan.

DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF SASKATCHEWAN
INFORMED CONSENT FORM

Research Project: **Group coordination with embodiments**

Investigators: Dr. Carl Gutwin, Department of Computer Science (966-8646)

Andre Doucette, Department of Computer Science

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

This study is concerned with studying how groups' behaviours change when there is a cost to crossing embodiments.

This session will take approximately 90 minutes during which you will be asked to build a series of haiku poems. You will receive vibrotactile feedback (similar to a cell phone vibrating) either in your mouse or in your pocket.

At the end of the session, you will be asked to fill out a questionnaire and be asked a few interview questions. We will provide more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (usually within two months). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

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- Dr. Carl Gutwin, Full Professor, Dept. of Computer Science, (306) 966-8646, gutwin@cs.usask.ca
- Office of Research Services, University of Saskatchewan, (306) 966-4053

Participant's signature:____

Date:____________________

Investigator's signature:____

Date:____________________

A copy of this consent form has been given to you to keep for your records and reference. This research has the ethical approval of the Office of Research Services at the University of Saskatchewan.

DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF SASKATCHEWAN
INFORMED CONSENT FORM

Research Project: **Distributed group coordination with embodiments**

Investigators: Dr. Carl Gutwin, Department of Computer Science (966-8646)

Andre Doucette, Department of Computer Science

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

This study is concerned with studying how groups' interact with different digital embodiments while sitting in different rooms.

This session will take approximately 90 minutes during which you will be asked to build a series of haiku poems using both physical touch and mouse input. You will receive vibrotactile feedback (similar to a cell phone vibrating) on your hand.

At the end of the session, you will be asked to fill out a questionnaire and be asked a few interview questions. We will provide more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (usually within two months). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

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- Dr. Carl Gutwin, Full Professor, Dept. of Computer Science, (306) 966-8646, gutwin@cs.usask.ca
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- Office of Research Services, University of Saskatchewan, (306) 966-4053

Participant's signature:____

Date:___________________

Investigator's signature:____

Date:___________________

A copy of this consent form has been given to you to keep for your records and reference. This research has the ethical approval of the Office of Research Services at the University of Saskatchewan.

APPENDIX D

DEMOGRAPHICS QUESTIONNAIRE FOR ALL STUDIES

1. Gender: Male Female

2. Age: ________

3. Occupation: ____

4. Handedness: Left Right

5. What is your first language: ____

6. Please check all that apply to your vision:

- ❑ Normal or corrected to normal vision
- ❑ Wear glasses or contact lenses
- ❑ Color vision deficiency (CVD)
- ❑ Any visual impairments

7. How often do you use a computer?

1. Never
2. Sometimes
3. Often
4. Every day

8. Which input device do you use most frequently?

1. Mouse
2. Trackpad
3. Touchscreen
4. Stylus
5. Other (Please specify): __________________________

8. Please rate your experience with digital tabletops:

1. Never heard of them
2. Heard of them, but never used them
3. Some experience using them
4. Lots of experience using them

9. Do you know your partner? YES NO

If yes, please give details:

- **a. How long have you known them:** __________________________
- **b. In what role:** __________________________
- **c. How many times do you interact each week?** _______________________________
- **d. How much time do you spend together each week?** __________________________

Date: **SessionID:** **Left or Right**

APPENDIX E

INTERVIEW QUESTIONS

Study 1

No interview script; interview was open-ended and guided by the group.

Study 2

1. Did the feedback types change your behaviour? How?
2. Was it important to you to avoid touching the other person's embodiment?
3. How well do you think you coordinated with your partner? Why?
4. Did the coordination change depending on which feedback type you had?
5. Was it frustrating to have to coordinate with the other person?
6. How would you compare the slow down to the blocking?
7. How would you compare the mouse vibration to the pocket vibration?

Study 3

1. Was it important to you to avoid touching the other person's embodiment?
2. Did it seem like the other person's embodiment was *them*? Did this change during the study?
3. What about your own embodiment? Did it seem like it was *you*?
4. How would you compare the picture embodiment with the video embodiment? Did it change your willingness to cross the other person's embodiment?

5. How would you compare interacting with the mouse versus reaching with your physical arm? Did it change your willingness to cross the other person's embodiment?
6. Did the vibrations change your behaviour? How or why?
7. How would you compare interacting at the same table versus when you were at different tables? Did this change based on the embodiment you were using?

APPENDIX F

STUDY 1 – POST-EXPERIMENT QUESTIONNAIRE

Post-Experiment Questionnaire
Social Embodiments

Date: **SessionID:** **Left or Right**

1. Please rate your agreement with the following statements, with the scale:

1 strongly disagree	2 disagree	3 slightly disagree	4 neutral	5 slightly agree	6 agree	7 strongly agree

I am uncomfortable when others touch me.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I am uncomfortable touching others.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I am conscious of other people's personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I am uncomfortable invading others' personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I am uncomfortable when others invade my personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
My cultural norms are different than the cultural norms of Canadians.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I understand my cultural norms regarding personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I understand Canadian cultural norms regarding personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I am comfortable with invasions of personal space as dictated by the Canadian norms regarding personal space.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I think it is more awkward for members of the opposite gender to enter each others' personal space (e.g., cross arms, touch hands).	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I think it is awkward for two males to enter each other's personal space (e.g., cross arms, touch hands).	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I think it is awkward for two females to enter each other's personal space (e.g., cross arms, touch hands).	**1**	**2**	**3**	**4**	**5**	**6**	**7**

2. For each of the embodiments, please rate your agreement with the following statement: I felt like my partner was invading my space.

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. For each of the embodiments, please rate your agreement with the following statement: I felt like I was invading my partner's space.

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

4. For each of the embodiments below, please rate your agreement with the following statement: "It felt awkward to *cross* my partner's embodiment / arm"

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

5. For each of the embodiments below, please rate your agreement with the following statement: “It felt awkward to *reach* to the other side of the table”

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

6. For each of the embodiments below, please rate your agreement with the following statement: “I felt like my embodiment was a part of my body.

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

7. For each of the embodiments below, please rate your agreement with the following statement: “I felt like my partner’s embodiment was a part of their body”

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

8. Please rate your agreement with the following statement: “I was aware of my partner’s position on the table while using this embodiment”

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

9. Please rate your agreement with the following statement: “I felt my partner and I were sharing the same space while using this embodiment.”

Pens	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
ThinArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
SolidArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
TransparentArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArms	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

10. Briefly describe why you avoid crossing over (or under) someone’s physical arm.

11. Briefly describe how crossing over (or under) someone's physical arm is different than crossing over (or under) someone's digital embodiment.

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12. For each embodiment, please rate your feeling of ownership over the following:

Pens	No ownership				Complete ownership
Piece of paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Piece of paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the **left half** of the table.	**1**	**2**	**3**	**4**	**5**
Words on the **right half** of the table.	**1**	**2**	**3**	**4**	**5**
ThinArms	No ownership				Complete ownership
Piece of paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Piece of paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the **left half** of the table.	**1**	**2**	**3**	**4**	**5**
Words on the **right half** of the table.	**1**	**2**	**3**	**4**	**5**

SolidArms	No ownership				Complete ownership
Piece of paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Piece of paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the **left half** of the table.	**1**	**2**	**3**	**4**	**5**
Words on the **right half** of the table.	**1**	**2**	**3**	**4**	**5**
TransparentArms	No ownership				Complete ownership
Piece of paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Piece of paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the **left half** of the table.	**1**	**2**	**3**	**4**	**5**
Words on the **right half** of the table.	**1**	**2**	**3**	**4**	**5**
PictureArms	No ownership				Complete ownership
Piece of paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Piece of paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where you built your haiku.	**1**	**2**	**3**	**4**	**5**
Words on the paper where your partner built their haiku.	**1**	**2**	**3**	**4**	**5**
Words on the **left half** of the table.	**1**	**2**	**3**	**4**	**5**
Words on the **right half** of the table.	**1**	**2**	**3**	**4**	**5**

13. Please circle yes or no for each of the following questions:

Did you notice the words for your haikus were on the other side of the table?	**Yes**	**No**
Was the half of the table **in front of you** your space?	**Yes**	**No**
Was the half of the table **in front of your partner** their space?	**Yes**	**No**
Was your piece of paper your space?	**Yes**	**No**
Was your partner's piece of paper their space?	**Yes**	**No**
Were the words on **your** piece of paper yours?	**Yes**	**No**
Were the words on **your partner's** piece of paper theirs?	**Yes**	**No**
Did you ever reach onto your partner's piece of paper?	**Yes**	**No**
Did your partner ever reach onto your piece of paper?	**Yes**	**No**

14. Briefly describe how you felt the table and words were split between you and your partner:

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APPENDIX G

STUDY 2 – POST-EXPERIMENT QUESTIONNAIRE

Post-Experiment – Group Coordination with Embodiments

Date: **SessionID:** **Left or Right**

1. For each of the embodiments, please rate your agreement with the following statement: I was aware of my partner's *position* on the table.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

2. For each of the embodiments, please rate your agreement with the following statement: I was aware of my partner's *actions* on the table.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. For each of the embodiments below, please rate your agreement with the following statement: I felt like my embodiment was a part of my body.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

4. For each of the embodiments below, please rate your agreement with the following statement: I felt like my partner's embodiment was a part of their body.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

5. For each of the embodiments below, please rate your agreement with the following statement: It felt awkward to *cross* my partner's embodiment.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

6. For each of the embodiments, please rate your agreement with the following statement: I avoided touching my partner's embodiment.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

7. For each of the embodiments, please rate your agreement with the following statement: It was important to coordinate with my partner to avoid touching embodiments.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

8. For each of the embodiments, please rate your agreement with the following statement: I felt like my partner was invading my space.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

9. For each of the embodiments, please rate your agreement with the following statement: I felt like I was invading my partner's space.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

10. For each of the embodiments below, please rate your agreement with the following statement: It felt awkward to *reach* to the other side of the table.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

11. For each of the embodiments below, please rate your agreement with the following statement: This embodiment was annoying to use.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

12. For each of the embodiments, please rate your agreement with the following statement: It was frustrating to coordinate with my partner to avoid touching embodiments.

No feedback	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Slowed	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Blocking	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Mouse Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Pocket Vibration	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

13) a. Did you and your partner coordinate in order to avoid crossing each other?

Yes	No

13) b. If yes, please describe how you coordinated:

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____

____

14. Did you notice the words for your haikus were on the other side of the table?

Yes	No

APPENDIX H

STUDY 3 – POST-EXPERIMENT QUESTIONNAIRE

Post-Experiment – Distributed Group Coordination with Embodiments

Date: **SessionID:** **Left or Right**

1. **For each embodiment, please rate your agreement with the following statement:**
   I was aware of my partner's *position* on the table.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

2. **For each embodiment, please rate your agreement with the following statement:**
   I was aware of my partner's *actions* on the table.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. **For each embodiment, please rate your agreement with the following statement:**
   It was awkward to *cross* my partner's embodiment.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

4. **For each embodiment, please rate your agreement with the following statement:**
   I avoided *crossing* my partner's embodiment.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

5. **For each embodiment, please rate your agreement with the following statement:**
   It was important to coordinate with my partner to avoid touching embodiments.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

6. **For each embodiment, please rate your agreement with the following statement:**
   I felt like my partner was invading my space.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

7. **For each embodiment, please rate your agreement with the following statement:**
   I felt like I was invading my partner's space.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Co-located	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

8. **For each embodiment, please rate your agreement with the following statement:**
   It was awkward to *reach* to the other [left/right] side of the table.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

9. **For each embodiment, please rate your agreement with the following statement:**
This embodiment was annoying to use.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Sitting at the same table	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

10. **For each embodiment, please rate your agreement with the following statement:**
This embodiment was similar to interacting at the same table.

PictureMouse-Transparent	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureMouse	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
PictureArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
VideoArm+vibe	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

11. **Did you notice the words for your haikus were on the other side of the table?**

Yes	**No**

APPENDIX I

STUDY 3 – BETWEEN-CONDITIONS QUESTIONNAIRE

Trial – Distributed Group Coordination with Embodiments

Date: **SessionID:** **Left or Right**

TransPicture	PictureMouse	PictureArm	VideoArm	VideoArm+Vibe

For this embodiment, please rate your agreement with the following statements:

1. I was in control of the virtual arm.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

2. My partner was in control of the other virtual arm.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. It seemed as if the virtual arm was my arm.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

4. It seemed as if the other virtual arm was my partner's arm.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

5. I had a sense that I was in the same space as my partner.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

6. I had a sense of personal contact with my partner.

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

Please circle a number indicating the extent to which you responded to your partner's virtual arm: more as you would respond to a person, or more as you would respond to a computer interface.

1	2	3	4	5	6	7
The way I would respond to a person						The way I would respond to a computer interface