Sometimes When We Touch: How Arm Embodiments Change Reaching and Coordination on Digital Tables

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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.

Author Keywords

Social norms, reaching, tabletops, embodiments.

ACM Classification Keywords

H.5.3 [**Group and Organization Interfaces**]: *CSCW*

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 [5].

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 [1] 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 [19] 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.

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.

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." [28, p.24]. Touch has many social functions – for example, it can demonstrate dominance or increase compliance (see [28] 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 [13,20]. Studies have shown that people are comfortable with touches on their arms and hands, regardless of gender [18] or relationship [8]; however, other principles of social interaction – such as touch avoidance [1] or inter-personal distance norms [6] – 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 [7]. Although invasions of personal space are generally avoided, people can accommodate these situations when necessary (e.g., in crowded elevators) [7].

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 [2] (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 [12], that they are uncomfortable with invasions of their avatar's personal space (e.g., [12,21,22]), and that they use gaze avoidance to compensate for these invasions [31]. In addition, people avoid actions that could cause others to be uncomfortable (e.g., walking though another's avatar) [21].

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., [3]); however, other researchers reported this is not always the case [11,15]. 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 [15]. 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" [25].

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 [10]. Other remote collaboration systems have used varying degrees of realism in representations of people's arms [25,26,30]. 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 [27]. Prior research in this area focused on comparing direct and indirect input and the effects on performance [5], coordination and conflict [9,17,19], and spatial interference [24,29]. Some evidence suggests that indirect input changes natural collaborative behaviours such as territoriality [23], and leads to an increase in coordination problems [16].

Pinelle et al. [19] 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 [19].

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.

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.

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 1, 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 1, 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 [14]. Our setup ensured that all words were equally available to both people.

Figure 1 - 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 1), which is common for tabletop work [23]. Second, the haiku task is a mixed-focus collaborative task [4], 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.

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.

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 2). This behaviour was also observed in [9].

Figure 2 - 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 3 – Accommodation.

Territoriality

The second obvious behaviour that we observed was territoriality [23]. People immediately adopted the area in front of them as their personal territory. This organization is normal for tabletop work [23], 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.

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.

Visual Factors of Arm Embodiment Design

Previous work in embodiment design has shown that cursors provide only low levels of awareness in group work [19], and that arm embodiments (which maintain a visual link between the cursor and the user’s seated location) provide better awareness [17].

To determine which embodiments to study, we conducted small pilot studies of different digital embodiments based on Pinelle et al.’s exploratory study [19]. 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 [19], 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.

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.

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.

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.

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.

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 [6,7]. 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.

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., [9,23]) 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.

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

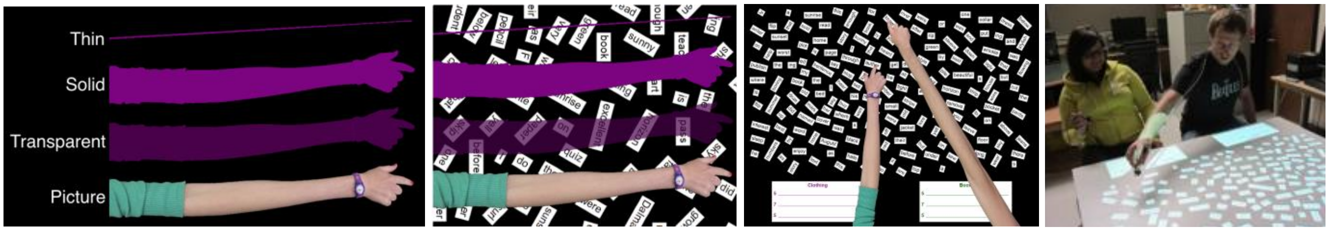

Figure 4. Left to right: the four arm embodiments, different levels of occlusion, Picture arms in the system, and Pen embodiments.

Visual inspection of the distribution of the objective counts indicate that parametric analyses were adequate; therefore we run repeated measures ANOVAs with $\alpha=0.05$. 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.

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.

Touch Avoidance

There was a main effect of embodiment on the number of crossing events ($F_{(4,116)}=30.02$, $p\approx0.000$, $\eta^2=0.53$). 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 5 shows that physicality was the dominant factor affecting touch avoidance as measured by crossings.

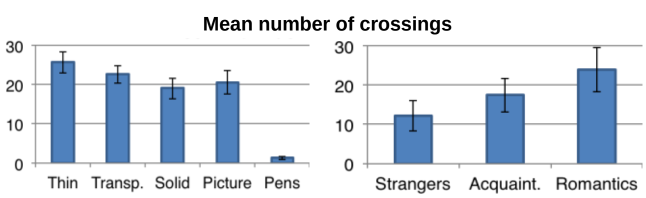

Figure 5 - Mean (±SE) number of crosses, by embodiment (left) and by relationship (right).

Although there was a main effect of relationship on the number of crosses ($F_{(2,27)}=4.45$ $p=0.021$, $\eta^2=0.25$), there was no interaction with embodiment ($F_{(8,108)}=1.27$, $p>0.05$, $\eta^2=0.09$). As Figure 5 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 6 (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 $\chi^2(2)<3.53$, $p>0.17$).

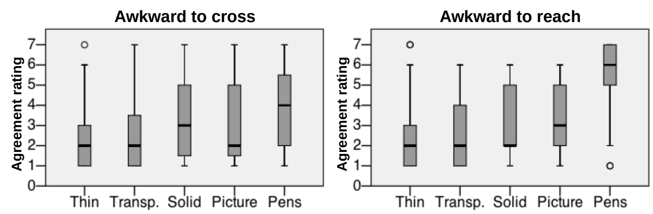

Figure 6 – Subjective feelings of awkwardness.

Territoriality

Figure 6 (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 7).

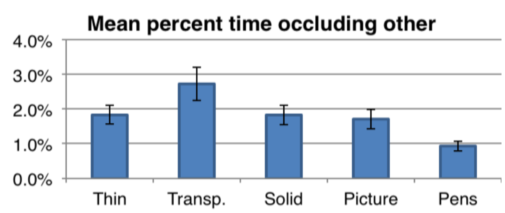

Figure 7 - Mean (±SE) percent time occluding other's haiku.

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

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)

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).

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 8). Friedman tests showed a main effect of embodiment on participants' feelings of being invaded by their partner ($\chi^2(58)=52.66$, $p\approx0.000$) and of invading their partner's space ($\chi^2(58)=63.69$, $p\approx0.000$). 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 $\chi^2(2)<2.35$, $p>0.309$).

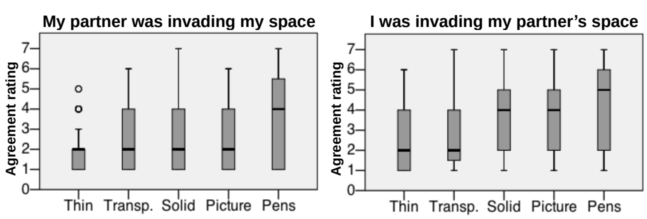

Figure 8 - Feelings of being invaded, and of invading partner.

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.

Awareness

Figure 9 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 ($\chi^2(58)=63.69$, $p\approx0.000$). As Table 1 shows, increases in size, physicality, and realism increased awareness, while transparency reduced awareness.

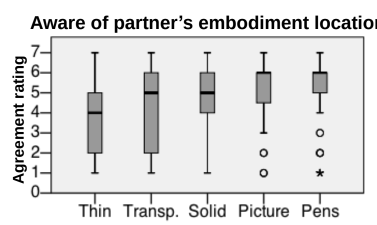

Figure 9 – Subjective awareness of partner's embodiment location.

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).

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 4). 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.

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.

Interpretation of Results

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., [12,21,22]). 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).

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., [5,23]), people's subjective ratings matched previous work (e.g., people are uncomfortable reaching to the other side of the table [9]).

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 9 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 6, 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.

Implications for Design

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

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.

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.

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.

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.

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.

Directions for Future Research

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).

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 [26]). It is not known whether the real-arm origin of a remote representation would change behaviour.

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.

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.

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