

Improving Digital Object Handoff Using the Space Above the Table

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ABSTRACT

Object handoff – that is, passing an object or tool to another person – is an extremely common activity in collaborative tabletop work. On digital tables, object handoff is typically accomplished by sliding them on the table surface – but surface-only interactions can be slow and error-prone, particularly when there are multiple people carrying out multiple handoffs. An alternative approach is to use the space *above* the table for object handoff; this provides more room to move, but requires above-surface tracking. We have developed two above-the-surface handoff techniques that use simple and inexpensive tracking: a force-field technique that uses a depth camera to determine hand proximity, and an electromagnetic-field technique called ElectroTouch that provides positive indication when people touch hands over the table. We compared the new techniques to three kinds of surface-only handoff (sliding, flicking, and surface-only Force-Fields). The study showed that the above-surface techniques significantly improved both speed and accuracy, and that ElectroTouch was the best technique overall. This work provides designers with practical new techniques for substantially increasing performance and interaction richness on digital tables.

Author Keywords

Digital tables, coordination, digital object handoff

ACM Classification Keywords

H.5.2. Information interfaces (e.g., HCI): User Interfaces

INTRODUCTION

When people interact around a table they often pass objects to others – this object transfer is called ‘handoff’, and occurs in many situations, such as when a desired object is out of reach but close to someone else, and when an object is within someone else’s personal territory [19]. Handoff can be initiated by the giver (“I think you need this”) or the receiver (“May I have that?”), and can be performed with little to no verbal coordination (e.g., exchanging cards during a card game, or passing tools during a work session).

Handoff is also common in digital tabletops, but has traditionally been limited to surface-based interactions where users transfer objects by sliding them across the table surface. However, surface-based handoff can be slow and difficult in some cases. First, handoff speed can be reduced because of *friction*, since users’ fingers must be in contact with the surface throughout the action [3]. Second, when there are several people working in the space, handoff can be impaired by *interference* – either occlusion of objects or collision with others’ hands and arms. Both of these factors lead to longer completion times, coordination difficulties, and increased errors, and since handoff is a common task in tabletop collaborative work, even small reductions in performance can have a substantial effect on the overall usability of the groupware system.

Researchers have proposed new on-the-surface techniques such as object flicking (e.g., [18]) or force-field transfer [14] that could improve on these problems, but there is very little evaluation of these techniques for object handoff. In addition, new types of table workspaces that are based on physical simulation (e.g., BumpTop [1]) make surface-based transfer techniques even more difficult.

An alternate approach for digital handoff is to use the space above the table rather than just the surface. This has the potential to solve both the friction and interference problems. At real world tables, people naturally and easily overcome many of the limitations of surface-based handoff by simply raising the location of the handoff. This approach can also work at digital tables, but it does present an additional challenge – the handoff action must now be tracked above the table. 3D tracking technologies have existed for some time, but are traditionally both expensive and immobile, limiting their use for practical deployment.

We have developed two new above-the-surface handoff techniques, both of which address the problems of friction and interference, and require only simple and inexpensive above-table tracking. Our first technique extends Force-Field transfer [14] to three-dimensional use, by using a Kinect depth camera to track hand location and proximity. Second, we developed ElectroTouch, which senses physical touches through changes to electromagnetic fields – allowing users to perform handoffs by touching hands over the table. ElectroTouch uses similar technology to the identity-touch sensors of the DiamondTouch table [4], but

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uses the sensory capability in a novel way – to determine person-to-person touches rather than touches on a table.

We tested the effectiveness of our new techniques by conducting a study that compared them to three existing surface-only handoff methods: traditional sliding, object flicking, and surface-based force-fields [14]. Thirty-two participants carried out repeated handoffs to a partner by themselves or with multiple people working at the same time. Our study provides five main results:

- the above-the-surface techniques resulted in the fastest completion times and the lowest error rates;
- ElectroTouch was significantly faster and significantly more accurate than any other technique;
- depth-based sensing is prone to error when there are four people at the table, but ElectroTouch is robust to increased group size;
- object flicking was the best of the surface techniques;
- participants rated both ElectroTouch and object flicking best for effort and preference.

This work makes four main contributions. First, we introduce two new techniques for object handoff at digital tables, and provide empirical evidence about the performance characteristics of those techniques as well as three traditional transfer techniques. Second, we demonstrate a new tracking technology – ElectroTouch – that can provide physical contact sensing easily and inexpensively. Third, we indicate some of the limitations of depth-camera-based sensing, and show that a low-bandwidth but high-confidence sensor can be better for tasks like object handoff that require conclusive feedback. Fourth, we show the value of object flicking for surface-only handoff when several people are working at the table. Overall, our work provides several new insights and new practical techniques that designers can use to improve collaborative work at tabletop groupware systems.

RELATED WORK

Digital Tabletops

A number of recent studies have explored ways in which digital tabletops can support co-located collaboration [2; 5; 17]. When people work together around a digital tabletop, their awareness of each other's actions is improved by the physicality of pointing, reaching, and using direct touch input [7]. Previous work has also shown that participants were more effective at a collaborative memory game using Stylus input rather than mouse input [13]. While direct touch input enhances certain aspects of co-located collaboration, it may lead to interference between multiple users' actions when many users are working at the same digital table.

Interference

Horneker et al. [11] define interference as, “unintended negative influence on each others' action.” In a two-person puzzle task Müller-Tomfelde and Schremmer [16] observed interference (physical collisions) when both people used

direct touch, but not when one or both people used mouse input. In a three-person collaborative task to design a floorplan, Horneker et al. [11] found that direct touch input had a positive influence on interaction, including unrequested assistance and non-verbal handoffs, but caused increased rates of interference and user effort. For example, re-negotiation was required between users when conflicts occurred during handoffs. They also note that forced turn taking, or pre-defined personal territories [22], “might interfere with fluent and dense interaction.”

Handoff

The transfer of artifacts between people is basic mechanism of collaboration. Such a transfer can be performed synchronously or asynchronously, and Pinelle et al. [17] defined these two interactions as *handoff* and *deposit*. While asynchronous depositing of artifacts is less prone to physical interference during collaborative work, previous work has suggested that synchronous handoff is important for digital tabletops both because it is faster, and because users are reluctant to deposit or retrieve artifacts in other's private areas on the tabletop [19].

In real world handoff, people can exchange objects with little negotiation, planning, or attentive effort. Huber et al. [12] used motion analysis of person-to-person handoffs to show that the basic mechanism of transferring an object exhibits a high degree of temporal and spatial coordination and is organized into three principal phases: reaction, manipulation, and finally post-handover recovery. Also, using motion analysis, Basili et al. [2] found that person-to-person handoff of a physical object is not well modeled by Fitts' law due to prehension, precision grip, and complexity of the motor task. They suggest that digital handoff techniques involving tangible objects may be slower than those based on pointing or aiming interaction. In a pointing-based handoff interaction, Sallnäs and Zhai [20] found that haptic feedback reduced handoff errors.

For collaborative work with many people, synchronous handoff of digital objects can be disrupted due to interference; therefore, interaction techniques are needed to support digital handoff while minimizing interference.

On-The-Tabletop Interaction Techniques

A number of techniques are commonly used for interacting with digital artifacts on a digital tabletop. Surface-only sliding is common on handheld tablets, but sliding objects on a large digital tabletop can be slow due to the friction of fingertips on glass surfaces [3]. Also, when working with multiple people, the active sliding artifacts can interfere with each other, due to occlusion and collisions from simultaneous reaches.

Flicking is another interaction that is widely used on tablets, typically to scroll through documents. It is more effective than sliding input for long distances because of the lack of friction. Reetz et al. [18] evaluated flicking for depositing

objects at long distances on tabletops. However, flicking has not been evaluated as a handoff mechanism.

Jun et al. [14] invented a novel handoff technique called surface-only Force-Field (SurfaceFF) in which objects are attracted to the reaching hand of the receiver. Their evaluation of a two-person task showed that SurfaceFF was faster than sliding-based handoff. In situations with more than two people, SurfaceFF may be more prone to negative interference, since there may be more than one reaching hand to which an object is attracted. Another potential drawback of the technique is that it requires sensing hardware to detect the receiver's hand above the surface in addition to the surface touch point. As a result, there is recent interest in using the space above digital tabletops for interaction in addition to touch on the surface.

Above-The-Tabletop Interaction Techniques

A number of recent studies have proposed new interaction techniques based on tracking gestures and motions above a digital tabletop, in addition to touch-based interaction on the surface. Genest and Gutwin [6] and Marquart et al. [15] have explored conceptual gestures for interaction above digital tabletops. High-bandwidth sensors such as the Kinect enable rich single-user interactions, by projecting shadows onto the surface [23], and by tracking hands above the surface [10]. Less work has been reported for above the table gestures for interactions with multiple users.

Robustness is a critical factor for multi-person interactions such as handoff. Interactions that fail to register, or that register inadvertently, can be highly disruptive to fluid person-to-person interactions. Direct-touch sensing between users shows promise as a low-bandwidth but highly robust solution for sensing interactions between users.

Direct-Touch Interaction Techniques

Direct touch sensing was first demonstrated in the DiamondTouch table [4]. It used capacitance-based touch sensing to identify the touch input of specific users in a multi-user digital tabletop. Touché [21] extended capacitance-based touch sensing for use with everyday objects of any variety. Skinput [8] is a direct-touch system that uses acoustic transmission to identify the location of taps on one's own body. While direct touch sensing has been used to interact with tabletops, real-world objects, and one's own body, it has not been adopted for sensing touch between people. As described below, we extend previous work in the development of a new direct-touch system – ElectroTouch.

FORMATIVE STUDY OF HANDOFF ABOVE THE TABLE

To better understand how people exchange objects in the real and digital worlds, we carried out three small observational studies. In the first study, we created a game that required the exchange of different types of real-world objects. From this, we made two observations. First, people are able to give and receive a wide variety of objects that require different hand positions without expending much

mental effort. Second, people use a wide array of hand gestures to give and receive even the same object. These observations revealed that a digital object handoff system must be very flexible (able to handle a variety of gestures), and natural, so as to not create an unacceptable increase in effort or mental demand.

In the second study, we examined how people would transfer digital objects if they were not confined to the surface of the table. We created a system that had a variety of digital objects and asked people to exchange those objects in the space above the table in any manner that felt natural to them. In this Wizard-of-Oz system, we had the experimenter manually trigger events to give the illusion of a fully working system. We observed people using a variety of hand positions when exchanging objects as they maintained mental models of the digital objects once they were removed from the surface. We additionally observed that individuals would often make physical contact when exchanging the intangible objects, and that the actions for picking up and putting down digital objects frequently involved touching the surface of the table (i.e., tap-to-pick-up and tap-to-put-down). From these observations, we concluded that physical contact between people may be useful when exchanging digital objects in the space above the table, and that touching the surface of the table would be an appropriate indicator for picking up and putting down the digital object.

In a final study, we examined how people exchanged digital objects if they were required to do so quickly and repeatedly without any visual representation. We again observed that physical contact was very frequently used as a transfer mechanism: for example, people bumped fists or slapped hands in the space over the table. We also noted that the slapping-hand technique was extremely fast, that people did not seem to mind touching in order to complete the handoff, and that a visible representation of the object being transferred was not needed when physical touch was used. From this exploratory experiment, we concluded that physical contact could be a useful mechanism for carrying out above-the-table handoff.

ABOVE-THE-SURFACE HANDOFF TECHNIQUES

We developed two new techniques to enable handoff above the table surface: a force-field technique, and ElectroTouch. Both use the tap-to-pick-up and tap-to-put-down mechanisms determined by the formative study (see above), but differ in the way that the transfer action is achieved.

Above-the-surface Force-Field (AboveFF)

This technique, first introduced (without implementation details or evaluation) by Jun et al. [14], extends the surface-based Force-Field such that both the giver and the receiver use the space above the table for the handoff. Jun et al. implemented a version of AboveFF using pen input, requiring users to press a button to exchange objects. Our AboveFF technique uses a Microsoft Kinect to sense hand locations and proximity by performing depth-image edge

detection (ignoring the table surface) to capture only the participants' arms. This makes our implementation more practical (via inexpensive sensing equipment) and more natural (i.e., no trigger is required). The detected arms are assigned to participants using anchor points set in Kinect (3D) space. The furthest point from the user's body (i.e., the point furthest from the anchor point) is classified as the 3D hand location. A handoff occurs if the distance between two hands is 20 cm or less in 3D space (approximately 1.5 times the diameter of the digital object). Note that the use of 3D distance allows one person to cross above or below another's arm without unintentionally triggering a handoff. Additionally, hysteresis is applied so that additional transfers do not occur until the hands are more than 13 cm apart for at least one frame.

The Kinect depth camera is a high-bandwidth sensor that provides a large amount of information about the scene; however, this information can complicate the process of determining handoff. For example, vision algorithms are needed to filter out objects that intrude into the space of interest (e.g., people's heads), to determine the likely body location of each participant, and to determine arm identities. In addition, arms can block the depth camera's view, preventing good sensing of a proximity event (e.g., if the event happens below another person's arm).

ElectroTouch

ElectroTouch provides an interaction technique and an accompanying hardware sensor for sensing handoffs that use physical touch above the table. The sensing system is much lower bandwidth than the Kinect sensor, but provides a much more robust indication of person-to-person touches.

ElectroTouch detects small electrical signals flowing through users' bodies when they make physical contact. Users stand on wire 'antenna pads' to create a capacitive connection; these pads are about 0.5×0.5 m, and have two sets of conductors arranged on a dielectric base: one set for transmitting and one for receiving. The wires from the pads are connected to line inputs and outputs of a common computer sound card using a shielded electrical cable. The computer continuously sends a different frequency sinusoidal signal, in the range of 16–19 kHz, to each pad

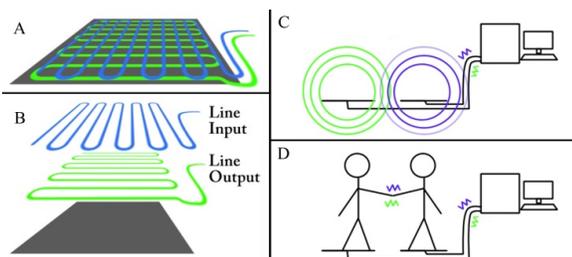


Figure 1: The ElectroTouch system built using cost-effective pads (A) connect to the line input/output (B) of a soundcard transmit EM waves (C) which are transmitted through a person's body and can be detected when two people touch (D).

and senses the signal coming back. Normally, the pads will send back the same signal that they receive. However, when two users make a physical contact, they will also establish a weak electrical circuit connecting the corresponding pads. In this case the sound card receives more than one signal from the pad. The system uses a Fast Fourier Transform to determine if the signal for a touch is above a threshold; these events are interpreted as touches between the users standing on the corresponding pairs of pads.

The system uses only the voltage produced by a standard sound card, and the electromagnetic exposure is comparable to that experienced when wearing wired headphones (and is far below that of a mobile phone). The underlying technology in ElectroTouch was seen in the DiamondTouch table [4], where it was used as an identity-based touch mechanism on a tabletop display. ElectroTouch differs from this work in that it is used for person-to-person touch sensing, and in our use of simple and inexpensive components (the system can be made for a few dollars with wire, cardboard, and a standard multi-port sound card).

With this touch-sensing technology in place, the ElectroTouch handoff technique is simple. Users pick up an object by tapping it on the table, touch hands above the table, and put the object back down by tapping again.

EVALUATION OF ABOVE-THE-SURFACE TECHNIQUES

We conducted a user study to compare the performance of surface-only handoff techniques (Slide, surface-only Force-Field, Flick) to above-the-surface Force-Field and ElectroTouch. We were interested in both time and accuracy: the time needed to carry out handoff actions, and the number of times a handoff went to the wrong person.

Apparatus and Setup

The study was carried out on a custom-built table that uses a 60" 1920x1028 LCD TV as its surface. A G3 PQLabs overlay frame provides multi-touch sensing, which caused a latency of 85ms between touch and display update. For tracking of arm locations for the Force-Field techniques, a Microsoft Kinect sensor was placed 120 cm above the table,

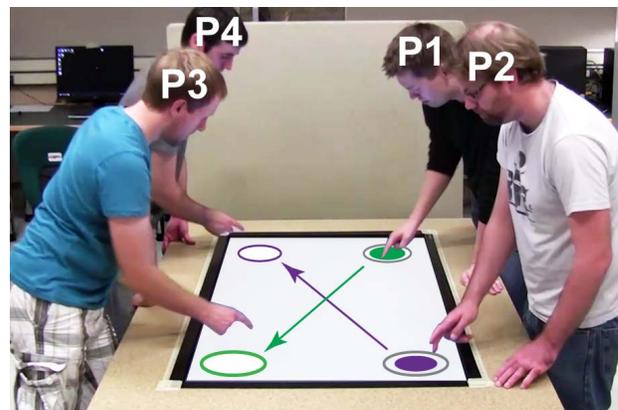


Figure 2: Participant locations and study interface. Handoffs always occurred diagonally across the table.

pointing down at the table surface. Four ElectroTouch pads, one for each participant, were situated around the table (see Figure 1 A). The study used custom software built in C++, and ran on a Core i5 Windows PC. Participants were located as shown in Figure 2 and saw a simple interface with coloured transfer objects and circular drop zones (Figure 2, without the arrows).

Handoff Techniques

We implemented five techniques for the study: three surface-only techniques, and two above-surface techniques.

Slide. The Slide technique is performed as typically seen in many touch-based systems. Object exchange can be performed in two ways. The receiver can touch and drag the object to take possession while it is still being dragged by the original holder. Alternately, the giver can release the object and thereafter have the receiver take it.



Figure 3: Slide technique

Flick. Flicking is similar to sliding except that objects can continue moving after being released. Velocity and direction are calculated using the three previous positions for the object before release. Friction is applied to the object such that it loses 20 pixels per second of velocity. If an object collides with a table edge, it bounces off and loses 20% of its velocity in the bounce direction. The values for friction were chosen through extensive informal testing to ensure this technique performed as well as possible. Exchange occurs when the receiver touches and drags the object at any point during its travel.



Figure 4: Flick technique

Surface-only Force-Field (SurfaceFF). This technique is similar to sliding, but contains a force-field effect in which the object drifts towards any other hand that is within a 13 cm proximity (based on Jun et al. [14] and refined through pilot studies). The implementation of the Force-Field is similar to that described above for AboveFF, using the Kinect to track receivers' hands and calculate a proximity matrix. The force-field effect is similarly applied to all hands in the space that are within the 13 cm threshold.



Figure 5: Surface-only Force-Field technique

Above-the-surface Force-Field (AboveFF). This technique was implemented as described in the design section above;

in addition, the system provided coloured indicators to show who was 'holding' the object that had been picked up.



Figure 6: Above-the-surface Force-Field

ElectroTouch. ElectroTouch was implemented as described above (participants removed their shoes while standing on the antenna pads to ensure a good capacitive connection, but this is not a requirement for the technique). The 'picked-up' indicators were also used as with AboveFF. For both above-the-surface techniques, the 85ms latency of the display was an insignificant factor since visual feedback was not a requirement for a transfer to take place.



Figure 7: ElectroTouch technique

Participants

We recruited eight groups of four participants (mean age 25.9, 15 male, 29 right-handed) from the local community. 23 of the participants had never used a digital tabletop, while 20 reported frequent use of other touch devices. Each group of four participants was randomly divided into pairs.

Both members in a pair acted as sender and receiver an equal number of times during the study and performed both tasks from the left and right side of the table. Participants were located at the corners of the table during the study and were required to use only their right hand for all tasks.

Task

We chose a task that was representative of the basic interaction underlying natural handoffs. People commonly execute handoffs without switching attention. This is particularly true for the person who does not initiate the handoff. We define the basic mechanism of handoff as a largely autonomous interaction involving four atomic actions: pick-up, give-to, take-from, place-down. This basic handoff mechanism underlies a wide range of possible handoff situations. Any disruption to the basic handoff mechanism in a digital context is likely to have a substantial impact on handoff performance and acceptance of the technology enabling handoff. Disruptions to the basic handoff mechanism are also likely to complicate other situation-specific handoff tasks, such as determining which object to pick up, deciding who to give the object to, and other decision-making processes.

In the study, pairs carried out repeated handoff actions as shown in Figure 2. In each task, one person picked up or selected the 13 cm-diameter coloured object on the table, and transferred it to their partner located diagonally across the table; the partner would then put the object into a circular drop zone 14 cm in diameter (sizes based on Jun et

al.'s work [14] and refined through pilot studies). Tasks were successful if the receiver released his or her finger anywhere inside the target zone while dragging or putting down the object. If an object was left untouched on the table (other than in the start state) for more than one second, the trial was reset.

Procedure

Participants carried out trials with all handoff techniques, in both one- and two-pair conditions. Each session was split into two one-pair blocks and one two-pair block. A one-pair block consisted of two participants performing a series of object transfers for each of the five techniques, whereas the two-pair block involved four participants completing object transfers simultaneously. To encourage participants to perform quickly and accurately, a small element of competition was added: the system displayed the scores of the participants at the end of each series. Participants were given the impression that it was a timed event even though the session ended when the players (the losing team in the two-pair case) reached the minimum number of object transfers (ensuring we had enough trials for each pair). The object transfers always occurred from corner to corner (e.g., from P1 to P3 or P2 to P4 in Figure 2). For each technique, a series of at least 10 training trials were performed in both directions (e.g. participant A as giver, then participant A as receiver) for a total of a minimum of 20 training trials. This was followed by a minimum of 12 actual trials in each direction (participant A as giver, then participant A as receiver) from both ends of the table (left position and right position) for a total of 48 actual trials. After each technique, each participant completed a NASA Task Load Index (TLX) survey [9]. When a pair finished the one-pair block (all five techniques), and again after finishing the two-pair block, they individually filled out a subjective-response questionnaire, ranking the five techniques on scales of naturalness, preference, and learnability. Once all trials were complete, participants stated overall preferences for the techniques in the one- and two-pair scenarios.

Each participant performed a minimum of 680 trials (20 training + 48 transfers) \times 5 techniques \times 2 blocks/participant. Order of technique was counterbalanced using a Latin square design.

Study Design

We used a repeated-measures factorial design with two within-participants factors: *Handoff technique* (Slide, Surface-Force-Field, Flick, Above-Force-Field, and ElectroTouch) and *Number of pairs* (one or two pairs).

Two dependent variables were recorded by the system: *mean object transfer time* (for all conditions) and *accidental handoff rate* (for two-pair conditions).

- Mean object transfer time was calculated by dividing the total elapsed time between each consecutive pair of successful deposits by the total number of successful deposits. Measuring elapsed time between deposits is crucial in the two-pair conditions, since the sender

commonly waited to pick up the object in order to avoid a collision with the other pair. These pre-pickup delays are indicative of increased coordination effort (turn-taking), reduced fluidity of handoff, and reduced handoff throughput. As this measure utilizes successful deposits, it incorporates time added due to errors.

- Accidental handoff rate is used only for the two-pair conditions, and is defined as the total number of times the object was transferred to the wrong person, divided by the total number of successful deposits.

We used RM-ANOVA to test for the effects of handoff technique and number of pairs on time per handoff and accidental handoff rate, and to look for interactions. We used planned Bonferonni-corrected post-hoc *t*-tests to analyze interactions between the surface-based techniques, between the above-the-surface techniques, and between the best surface-only and the best above-the-surface techniques.

Subjective analysis used NASA TLX ratings from each participant for each technique (in the one-pair and two-pair conditions), as well as participant rankings of subjective preference, naturalness, and learnability for each technique in the one and two-pair conditions. We report summary statistics of these findings below.

Results

Handoff time

Mean object transfer times with outliers removed (outside 3 standard deviations, 156 of 8040 samples removed) for each technique and group size are shown in Figure 8. RM-ANOVA found main effects of *Handoff technique* ($F_{4,28} = 261.96, p < .001$) and *Number of pairs* ($F_{1,7} = 18.62, p < .001$), as well as an interaction ($F_{4,70} = 86.11, p < .001$).

Planned post-hoc *t*-tests (Bonferroni-corrected, $\alpha = 0.003$) indicated that Slide and Flick were not significantly different in either group size (one-pair $p = 0.16$, two-pair $p = .06$), but that Flick was faster than SurfaceFF in both group sizes ($p < .001$) and Slide was faster than SurfaceFF for two-pairs ($p < .001$).

For above-the-surface techniques, ElectroTouch was faster than AboveFF (both $p < .001$), and ElectroTouch was also faster than the fastest surface-based technique (i.e., Flick) for both one and two-pairs (both $p < .001$).

Comparing the techniques within the group sizes, there were no significant differences for Slide ($p < .05$) or SurfaceFF ($p > .05$). Flick ($p < .001$) and ElectroTouch ($p < .001$) were faster in the two-pair condition, and AboveFF was slower ($p < .001$).

In summary, we found that ElectroTouch was the fastest technique for both one and two-pair conditions. AboveFF was the second-fastest technique for one pair, but the slowest technique for two pairs. All of the surface-only techniques showed similar mean transfer times, with Slide and Flick being slightly faster than SurfaceFF.

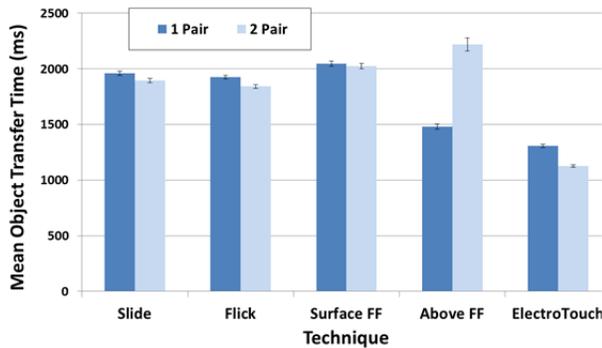


Figure 8. Mean object transfer time (ms) \pm s.e. for each technique for one and two pairs.

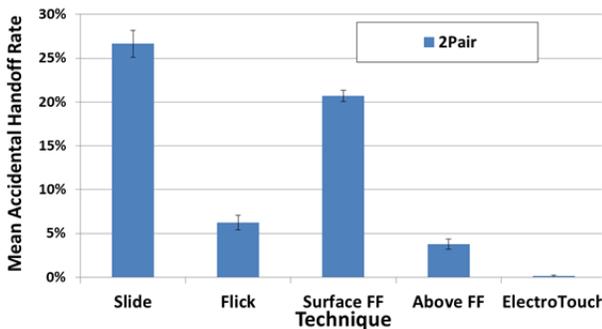


Figure 9. Mean accidental handoff rate (%) \pm s.e. for each technique (two-pair condition).

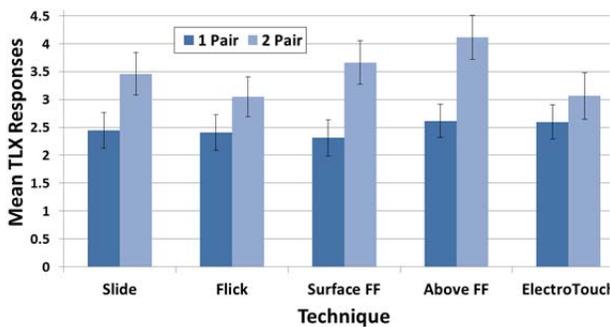


Figure 10. Mean TLX responses (\pm s.e.) for all TLX columns and participants per technique for one and two pairs.

Accidental handoff rate

Mean accidental handoff rates for each technique are shown in Figure 9. Using RM-ANOVA, we found a main effect of *Handoff technique* ($F_{4,28} = 199.33, p < .001$). Planned post-hoc *t*-tests (Bonferroni-corrected $\alpha = 0.002$), showed significant differences between all techniques except Flick and AboveFF ($p = .03$). These results show that ElectroTouch has the lowest accidental handoff rate.

TLX responses

Each participant completed a NASA TLX task load self-report when they finished each technique in the one and two-pair conditions. We averaged all TLX responses for each technique for all participants and present these results in Figure 10. RM-ANOVA found a significant effect for

number of pairs ($F_{1,7} = 19.95, p < .001$), and a post-hoc Tukey HSD test showed that above-the-surface Force-Field was rated as having a higher average load than Slide, Flick, and surface-only Force-Field (all $p < .05$). Visually inspecting Figure 10, it is evident that participants rated the two-pair condition as higher demand for each technique.

Subjective responses

We also had participants rank each technique in terms of learnability, naturalness and preference. These results are presented in Figure 11 and show that people generally favoured Flick and ElectroTouch in both group sizes. Participants' overall subjective rankings of which techniques worked best are shown in Figure 12.

DISCUSSION

Summary of Results

Our study showed five main findings:

1. Above-the-surface handoff techniques are faster than surface-only techniques;
2. ElectroTouch was better than any other technique both for speed and accuracy;
3. Flick was the best of the surface-only techniques;
4. There was no substantial work load increase in using above-the-surface techniques based on TLX surveys;
5. There was no substantial difference in the preference, learnability, and naturalness of the various techniques.

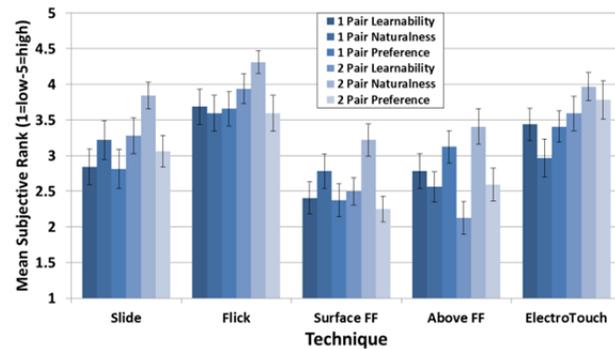


Figure 11. Mean subjective rankings (\pm s.e.) for each technique for one and two pairs (1=low, 5=high).

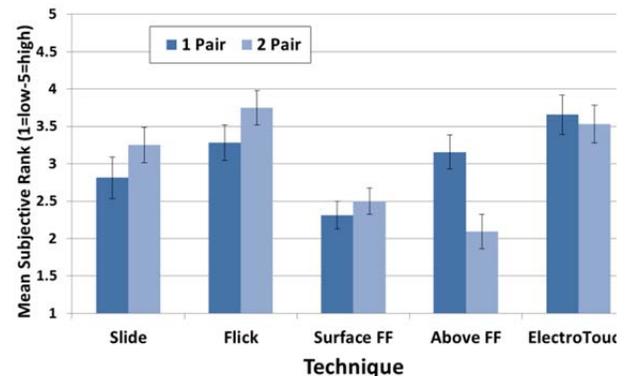


Figure 12. Mean subjective rankings (\pm s.e.) for each technique of how well each technique worked for one and two pairs.

In the following sections, we interpret and explain these results, discuss how they can be generalized to other contexts, and indicate future possibilities for above-the-surface interaction techniques.

Explanation of Results

Why were above-the-surface techniques better?

Our above-the-surface handoff techniques had shorter completion times and reduced errors compared to surface-only techniques. We believe the performance gains for the above-the-surface technique are due to these techniques' success in solving the two main problems of surface-based handoff – friction and interference. Friction was a noticeable problem in the study, and a main cause of poor performance. This is a significant concern, because object transfer often happens in an outward direction; this requires that people carry out a 'pushing' action with their finger, which incurs much higher friction than a 'dragging' action [3]. Similarly, interference was clearly a common problem for the surface techniques in the two-pair condition: there were many situations where all four hands were in close proximity to one another, forcing people to wait and causing accidental handoffs. In contrast, the above-the-surface techniques allowed participants to move quickly to their chosen handoff location in 3D space, and to choose that location so that there was no interference from the other pair.

Why was ElectroTouch best overall?

ElectroTouch performed well for several reasons. First, accidental handoffs rarely occurred – the positive tactile feedback that participants received when transferring an object (via touching their partner's hand) made it much easier for them to carry out the handoff, and much easier to determine that a handoff had happened correctly. Also, the touch sensor was sufficiently robust that people were confident that their touches would be registered. Second, tactile feedback also allowed participants to speed up their transfers: it allowed people to focus on the task of pick-up or put-down rather than on the exchange itself – touch notified the participant that the exchange had taken place and that they could proceed with the next stage of the transfer. Third, ElectroTouch allowed for a wide variety of hand postures and methods for touching, such as the fist bump or the hand slap. This provided users with considerable flexibility when exchanging digital objects.

Why was Flicking the best surface-only technique?

Flick was the best-performing and most-preferred of all the surface-only techniques. It was not remarkably faster than the other surface-only techniques, but it had substantially fewer errors. The reason for the low accidental-transfer rate arises from the technique's design – people were able to stay out of each others' way by flicking the object from their own side of the table. We did notice other types of errors, however – in particular, when users missed 'catching' the flicked object (suggesting that although the handoff speed of Flick could be increased with higher-

velocity motion, this could cause other difficulties for the technique). Participants also enjoyed the Flick technique: we received several positive comments from participants, such as "Flick is the most fun and natural", and "Flick works very well because the [objects] don't get in the way". We also observed that people tended to play with Flick much more than the other surface-based techniques.

Which technique requires the most effort?

The NASA-TLX surveys revealed no substantial difference in the workload for all of the techniques with the exception of temporal demand. The TLX results in the one-pair condition showed an increase in temporal demand for the above-the-surface techniques. Participants were required to complete the same number of trials with each technique. We expect that the high TLX score for temporal demand with above-the-surface techniques may be related to the high transfer rate achieved with those techniques, i.e. participants completed the task faster and therefore they may have perceived that the task was more temporally demanding. Apart from this anomaly, there are few differences between the techniques, suggesting that the fastest and least error-prone technique should be used.

Main types of errors for each technique

Although the most important kind of error for a transfer technique is whether the object is given to the correct person, there are other error types that we noted that differed between the techniques.

Slide suffered from accidental contact with the surface with other fingers or wrists, causing the object to stop part way through the transfer. Additionally, taking the object from the giver would occasionally fail if the participant placed their finger at the same approximate location as their partners, or if other parts of the hand touched the surface first outside the boundary of the digital object.

Flick performed well, except when the sender 'threw' the object too fast, which caused the receiver to miss the 'catch'. In addition, the algorithm used to calculate exit velocity uses the previous three locations, so flicking is not as responsive to quick motions as it is in the real world.

Surface-only Force-Field performed reasonably well in the one-pair scenario. However, in the two-pair trials, this technique suffered from interference where objects drifted toward the wrong participant as everyone reached in towards the center of the table. The Force-Field interference resulted in participants ignoring the force fields almost entirely and treating the technique similar to Slide.

Above-the-surface Force-Field encountered errors due to the occlusion of participants hands (i.e., higher-up arms blocking the Kinect camera), which sometimes led to handoffs to the wrong participant. This type of error was avoidable with correct coordination between participants, but required more practice and understanding.

ElectroTouch encountered the least errors of any technique. Accidental handoffs did occur, but were rare. People are quite good at avoiding accidental touches and our results show that this type of error did not occur frequently. We did observe participants attempting to pick up the object too early in the process, and placing the object down in the incorrect location. We attribute these errors to the high transfer rate achieved by participants using ElectroTouch.

Generalizability

Both ElectroTouch and above-the-surface Force-Field are easy and cheap to implement both in terms of software and hardware. Therefore, adding these capabilities to any touch table or other large display device is relatively straightforward. The ElectroTouch pads are flexible and could be placed on any surface where a person may be sitting or standing. The Kinect is a relatively cheap device that can be mounted above or in front of the interaction surface, providing depth information in order to determine the proximity of the hands. While both techniques are practical, our study demonstrates that the direct touch feedback provided by ElectroTouch is an effective cue for handoff without tangible objects.

Our findings for the AboveFF technique (both the speed and the high error rate) will likely generalize to other implementations and sensors as well. The Kinect is a low-resolution device compared to other sensors (such as a Vicon tracker), but the Kinect was sufficient in our implementation of AboveFF to provide reliable arm tracking and an effective force-field mechanism. The main problem with the AboveFF technique was occlusion, and this issue will arise even with much more expensive sensors which also rely on line-of-sight cameras (multiple cameras will reduce but not remove occlusion).

In terms of the generalizability of the techniques to other tasks and table scenarios, one obvious issue is the effective range of the techniques. ElectroTouch, sliding, and the Force-Field techniques all rely on people being able to bring their hands into touch or close proximity; this means that on large tables, it will be difficult or impossible to transfer objects with these methods. The Flick technique, however, is not overly affected by distance (depending on the amount of virtual friction), and could easily be used to transfer objects over larger distances.

It is also clear that the handoff techniques used here are not mutually exclusive, and that the best way to improve handoff performance in real-world situations is likely to implement multiple techniques that can be used in different work contexts. For example, Slide and Flick can easily be merged into one technique, and ElectroTouch can work well with surface based techniques – sliding actions can be easily differentiated from pickup actions, and so the system would be able to support both kinds of interaction.

Limitations

Our system provided a visual representation of who was ‘holding’ an object that had been picked up from the table surface (a small, semi-transparent version of the object near the person who possessed the object). This visual representation is an important consideration for the practical application of above-the-surface handoff. This visualization occasionally led to confusion, and will need to be carefully designed in future applications. In general, any system that uses virtual pick-up from the table surface needs to provide feedback about the state of that activity; there are several possibilities that would work well for different applications (e.g., a marker object as used here, or a dynamic arm ‘shadow’ cast on the table and holding a semi-transparent version of the object).

The Kinect subsystem presented a number of technical limitations, as discussed above, including resolution, frame rate and occlusion. These drawbacks reduced the robustness of the system and caused both unintended handoffs and intended-handoff failures. A number of these issues are not easily resolved, even with other types of sensors, such as infrared trackers, due to the occlusion that occurs with multiple people in a small workspace, such as around a tabletop. In our assessment, if systems to support collaborative interactions are to remain trackerless and not rely on touch, then a novel sensing technology is required. These problems with the depth-based sensor argue for systems like ElectroTouch that provide robust sensing of a very particular event, rather than a general-purpose sensor like the Kinect that provides a great deal of information that must be processed in order to be useful. In the case of object transfer, our low-bandwidth but robust sensor proved to be the better approach.

ElectroTouch is limited by the requirement that people stand on the antenna pads, reducing their ability to walk around the table. However, the technology underlying ElectroTouch is not tied to these fixed pads, and could be made mobile to allow user movement. For example, a set of smaller pads could be joined together to cover a much larger area, allowing user movement anywhere around the table. Also, a mobile version of the device could be produced using a smartphone and a smaller antenna, where the smartphone processes the electromagnetic signals and sends touch events to the table computer.

Finally, the type of errors varied across technique, which made identifying and comparing errors difficult in practice. Future studies would benefit from having these error types categorized and quantitatively assessed.

CONCLUSION AND FUTURE WORK

Current handoff techniques over digital tabletops are restricted to surface-only gestures. When multiple people need to exchange digital objects, friction and interference can cause slow performance and frustration. To address the problems of surface-based handoff, we developed two new above-the-table handoff techniques. We evaluated these

techniques and found them to be significantly faster and less error-prone. One technique in particular that senses actual person-to-person touch in order to carry out the handoff – ElectroTouch – was the best of all techniques, with fast performance and very few accidental transfers.

In the future, we plan to extend our results in several ways. First, we are building extended versions of the ElectroTouch technology as described above. Second, we will refine AboveFF to utilize an adaptive force-field that shrinks as the number of arms in the above-table space grows, to reduce the frequency of handoff errors. Third, we will develop combinations of the techniques and test them in a variety of large and small tabletop environments.

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