A Comparison of Techniques for Cross-Device Interaction from Mobile Devices to Large Displays

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ABSTRACT

In recent years there has been an increasing interest in cross-device interaction research involving mobile computing. We contribute to this research with a comparative study of four interaction techniques for moving information from a mobile device to a large display. The four techniques (*Pinch, Swipe, Throw,* and *Tilt*) were compared through a laboratory experiment with 53 participants, measuring their effectiveness, efficiency and error size. Findings from the experiment revealed that the *Swipe* technique performed best on all measures. In terms of effectiveness, the *Tilt* technique performed the worst, and especially so with small targets. In terms of efficiency and error size, the *Pinch* technique was the slowest and also the most imprecise. We also found that target size mattered considerably for all techniques, confirming previous research. Based on our findings we discuss why the individual techniques performed as observed, and discuss implications for using mobile devices in cross-device interaction design.

Categories and Subject Descriptors

H5.2. User Interfaces: Interaction styles.

General Terms

Measurement, Design, Experimentation, Human Factors.

Keywords

Cross-Device Interaction; mobile devices; large displays; Interaction Techniques; Kinect, Mid-air Gestures.

1. INTRODUCTION

As the number of interactive computing devices around us continues to grow, there is an increasing need for research investigating how to best facilitate people's interaction using their mobile devices, with other devices, in concert. This has led to a growth in human-computer interaction research on "cross-device" and "digital ecosystem" interaction. This research has investigated how cross-device interaction can be applied in practice (e.g.[9]), how it is used and understood by users, (e.g. [17]), how it can be modeled conceptually (e.g. [22]), how it can be implemented (e.g. [6]), and how it can be supported by concrete interaction techniques (e.g. [12]). In terms of the latter, the opportunities and challenges of cross-device interaction using mobile devices, in particular, have inspired a renewed focus on new interaction techniques that go beyond traditional point-and-click type interactions. Instead, researchers have explored new input technologies, such as the accelerometers in smartphones [5], radio modules [12], and the use of mobile phones as styluses on touch tables [19]. The use of these interactions for mobile devices allows people to operate several devices in parallel with their personal device, and to move information and activities easily from one device to another. This has been investigated for many different cross-device combinations, for example, phones and watches (e.g. [5]), mobile devices of different sizes (e.g. [21]), phones and tabletops (e.g. [20]) and phones and large displays (e.g. [3]).

Although previous investigations cover different aspects and qualities of various cross-device interaction techniques, there are limited investigations and empirical studies specifically comparing techniques used to transfer data from a personal mobile device to a large display. A comparative study focussing on the strengths and weaknesses of different techniques in terms of their effectiveness, efficiency and accuracy would give interaction designers valuable knowledge about performance of these techniques, useful for informing the design of cross-device systems. These systems, such as large public displays that encourage passers-by to interact with them using their personal mobile devices, are becoming more prevalent, for example, in public squares and building foyers. This therefore is driving our interest in learning more about alternative interaction techniques for such systems. It is important to evaluate techniques that transition interaction from one device to another.

In the work presented here, we have specifically investigated different gesture-based interaction techniques for facilitating interaction that begins on a handheld mobile device, and continues on a large display. Within this scope we have investigated the relative strengths and weaknesses of different techniques making use of combinations of sensors in the phone and sensors mounted under the large display. We have done this through an experiment with 53 participants, measuring the respective effectiveness, efficiency and error size of four existing interaction techniques. We begin this paper by providing an overview of related work in cross-device interaction. We then present our four interaction techniques, *Pinch*, *Swipe*, *Throw*, and *Tilt*, and the experiment comparing their use for cross-device interaction from a mobile device to a large display. We then report our findings, and discuss their implications for the design of cross-device interaction.

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2. RELATED WORK

The idea of cross-device interaction can be traced back to the work of Rekimoto [16] who envisioned what was called "multiple-computer user interfaces", and argued that dedicated interaction techniques would be needed to overcome the boundaries among devices in multiple-computer environments. Since then, a large amount of research has been conducted following this line of thinking, and investigating, among others, how cross-device interaction can be applied in practice, how it is used and understood by users, how it can be modeled conceptually, how it can be implemented, and how it can be supported by concrete interaction techniques. While exploring the notion of ubiquitous computing, Rekimoto [15] devised the pick-and-drop technique that operates between multiple devices allowing users to "pick up" an object on a display and "drop it" on another display as if manipulating a physical object. This use of natural gestures has continued as a useful analogy for the design of interaction techniques that transfer data from one device to another.

One of the earliest operational cross-device applications, presented by Myers, in 2001 [13], was the Pebbles Slide Show Commander, which utilized Personal Device Assistants (PDAs) to control a PowerPoint presentation running on a separate computer or laptop. Participants could remotely initiate a move between slides by enacting it on the PDA. Additionally, annotations made on the PDA screen would be shown on the presentation screen for the audience. This was an early investigation of the use of personal mobile devices to interact with fixed displays.

In more recent research, Boring et al. [2] built a cross-device application to explore the implications of different approaches to transferring data from a large public display onto a mobile device. One approach was to use the camera on the smartphone. The user simply had to take a picture of the information they wanted to transfer to their phone. A content server then visually analyzed the picture to determine which content the user was interested in and then sent that content to their phone. In this study, Boring et al. confirmed the need for enabling data exchange between mobile devices and public displays. In a follow up study, Boring et al. [3] compared three different interaction techniques, Move, Tilt and Scroll, to continuously control a pointer on a large screen using a mobile device. They found that Move and Tilt enabled a faster selection time compared to Scroll, but at the cost of higher error rates.

While Boring et al. [3] focused on passing data between public and personal displays, research by Nielsen et al. [14] explored techniques for aligning multiple mobile devices of varying sizes to present common content. Their collaboration surface combines multiple devices, which then appear as one larger collaborative workspace. Two or more mobile devices aligned along an edge can be "pinched" together to show a single image, which adjusts seamlessly across all screens as additional devices are added or taken away. In this way, the interaction area can expand or contract depending on the number and size of devices that make up the surface. This pinching motion, like the pick-and-drop motion proposed by Rekimoto [15], indicates the successful application of a technique that uses a natural motion of putting things together, to achieve the digital equivalent.

Also creating a common workspace, Schmidt et al. [19] proposed a cross-device interaction style for mobiles and surfaces where multiple phones could be used to interact with a digital surface. They considered the role of natural user interaction when using multiple devices and stated that "natural forms of interaction have evolved for personal devices that we carry with us (mobiles) as well as for shared interactive displays around us (surfaces) but interaction across the two remains cumbersome in practice". To make the interaction more natural, they proposed the use of mobile phones as tangible input devices on the surface in a stylus like fashion. This indicates the need for investigation into identifying the kinds of interactions that might work more effectively between mobiles and surfaces.

Marquardt et al. [12] and Bragdon et al. [4] also investigated cross-device interaction in relation to natural user interactions. Marquardt et al. studied cross-device interaction on tablets using natural modes of communication, involving spatial information through proxemics. Based on the constructs of f-formation, micro-mobility, and co-present collaboration, they built a prototype for document transfer that supports fluid and minimally disruptive interaction. Bragdon et al. proposed *Code Space*, a system using a combination of mid-air gestures and touch to support co-located, small group developer meetings. Their interaction techniques used a combination of in-air pointing and touching with precise gestures and mobile devices. This allowed a group of users to interact, using air and touch gestures to control and share items across multiple personal devices such as smartphones and laptops to a large multi-touch display. Although this research explores different interaction options using mobile devices and a shared display, they do so in a qualitative way, with a pilot user study collecting user feedback on the various techniques used in *Code Space*. In fact, in looking at future work, the authors themselves support the value of a quantitative study of these techniques to inform further knowledge about cross-device interactions.

Skov et al. [21] compared six different cross-device interaction techniques in a quantitative study both in the lab, and in the field. They used the case of card playing to study techniques. In their experiment, a player could see their "hand" of cards on their phone and use three different "play" techniques to play a card to a tablet that represented the common play area. Players could also draw a card from the play area (tablet) using one of three "draw" techniques. The study found differences in time and error rates between techniques, e.g., the swipe gesture caused significant interaction errors while trying to swipe a card from mobile phone to the shared tablet. More interestingly to our study, they found that those techniques that mimicked the natural gesture of playing cards were slower than others and participants found them less useful when playing an actual game. This appears to be in contrast to other studies we have looked at, where the more natural gestures were the recommended ones.

In an effort to formalize knowledge about data transfer between devices, Hamilton and Wigdor [6] created *Conductor*, a prototype framework for cross-device applications, which acts as an exemplar for the construction of cross-device applications. *Conductor* was designed to provide a set of generic interaction techniques, generalized across different applications, allowing several forms of cross device interaction and enabling users to work simultaneously across multiple devices and by which users can easily share information. The set of inter-device communication mechanisms were inspired by mechanisms and transfer concepts found in related research. They also present an example usage scenario as well as a user study to evaluate Conductor. A qualitative evaluation was based on observed behaviors and interviews with participants as feedback on the success of *Conductor*, in respect to which mechanisms they chose to use to complete the given task.

3. EXPERIMENTAL METHOD

From our literature review we found that quantitative research on cross-device interactions for transferring data from a mobile device onto a large display is currently limited in HCI. To be able to contribute new knowledge about the comparative strengths and weaknesses of different cross-device interaction techniques, we devised an experiment to empirically measure the hit success rate, the time taken to transfer data and the distance of error for missed targets of four different techniques (*Pinch, Swipe, Throw* and *Tilt*) in a laboratory situation.

3.1 Interaction Techniques

The four techniques implemented in this experiment were designed with respect to techniques presented in previous research as being of interest to the cross-device interaction problem. By combining different qualities of the techniques studied we were able to make a diverse and yet representative set of interaction techniques. The four selected techniques of our study were designed to be different to each other in respect to several qualities, to evaluate them against each other in a controlled situation.

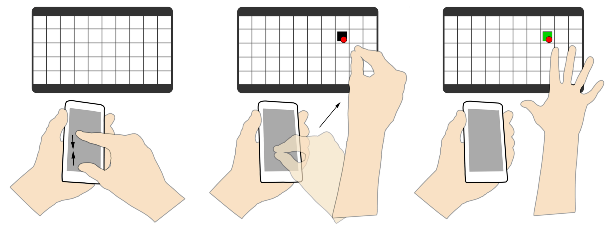
There are many different selection criteria that could have been used, but we decided to use criteria raised with respect to the gestures used in studies found in the literature. This resulted in looking at techniques based on the following attributes. Two techniques should use one hand (*Swipe, Tilt*) and the other two should require the use of both hands (*Pinch, Throw*). The method of moving the cursor on the large display would use the hand or finger as a pointer for two techniques (*Pinch, Throw*) and the phone as a pointer for the other two (*Swipe, Tilt*). We were also interested in related work that looked at natural gestures and therefore wanted two gestures that were mobile device-centred (*Swipe, Tilt*) to be compared against two others that used natural bodily gestures (*Pinch, Throw*) in an analogous way.

Our four techniques: *Pinch*, *Swipe*, *Throw* and *Tilt*, were designed to represent existing attributes of techniques, and at the same time by making hybrid gestures, uncover new opportunities and challenges in this design space. The following sub-sections detail the studies these techniques were inspired by and why this technique was interesting to us.

3.1.1 Pinch

The *Pinch* technique (Figure 1) was used by Ikematsu and Siio [8] as part of a drag-and-drop method for moving data objects between devices. Chen et al. [5] also use a pinching gesture for cross-device interaction between a smartphone and a smartwatch to control volume. Benko and Wilson [1] used a Pinch technique for interacting with omni-directional visualizations in a dome. Nielsen at al. [14] used it to indicate a joint seam between mobile devices. Our technique is a combination of these techniques, and the technique used by Scheible et al. [18] to share mobile multimedia art on large public displays.

The *Pinch* technique was included to mimic the natural action of picking up a real object, e.g., a piece of paper, and moving it to another location. With *Pinch* we have a two handed technique which requires the user to perform a series of steps and therefore has high complexity compared with other techniques tested. *Pinch* is performed by: 1) holding the phone in one hand and making a pinching gesture on the phone's screen with the other hand (fig. 1a), subsequently closing the hand; 2) then using the pinched hand to point at a target location on the large display (fig. 1b); and 3) opening the hand to complete the data transfer (fig. 1c).



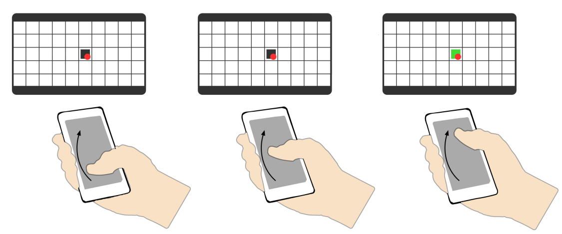
(a) (b) (c)

Figure 1. The Pinch technique

3.1.2 Swipe

The *Swipe* technique (Figure 2) is used in the *Code Space* system [4]. They describe the technique as, "*cross-device interaction with touch and air pointing*" and the swipe motion is described as "*flicking up on the touch screen*". This technique is also similar to the swipe technique used by Skov et al. [21] to send cards from a mobile device to a shared tablet in a card playing game.

This technique was chosen to complement the *Pinch*, with its low level of complexity and single-handed interaction. It is mobile device-centred; being a familiar gesture used on smartphone touch screens to scroll content. The amount of time required to execute this technique is low. *Swipe* is performed by: 1) pointing at a target on the large display with the phone in an out stretched hand (fig. 2a), and 2) making a forward swipe motion with the thumb onto the phone's screen (figs. 2a,b).



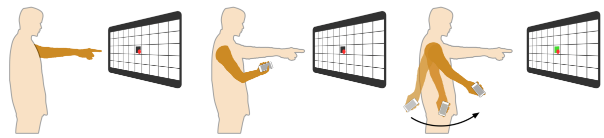
(a) (b) (c)

Figure 2. The Swipe technique

3.1.3 Throw

The *Throw* technique (Figure 3) is a combination of a technique for pointing from Scheible et al. [18], that is, using a hand as a cursor in mid-air, and the throw technique described by Walter et al. [23] used for sharing information to large public displays. The inclusion of this type of natural user interaction technique is inspired by the call for more investigation into the use of natural gestures in the area of cross-device interaction by Schmidt et al. [19].

This technique was included based on its natural feel and playful design. The technique has a natural bodily gesture that mimics the real world scenario of throwing something like a ball. *Throw* is two-handed, and is the most complex of our techniques. It takes a little longer to execute because of the number of steps required. *Throw* is performed by: 1) pointing at a target on the large display with one hand (fig. 3a); 2) holding the phone in the other hand and tapping on the smartphone to select the target data (fig. 3b); and 3) making a swinging motion with the phone towards the large display to transfer the data (fig. 3c).

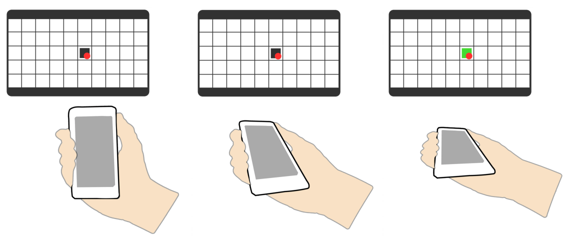


(a) (b) (c)

Figure 3. The Throw technique

3.1.4 *Tilt*

The *Tilt* technique (Figure 4) is used in a collaboration system by Lucero et al. [10] to transfer an object from a large display to the user's smartphone. Our *Tilt* is a copy of Lucero et al.'s technique, but in reverse. Boring et al. [3] also use a tilt technique when directing a pointer on a large display using a phone. We chose this technique because it is one-handed, has a relatively low complexity, and like *Swipe* is relatively fast to use. *Tilt* is performed by: 1) pointing at a target on the large display with the phone in an out stretched hand (fig. 4a); selecting the target on the phone screen; and 2) tilting the phone forward (figs. 4b and 4c).



(a) (b) (c)

Figure 4. The Tilt technique

3.2 Experimental Design

The experiment was conducted as a within-subject design, with the four different *interaction techniques* and two *target sizes* as independent variables, ensuring that all 4 interaction techniques (*Pinch, Swipe, Throw* and *Tilt*) were performed in the experiment by all participants, to maximise the number of data points collected on all techniques given the available number of participants. We also used two target sizes in our experiment to investigate the influence of target size on the results for the different techniques.

Four variables were experimentally controlled in order not to influence our results. Even though the four techniques were very different from each other, we chose to experimentally control for the *learning effect* by mixing the order of the sequence the participants experienced the four techniques. In the end, the *Swipe* started 22.7% of tests, *Pinch* started 26.4% of all tests, *Throw* started 24.5%, and *Tilt* started 26.4% of tests. The second variable that was mixed to appear random was *target size*. We made sure that each participant experienced an equal number of small and large targets, but we mixed the order they were presented to them. Thirdly, we chose to experimentally control for the *distance* participants had to cover on the screen between two attempts. Since, we believed that this could become a significant parameter, we made sure that each participant would experience the same distribution of distances for each technique but in a mixed order. Finally, we experimentally controlled for the *distance* each participant stood from the screen. They were all instructed to stand on a mark exactly 2.35m from the screen, based on the optimal operating distance for the Kinect.

3.2.1 *Participants*

In total, 53 people took part in our experiment, which was conducted in a usability lab. Each filled in a short demographic survey. The participants where between 20-45 years old (M: 24.4, SD: 4.3) and were between 1.63 and 1.95 meters tall (M: 1.82, SD: 7.8). 88.7% of users were right handed, 90.6% were male, and 96.2% of them were smartphone users. Of those who owned smartphones, they had owned them for 2-15 years (M:5, SD: 2.1). Participants were recruited through a combination of social networking and posters around campus.

3.2.2 *System Setup*

The experimental setup included a 65-inch Panasonic screen with 1920×1080 resolution mounted directly above a Microsoft Kinect (see Figure 5). The Kinect was mounted exactly 1m above floor level, based on an approximation of participants' average height. Each participant stood on a mark exactly 2.35m from the screen, based on the optimal operating distance for the Kinect. From this point they used a Samsung Galaxy SII smartphone as their mobile device to complete the tasks.

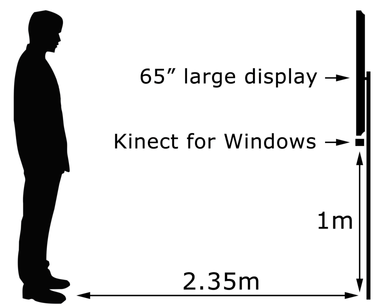
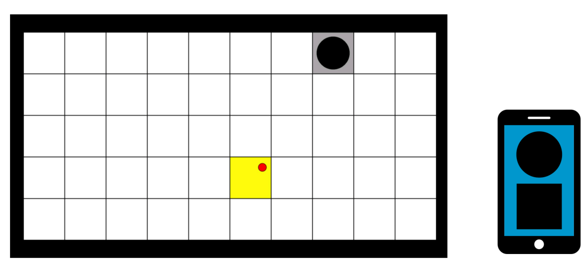


Figure 5. The System Setup

The large display screen was divided into a grid with a red dot acting as a cursor on the screen - it was the location that would be hit when the user performed the technique. A yellow highlight showed the grid cell in which the cursor was currently registered (see Figure 6a).



(a) (b)

Figure 6. The large display and the mobile phone screen

At the same time, the smartphone showed two shapes, a circle and a square, which the user would choose from to transfer to the display (Figure 6b). The display would also indicate which shape had to be moved to it by showing that shape as the target in one of the grid cells (Figure 6a).

We used two shapes to minimise the need to search, while still requiring the user to make an active selection before enacting a technique. This decision actively included the mobile phone in the interaction and simulated the real world situation of selecting data and moving it to a screen. The two shapes on the phone changed positions randomly, so users would have to check the phone for each target. Users chose with which hand they held the phone and with which they pointed. They could also swap hands at any time during the experiment. Participants were presented with one target at a time. For each target and every technique, if the cursor was within the shape's grid when the technique was performed, the system regarded it as a hit, and the shape turned green. If the cursor was outside the target grid square, this was logged as a miss, and the shape turned red.

3.2.3 Tasks

After entering the usability lab, each participant was given a short introduction to the tasks they had to perform. We explained that they would experience four different interaction techniques that they would use to move data from the mobile device to the large display.

We then provided the participants with the smartphone, asked them to stand on the marked cross on the floor and commenced the test. The system then randomly chose one of the four techniques and played a short explanatory video of how to perform it on a second screen located beside the target display (See Figure 7a).

(a) (b)

Figure 7. The experiment in progress

Each participant was given three practice attempts per technique, in order to get familiar with it. After the practice phase, a calibration target would appear so we could control for the *covered distance*. After the practice phase, participants would go through the test, comprised of 18 targets. In the end, each participant experienced three practice rounds + one calibration target (for each technique) which were not included in the results, and (9 small + 9 large targets) x (4 techniques) = 72 targets, as recorded data. The test per participant took on average 15 minutes. Repeat attempts at a target were not permitted and the system proceeded to the next target regardless of whether the participant hit the target, or missed.

3.3 Data Collection

A simple logging program was developed, which collected data for each user. The collected data for all users included a time stamp, whether they hit a target or not, whether they selected the correct shape on the mobile phone, the position of the target on the screen, the size and shape of the target, and the position of the cursor on the screen when each attempt was performed. From this dataset, the following measures were calculated and used in the analysis:

- *Effectiveness*: the number of successful attempts per user, per technique – a successful attempt, besides hitting the target, also required selecting the correct shape on the mobile device
- *Efficiency*: the time each user spent to hit each of the targets
- *Error size*: the distance from the target in pixels, when a user missed a target

Besides automatic logging of user's interactions, we also video recorded the experiment, both as a backup if the automatic data logging failed, and also to identify any technical problems with the gesture recognition software to be refined for any follow-up studies.

4. EXPERIMENTAL RESULTS

We analysed our data in respect to *effectiveness* (based on successful attempts), *efficiency* (based on time per target), and *error size* (based on distance to target). As each of the four interaction techniques were used 18 times per participant, in the end, each technique was performed 954 times.

The first step in the process was to clean the dataset up. We focused on each technique and removed the scores that belonged to outliers. Outliers were defined by applying the outlier-labelling rule and using 2.2 as a multiplier [7]. The majority of extreme scores came from participants that experienced glitches while interacting in the system. After removing outliers, the initial 4x954= 3816 tries were narrowed down to 3564.

4.1 Effectiveness

In this study, we define *effectiveness* as the number of successful attempts per user, per technique. The average successful attempts per user for each technique, for small and large targets respectively, are listed in Tables 1 and 2. Each user could have a maximum of 18 successful attempts (9 for the small targets and 9 for the large ones). In the resulting dataset we performed one-way ANOVA since our dependent variable (effectiveness) was an interval.

Table 1. Effectiveness: average successful attempts per user, per technique for small targets. M= maximum possible value.

	Pinch	Swipe	Throw	Tilt
M=9	5.87	8.11	7.45	5.25

For the small targets we identified significant differences among the techniques ($F(3, 208)=34.713$, $p<.001$). A pairwise comparison showed that all the techniques were significantly different from each other, except *Pinch* and *Tilt*, $p=.054$. Consequently, *Pinch* and *Tilt* had the lowest average successful attempts (5.87 and 5.25 out of 9, respectively, Figure 8), while *Swipe* the highest (8.11 out of 9, Figure 8).

Table 2. Effectiveness: average successful attempts per user, per technique for large targets. M= maximum possible value.

	Pinch	Swipe	Throw	Tilt
M=9	7.02	8.64	8.4	7.02

The same process was then followed for the large targets. Again we identified significant differences among the techniques ($F(3, 208)=29.211$, $p<.001$). A pairwise comparison showed that all the techniques were significantly different from each other, except *Swipe* and *Throw*, $p=.284$, and *Pinch* and *Tilt*, $p=1.0$. As was the case for the small targets, *Pinch* and *Tilt* performed worst (7.02 out of 9, Figure 8), while *Swipe* (8.64 out of 9, Figure 8) was the best followed by *Throw* (8.4 out of 9, Figure 8).

We then extended our analysis and we performed a two-way repeated measures ANOVA in order to examine the combined effect of technique and target size on effectiveness. The effect of each technique on effectiveness was significant ($F(3, 416)= 62.264$, $p<.001$) and so was the effect of target size ($F(2, 416)= 62.285$, $p<.001$). Furthermore, their interaction was also significant ($F(3, 416)= 3.471$, $p=.016$), showing that a combined effect of technique and target size on effectiveness exists.

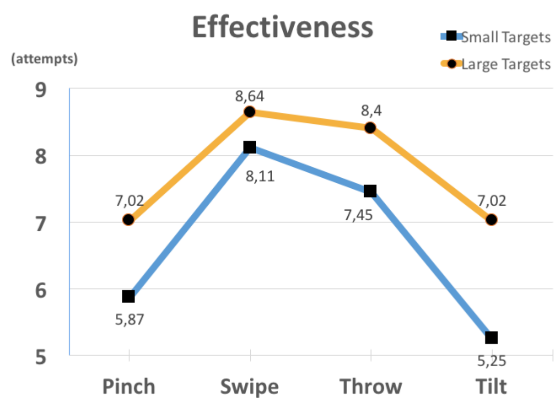


Figure 8. Effectiveness: Average successful attempts per user, per technique, for small and large targets

4.2 Efficiency

By efficiency, we mean the time it takes to complete an action as required by each technique. The number of attempts, the mean time to hit a target in seconds and the standard deviations (in parentheses) for each technique and for both target sizes, are shown in Tables 3 and 4, and combined in Figure 9.

To study the effect of each technique on efficiency for the different target sizes, we performed one-way repeated measures ANOVAs with a Greenhouse-Geisser correction, one for the small targets and one for the large ones.

Table 3. Efficiency: means and (standard deviations) of time spent for each technique per target for small targets

	Pinch N=448	Swipe N=449	Throw N=439	Tilt N=456
N=1741	7.94 (3.92)	5.67 (2.16)	6.32 (2.25)	6.03 (3.02)

For the small targets (Table 3), we identified significant differences among the techniques ($F(2.333, 111.506)=119.799$, $p<.001$). A pairwise comparison showed that all techniques were significantly different from each other (for all cases $p<.001$, except *Swipe* and *Tilt*, $p=.043$).

Table 4. Efficiency: means and (standard deviations) of time spent for each technique per target for large targets

	Pinch N=447	Swipe N=421	Throw N=454	Tilt N=450
N=1772	6.84 (3.22)	4.22 (1.14)	5.54 (1.89)	4.81 (1.97)

For the large targets, we also identified significant differences ($F(2.001, 952.686)=210.596$, $p<.001$). A pairwise comparison showed the same result as the small targets. All techniques were statistically different from each other (for all cases $p<.001$) in relation to efficiency.

We also extended our analysis and we performed a two-way repeated measures ANOVA in order to examine the combined effect of technique and target size on efficiency. The effect of each technique on efficiency was significant ($F(2.230, 2123.045)=309.362$, $p<.001$) and so was the effect of target size ($F(2.230, 2123.045)=57.386$, $p<.001$). On the contrary, their interaction was not significant ($F(2.230, 2123.045)=1.462$, $p=.23$).

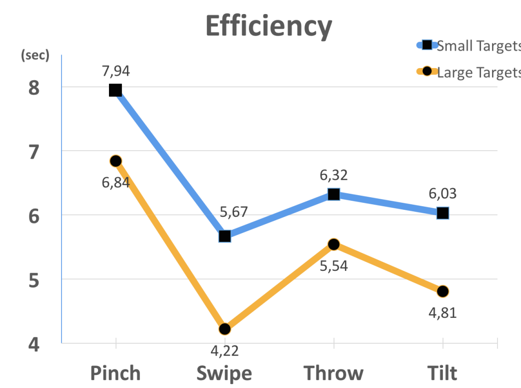


Figure 9. Efficiency: average time spent per target for each technique for small and large targets.

4.3 Error Size

We defined error size as the distance in pixels the cursor had from a target every time a participant missed the target. Means and standard deviations for the distance from target in pixels can be seen in Tables 5 and 6 and combined in Figure 10.

Table 5. Error Size: means and (standard deviations) in pixels per technique for small targets

	Pinch N=169	Swipe N=44	Throw N=80	Tilt N=197
	218.37 (241.29)	51.66 (143.89)	111.06 (210.48)	182.25 (236.57)

As a first step we performed two one-way ANOVA's, one for each target size. For the small targets our result show that there is a significant effect of technique on error size ($F(3, 483) = 8.457$, $p<.0001$). The pairwise comparisons showed that all techniques were significantly different from each other ($p < .001$), except *Pinch* and *Tilt* ($p = .793$), and *Pinch* and *Swipe* ($p =.987$).

Table 6. Error Size: means and (standard deviations) in pixels per technique for large targets

	Pinch N=105	Swipe N=16	Throw N=31	Tilt N=104
	342.57 (261.99)	68.343 (207.41)	190.75 (264.34)	270.07 (278.96)

For the large targets, the result was the same as before, F(3, 256) = 6.494, p<.0001). Pairwise comparisons showed that all pairs were significantly different from each other (p<.05) except *Pinch* and *Tilt* (p=.302), *Swipe* and *Throw* (p=.821), and *Throw* and *Tilt* (p=.882)

We continued our analysis and performed a two-way ANOVA in order to examine the combined effect of technique and target size on error size. The effect of each technique on error size was significant (F(3, 735)=18.903, p=.019) and so was the effect of target size (F(1, 735)=12.028, p=.009). On the contrary, their interaction was not significant (F(3, 735)=.774, p=.509).

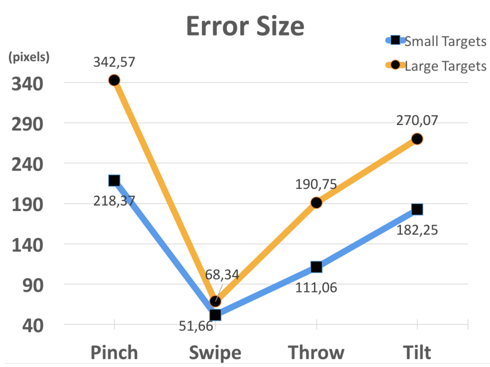


Figure 10. Error Size: average distance in pixels per technique for small and large targets.

5. DISCUSSION

Our results, based on empirical data collected through the experiment reported, make an important contribution to the research area of cross-device interaction techniques by giving new insights in respect to knowing more about how these four different techniques compare in terms of effectiveness, efficiency and error size.

5.1 Effectiveness

The technique with the highest average successful attempts was *Swipe*, both for large and small targets. In contrast, the least successful technique was *Tilt*, especially for the small targets. We believe that *Swipe* was the most successful for two reasons. Firstly, the users are already familiar with the technique as they are used to swiping during their everyday interactions with technology, and in particular with mobile phones. Secondly, because it was easier for the participants to keep the phone reasonably still while performing *Swipe*. When the phone is being used as the pointing device as well as for completing the interaction, then it needs to be able to keep pointing at the target, while enacting the data transfer gesture. In this situation, *Tilt* proved to be particularly challenging because when users tilted the phone forward, often this coincided with an unintentional phone movement, causing the cursor to move away from users' intended position on the target shape. *Throw* also had relatively high average successful attempts, and we believe that this can be explained by the fact that it required a very natural and easy gesture from the users. The metaphor of throwing something toward the screen matched the gesture required to transfer data from the mobile to the large display. Also, with *Throw*, the pointing hand can be held quite still. Finally, *Pinch* also performed slightly better than *Tilt* (especially for the small targets). This was most likely due to the fact that even though the pinching hand also acted as the pointer, releasing the data (completing the transfer) required the minimal movement of simply opening the hand while keeping it in place.

5.2 Efficiency

All the techniques were statistically different from each other, both for large and small targets. This result was validated when we examined the combined effect of technique and target size on efficiency. What is interesting though, is that both had a significant effect on efficiency but there was no significant effect of their interaction. Thus, the larger the target the faster a user is and this effect is similar for all techniques.

As with effectiveness, the best performed technique was *Swipe*. The users were very fast in swiping and hitting the correct shape on to the target on the display. They were also significantly faster when they interacted with large targets. The slowest technique was *Pinch*. We surmise that the reasons for having this result were twofold. Firstly, *Pinch* required a relatively complex gesture from the users to capture and release the data, that is, they had to pinch the shape on the phone, lift their hand up, point it on the screen, and then let go (see Figure 1). Secondly, often users would spend a considerable amount of time pinching the correct shape on the mobile phone screen once they had identified it. This did not happen for the *Swipe* technique as the users would simply touch on the correct shape on the mobile phone screen and swipe their finger forward in a single move. *Throw* and *Tilt* had significant differences to each other in relation to efficiency, but if we look closer at the averages (Figure 9) their statistical differences are not that meaningful, especially for the small targets (0.29 sec).

5.3 Error Size

Error size is defined as the distance in pixels between the cursor and the target when users failed to hit it. With respect to error size, the results were slightly different than for efficiency.

For small targets, whenever there was a failure, *Pinch* and *Tilt*, and *Pinch* and *Swipe* did not have as statistically significant differences as the rest of the pairs. For large targets, *Pinch* and *Tilt*, *Swipe* and *Throw*, and *Throw* and *Tilt* did not have statistically significant differences. As with efficiency, the effect of the interaction technique and target size on error size was also not significant. Interestingly, our results show that when the target size increases then the size of the error somehow becomes identical for all techniques.

If we observe the actual error size in number of pixels (Figure 10), then it is clear that the technique that produced the smallest error in pixels was *Swipe*. When users failed, then they were relatively close to their target. The technique that produced the largest error was *Pinch*, signifying that when users failed, the cursor was quite a large distance from the target when the transfer was performed. What is interesting though is that the actual size of the error in pixels was larger when users interacted with large targets. We treat this finding as somehow unexpected and suspect that a possible explanation for this result is that users were more careful to perform the techniques when the targets were small.

5.4 User Feedback

To balance the quantitative data, we would like to briefly discuss some qualitative data that was also collected during the experiment. At the end of each test, we asked participants to complete a questionnaire about the experience of using the four different interaction techniques, to get additional understanding on how users perceived the different techniques. The questionnaire had 6 questions, taken from the USE questionnaire [11] focusing on *ease of use* and *ease of learning*:

- Three items for *ease of use*: “This technique is easy to use”, “I can use this technique successfully every time”, and “Using this technique is effortless”, and
- Three items for *ease of learning*: “It is easy to learn to use this technique”, “I quickly became skillful with this technique”, and “I learned to use it quickly”.

Users scored their answers to each question on a 7-point Likert scale. We also used the video of the sessions to transcribe comments made during the experiment, and made notes on their actions, to get a better overall impression of user responses.

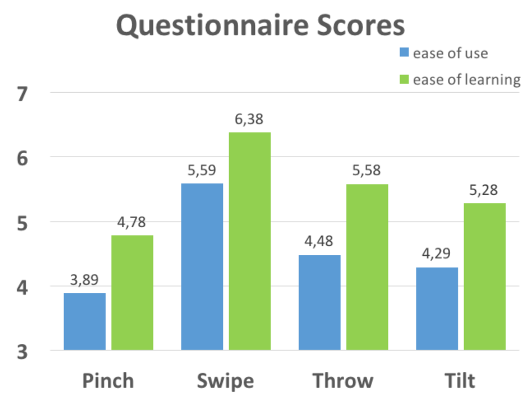


Figure 11. Average scores per technique for ease of use and ease of learning.

The results (Figure 11) showed that *Swipe* was perceived as the easiest to use (5.59) as well as the easiest to learn (6.38). *Pinch* collected the lowest scores both on *ease of use*, as well as *ease of learning*. From these results we can see that, in line with our quantitative findings, users considered *Swipe* as the most useful technique. *Throw* and *Tilt* were rated close to each other on ease of use, while *Pinch* trailed quite significantly behind. However, in the experiment *Throw* outperformed *Tilt* considerably, both in regards to successful attempts and time taken, indicating that perceived ease of use does not guarantee greater effectiveness or efficiency. Similarly, *Pinch* was perceived by users as the most difficult to use, even though it had an average successful attempt rate similar to *Tilt*.

Looking at user comments, we found that the relation between pointing direction and the location of the cursor icon (red dot) on the large display was critical to their acceptance of a technique. Some users mentioned having trouble reaching all areas of the screen, and almost all users showed signs of trouble, for example, by standing on their toes or stretching their arms as far as possible. One user got so frustrated that she asked for a chair to stand on. Some users also mentioned a problem of the mobile phone obscuring their view of the target on the large display whenever the targets were too high and they had to stretch their arms up. This all indicates that a relative rather than absolute pointing technique would be more suitable for cross-device interaction between a handheld mobile device and a large display.

In regards to interacting with the mobile device, some users complained that the screen was too small when performing a *Pinch*, making it hard to precisely select the correct shape. This may have influenced their low scoring on ease of use, and yet *Pinch* was not the worst in the successful placing of targets on the screen. Other users complained that the mobile device screen was too large when performing a *Swipe*, since it was hard to reach the correct shape with their thumbs while still maintaining precision with the pointer. Some users solved this by using two hands for the gesture. This increased both swipe-ability and pointer precision for them.

In terms of learnability, some mentioned that the *Pinch* technique was hard to learn, and a high number of participants had to be repeatedly told how to perform both the *Pinch* and the *Throw* techniques. This was surprising, as these two were the techniques with the most natural bodily gestures both having analogies with the actions of pinching and throwing real world objects. An explanation of this could be that the system set-up was quite rigid in its recognition of these gestures, while the participants tended to revert to an intuitive behavior for pinching and throwing, rather than the precise detailed movements given in the tutorial video. This lack of recognition of a gesture led to participant frustration with a technique, when they thought they were performing the technique correctly and nothing was happening on the display. This frustration was commented on for the *Pinch* technique, but also for the *Tilt* technique, which relied on a distinct movement of the mobile phone to register an accelerometer change. Not surprisingly, in the questionnaire, both *Tilt* and *Pinch* were given very low scores on successful and skillful ratings.

Finally, there is also the fun aspect to take into consideration. Many of the users mentioned having fun while performing the *Pinch* technique. They compared it to casting a spell or causing explosions on the screen. Users mentioned that this technique was especially interesting, and enjoyable to use, and yet according to the questionnaire, *Pinch w*as the hardest technique for users to use and to learn.

5.5 Implications for Design

From this research we can learn something about the comparative strengths of these four different cross-device interaction techniques.

In an application where speed is important when sending data from a mobile device to a large display, then *Swipe* is the fastest, and should be considered the interaction technique of choice.

Where accuracy is important, and placement of data from a smartphone to a shared screen needs to be precise, then *Swipe* has the highest success rates in terms of hitting the right place on the display. This holds true irrespective of the size of the target space being aimed at.

Another consideration in favor of *Swipe* is that users perceive it overall as the easiest to use, easiest to learn, most effortless to use, quickest to learn, and the most successful and skillful of the techniques.

An interesting finding for designers to note is that despite poor quantitative performance statistics and low qualitative usefulness ratings and comments, people seemed to have a fascination and fondness for the *Pinch* technique. It should therefore be considered in situations where effectiveness, efficiency and accuracy are not so important.

Target size matters for all of the studied techniques. This means that in transferring data from a mobile device to a large display, the larger the target – meaning the less precise people have to be in their placement of the pointer – the more effective and efficient they are. This is not a surprising result, however, we also found that when they miss, they actually miss by a greater distance when they are aiming at a bigger target. This was unexpected, and probably indicates that smaller targets encourage users to try more to be precise in the interaction.

A final consideration, based on informal observations made during the experiments, is that the laboratory set up and experimental design influences the way that people enact the techniques. During the experiment, we noticed that users would spend relatively little time using their pointing device (mobile phone or hand) to place the cursor in the general vicinity of the target and would spend most of their time, in each attempt, trying to place the cursor exactly on top of the actual target. This indicates that without the need for precision, as imposed by the rigid experimental set up, and given a more realistic task of transferring images or text from personal phones to a shared public display, the comparative outcomes might be different. However, this will have to be investigated through further research.

5.6 Limitations

There are some limitations in our experiment that are mostly related to our implementation of the four techniques. Registering correct gestures with the Kinect was the most problematic. Firstly, when users had to use a hand gesture to complete a data transfer, often the system would register interim hand movements as the completion movement, before they had actually finished performing the interaction. Secondly, the Kinect often had problems determining different arm joints and hands, especially when they moved behind each other or too close to each other. Both issues caused target errors and/or additional time to complete the tasks. Such incidents were noted down during the experiment and were removed from the dataset in order to not affect the results, but the ability of the Kinect technology to recognize different gestures was frustrating for users, and caused more problems with some gestures than others.

When we designed the gestures for our experiment, our intended system set-up did not influence our choices – therefore, our specific implementations were the best we could do with the technology available to us. This may have affected our comparative results, as some techniques could be registered more clearly than others. Further work should look at alternative, and perhaps more robust technologies for recognizing these gestures.

6. CONCLUSION AND FUTURE WORK

We have presented a study on cross-device interaction techniques focusing on moving data from a handheld mobile device to a large screen display. Specifically, we have compared the use of four different techniques (*Pinch*, *Swipe*, *Throw* and *Tilt*) in conjunction with two different target sizes, to investigate their respective effectiveness, efficiency and error size.

Our findings show that *Swipe* performed best on all measures. *Swipe* was the most effective technique, having the highest number of successful attempts, for both small and large targets. At the same time *Swipe* was also the most efficient technique, being the fastest one to use, for both small and large targets. The *Swipe* technique was also the most accurate one when looking at the size of the errors encountered. Again, this was the case for both small and large targets. From this we conclude that to design a cross-device interaction technique used to send data from a handheld mobile device to a large display, a swiping technique, like the one presented here, should be a first consideration. In terms of effectiveness, the *Tilt* technique performed the worst, and especially so with small targets. In terms of efficiency and error size, the *Pinch* technique was the slowest and also the most imprecise. We also found that target size mattered considerably for all techniques, confirming previous research, but surprisingly when people missed a target, they missed larger targets to a greater degree than smaller ones. These findings can be used to inform the design of applications with cross-device interaction through knowledge about their relative strengths and weaknesses in terms of effectiveness, efficiency and error size.

Our experiment has investigated four specific cross-device techniques, and the specific measures of effectiveness, efficiency and error size, in a laboratory setting. Future research should expand this with additional techniques and measures, such as usefulness for concrete tasks, and perceived user experience. We would also like to see comparative studies carried out in real-world settings.

7. ACKNOWLEDGMENTS

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