

Graspables Revisited: Multi-Touch vs. Tangible Input for Tabletop Displays in Acquisition and Manipulation Tasks

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ABSTRACT

We present an experimental comparison of multi-touch and tangible user interfaces for basic interface actions. Twelve participants completed *manipulation* and *acquisition* tasks on an interactive surface in each of three conditions: tangible user interface; multi-touch; and mouse and puck. We found that interface control objects in the tangible condition were easiest to acquire and, once acquired, were easier/more accurate to manipulate. Further qualitative analysis suggested that in the evaluated tasks tangibles offer greater adaptability of control and specifically highlighted a problem of *exit error* that can undermine fine-grained control in multi-touch interactions. We discuss the implications of these findings for interface design.

Author Keywords

TUI, Tangible, Interactive surface, Multi-Touch, Input

ACM Classification Keywords

H5.2. [User Interfaces]: Input devices and strategies.

General Terms

Experimentation, Human Factors.

INTRODUCTION

Since the inception of Tangible User Interfaces (TUIs), researchers have discussed at length how they might be categorized and conceptualized [3, 9, 17]. In particular, designers of TUIs have increasingly tried to understand the interactional benefits of TUIs over other kinds of interface (such as GUIs). Proposed benefits of TUIs have included spatial multiplexing and bimanualism [5], natural affordances of tangible objects [6, 11], various aspects of embodiment [10], and also the potential for experiential learning through action [13, 14].

However, in recent years, multi-touch surfaces [18] have also become prevalent. They allow users to interact with

digital data directly; using their fingers and hands at the interactive surface to manipulate graphically rendered virtual objects. These multi-touch surfaces invite us to question the use of TUIs. The oft-cited benefits of TUIs, such as arguments for two-handed interaction, parallel input and collaborative use (see [6] for discussion), could all arguably apply to multi-touch surfaces. This is particularly so when the tangible objects are necessarily tethered to an interactive surface (e.g., reacTable [12]). In these instances, conceptual frameworks created to underpin tangible interaction approaches, such as Fishkin's [3] exploration of metaphor, Hornecker's [10] exploration of embodiment and Ullmer and Ishii's MCRpd model [17] would, arguably, apply to graphically rendered objects just as much as to physical objects, and the ways in which we might bodily, spatially and cognitively interact with them.

Additionally, multi-touch systems offer various potential benefits that TUIs do not, such as providing dynamic content and controls that can be generated, reproduced, replayed, merged and deleted at will, and also (depending on hardware) offer near-field interactions that don't actually require physical contact for interaction.

If designers are to make informed decisions between using TUIs and using multi-touch on interactive surfaces, there is a need to better understand the tradeoffs involved. When should one use a multi-touch surface instead of a TUI? And what value is the tangible element really delivering to the user? In this paper we explore these issues in the context of simple, but common, interface actions found in many multi-touch and tangible surface interfaces. We explicitly compare TUIs and multi-touch input, using controlled experiments as a forcing function to develop a deeper understanding of user response to the technologies. This highlights interactional problems and potential benefits. Fitzmaurice and Buxton adopted such an approach in their seminal graspable user interfaces work [4, 5]. They experimentally compared spatially-multiplexed TUIs and time-multiplexed input to reveal the benefits of TUIs. However, there has been little comparable research exploring the benefits of TUIs versus multi-touch input (although see [15]). In this paper we address this issue.

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We offer an experimental comparison of tangible and multi-touch input methods, which observes a benefit of tangibles in simple control tasks in terms of both manipulation and acquisition time. These results suggest that in control tasks, tangibles are quicker to acquire on a table and easier/more accurate to manipulate once you've acquired them. We also provide an accompanying qualitative analysis of user behaviour which highlights how tangibles can offer greater adaptability of control and heterogeneity of user interaction. We also specifically highlight an under-reported problem with multi-touch systems, which we call "exit error", which can undermine users' attempts at fine-grained manipulation.

Of course this discussion does not cover all possible interactions with either multi-touch or tangible interfaces, and there may be benefits under particular circumstances of either approach. What we provide herein however, as a discussion point within a broader debate on the role of tangibility in interfaces, is an exploration of the impact of tangible or multi-touch input on one sub-set of common user interface actions, namely target acquisition and manipulation.

SITUATING THE STUDY

A recent study by Forlines et al [7] explored benefits of multi-touch input over mouse input. They illustrated how multi-touch input can be suitable for bimanual tasks but unnecessary in other tasks. To further develop this understanding of multi-touch input, we sought to compare multi-touch against more complex tangible input devices.

However, whilst studies of TUIs proliferate, few have experimentally compared tangibles versus alternative forms of input (although see [13, 15, 16]). Where studies have directly compared multi-touch with TUIs, the results have tended to either lack generalisability due to an overly-focused user group (such as children [15]) or have been hampered by the simplicity of their user task (e.g., limiting to WIMP-like behaviours during multi-touch use [16]).

The seminal graspable user interfaces work of Fitzmaurice and Buxton explored user response to more complex TUIs [4, 5]. They experimentally compared *spatial vs. time-multiplexed* input. This distinction was critical in understanding the benefits of TUIs. Time-multiplexed input is characteristic of GUI use with a mouse. A single input device (mouse) is used to access different GUI controls sequentially over time. The input device is non-specialised and operates all controls. Space-multiplexed input enables the user to interact with all controls concurrently. Their work empirically demonstrated that spatially-multiplexed input led to more accurate use of interface controls and reduced acquisition time. This was most evident with input delivered through specialised devices such as TUIs (where the physical form mirrors the underlying digital representation being manipulated).

From these experimental comparisons Fitzmaurice, Ishii & Buxton [6] began to develop a theoretical understanding of

the value of TUIs. Many of the theoretical benefits they discussed would appear to apply also to multi-touch input, but the data from the original experiment does not help designers decide which technology, multi-touch or tangibles, might be preferable. Consequently, we have adapted the experimental methods of Fitzmaurice and Buxton [4, 5] to enable an explicit comparison of TUIs and multi-touch input.

Since prior studies had shown clear support for TUIs over other input means, and that this had been explained in a variety of ways, such as eyes-free manipulation and haptic feedback [6], we hypothesised that TUIs would still outperform multi-touch input in a control-based task. We hypothesised that TUI controls would be quicker to acquire and would lead to less error in manipulation than observed in a multi-touch condition.

EXPERIMENT 1: MANIPULATION

Fitzmaurice and Buxton [5] discussed two phases of interaction during Graspable interface use, namely *acquisition* and *manipulation*. Consequently we designed two experiments to compare multi-touch and tangible interfaces. The first experiment considered the manipulation phase of interaction, and was based on elements of the study design used by Fitzmaurice [4].

Assuming users have already acquired a control widget, the experiment asks participants to manipulate, as quickly as possible, an on-screen object (highlighted in yellow) so that it matches the position and orientation of a target object (highlighted in blue) (Figure 1). This tests participants' abilities to perform rapid and fine-grained manipulations of a control widget. As an object, we chose a virtual ruler, similar in principle to that used by Fitzmaurice [4]. We introduce each of our three experimental conditions below.

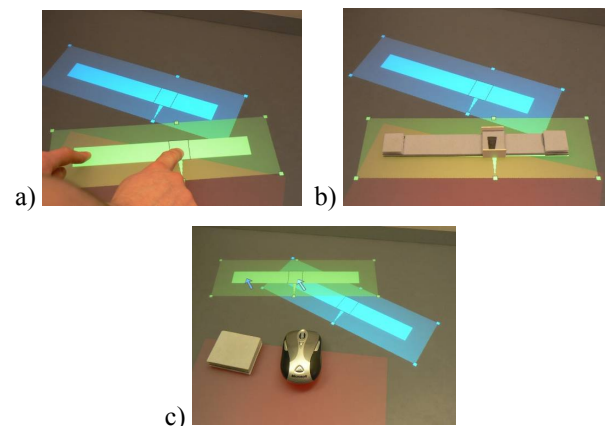


Figure 1. Rulers in each condition of the manipulation task: a) multi-touch; b) tangible; and c) mouse and puck

Multi-touch (Figure 1a). Touching the on-screen ruler with one finger translated the object. Two fingers translated and rotated, and, if one of the fingers was on the indicator, moved the indicator. Participants could also place two fingers either side of the indicator and use a third to move

the indicator. Participants could equally use either fingers of the same hand, or of different hands.

Tangibles (Figure 1b). A tangible ruler was constructed from foam-board and tracked using the multi-touch surface (in this study tangibles are inherently tethered to an interactive surface similar to [12]). The user could move the object on the surface, and also move the sliding indicator independently or simultaneously. An on-screen ruler (highlighted in yellow) followed the tangible ruler.

Mouse and puck (Figure 1c). This was intended as a control condition to act as a reference point. A single mouse is inadequate because it provides only two degrees-of-freedom (DoF), and so would require a user interface technique such as handles to enable the user to select whether to rotate or translate. This would require regular reacquisition of handles, effectively biasing against the technology. This would also represent the ‘time-multiplexed’ condition in the Fitzmaurice [4] study, which we were choosing not to examine.

Consequently we chose to use a mouse and puck to provide 4-DoF, rather like two contact points in the multi-touch condition. We chose a puck and mouse instead of two mice to support a level of asymmetry in the interaction and aid ergonomics. We sensed each absolutely using the same multi-touch surface (described later). This not only allowed us to reuse the same sensing technology across conditions, but also allowed us to move away from using relative pointing mice, which in our pilots we found remarkably difficult to use because the pointers would cross over on the screen while the mice did not cross. The mouse and puck controlled two differently-coloured pointers on the surface. When the mouse pointer was pressed, both pointers would act effectively as touch points in the multi-touch case. The mouse and puck were used in part of the surface shown with a red rectangle, which was kept clear of target shapes. The red rectangle was displayed in all conditions to avoid biasing. Right-handed participants held the mouse in the right hand and the puck in the left. Left-handed participants were generally used to holding a mouse in the right hand, and in this experiment held the mouse in whichever hand seemed most comfortable for them.

Method

Design

The experiment used a within-subjects repeated-measures design. Each of the 12 subjects matched each of 9 target stimuli using each of the three input technologies: multi-touch, tangible, and mouse and puck (the independent variables). Time to complete each matching task was measured and subjective reports of comfort and ease of use were taken for each technology (the dependent variables). Stimulus presentation order was randomised for each technology and participant, and the technology presentation order was counterbalanced using a Latin square design to avoid order effects. Participants were motivated to react

quickly during the task by the prospect of a bonus payment for the fastest person across all three technologies. The control shape started each trial in a set “home” position.

Participants

Twelve paid participants (aged 18-34, mean age 23.7, 4 females, 2 left-handed) were recruited from a computer science research lab and a university computer science department. All had normal or corrected-to-normal vision. Four had limited prior experience using tangible input, multi-touch or two mice; others had none. Participants were not aware of the hypotheses.

Equipment

The system was implemented on a Microsoft Surface, using the Microsoft Surface SDK for input and the XNA graphics library for rendering. The Surface uses a rear-projected display of resolution 1024×768 and is approximately 24"×18" in size. The Surface is a vision-based multi-touch tabletop, which uses diffuse infrared (IR) light to track multiple fingertips, outlines of objects, and special 2D visual markers (which can be tracked in 3DoF, i.e. position and orientation). The foam-board ruler had these markers stuck underneath one end and also underneath the indicator. The mouse and puck instead used white stickers stuck to their undersides – so they appeared like fingertips to the underlying sensor, as we did not require the additional orientation data to track them. The ruler was approximately 22cm x 3cm x 1cm in physical size. The system ran at approximately 60fps.

Task

In the experimental software, both the interactive yellow ruler and the blue target ruler are surrounded by a semi-transparent coloured halo so that the target position can be inferred from the halos even if the tangible ruler obscures the target itself (Figure 1). Surrounding the halo of each ruler are 6 coloured markers: 4 at the corners; and two on the indicator. When a marker of the interactive yellow ruler comes within 5 pixels of the corresponding marker of the blue target ruler, both markers turn red, indicating a sufficient match. When all 6 markers match for 0.75 seconds, the target is considered matched. Progression to the next test stimulus depends on successful completion of each stimulus in turn.

Procedure

Each participant began with an introductory session to familiarise themselves with the input method used in each of the conditions. Once the participants were comfortable with all of the technologies, the study began. For each condition, the experimenter first demonstrated how to match four example stimuli. Participants were reminded that they could use any combination of touch points they wished to manipulate objects. Participants then matched 9 randomly-ordered stimuli themselves as a practice before matching 9 further randomly-ordered stimuli. Pilot testing had indicated that 9 practices were sufficient to avoid

considerable learning effects. This was done for each condition. After each condition, participants completed a questionnaire that asked them to rate their perceived comfort and ease of use (of the input technology) on a continuous scale. After all conditions were completed, participants completed a post-study questionnaire that asked them to rank the input technologies in order of preference. The study concluded with a semi-structured interview.

Results

Figure 2 shows the results of Experiment 1. A three-way (two-tailed) repeated-measures ANOVA demonstrated a significant effect of experimental condition on target matching manipulation time ($F(2,214) = 45.529, p < 0.001$).

Post-hoc pairwise comparisons using t-tests (Bonferroni corrected) showed that all three conditions were significantly different ($p < 0.001$). The mean scores show that the tangible condition had the lowest manipulation time, followed by the multi-touch condition and finally the mouse and puck condition.

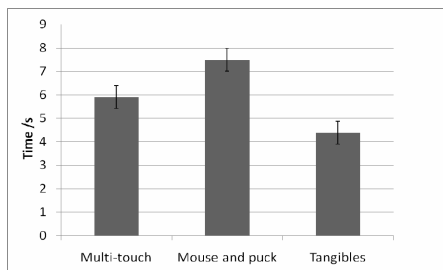


Figure 2. Mean time to complete manipulation task by experimental condition.

Participants' ratings of comfort for each of the three input conditions were also entered into a three-way (two-tailed) repeated-measures ANOVA. This showed no significant difference between the conditions ($p = n.s.$).

Analysis of participant's ratings of ease of use however, did show a significant effect of input technology, using a three-way (two-tailed) repeated-measures ANOVA ($F(2,22) = 5.471, p = 0.012$). Post-hoc (Bonferroni corrected) pairwise t-tests failed to show a significant difference between the conditions but the trend suggested that participants considered tangibles easiest to use (mean = 5.53), followed by multi-touch (mean = 4.83) and finally mouse and puck (mean = 4.15).

Overall preference rankings were analysed using a Friedman (non-parametric) test which demonstrated a significant difference between input technologies ($\chi^2(12) = 8.167, p = 0.017$). The trend was consistent with performance results, and pairwise comparisons (Wilcoxon signed rank tests) showed mouse and puck significantly less preferred than both tangibles ($Z = -2.506, p = 0.012$) and multi-touch ($Z = -2.392, p = 0.017$). Other pairwise comparisons were non-significant.

Discussion

Overall our results from Experiment 1 suggested that tangible widgets are significantly easier to manipulate (and therefore control) than multi-touch widgets. That the mouse and puck condition showed significantly poorer performance is somewhat to be expected: this is consistent with the study of bimanual input by Forlines et al. [7], which found that multiple mice were slower than multi-touch interaction during object manipulation. Our result builds on this finding by showing a further performance advantage when tangibles are used.

The results of Experiment 1 differ slightly from Fitzmaurice's earlier study [4]: he found no differences between generic space-multiplexed devices and specialized space-multiplexed devices; whereas we *did* find a difference between our comparable specialized devices (the tangible rulers) and our approximation of space-multiplexed *generic* input (mouse and puck). Broadly, however, the times for manipulation were similar to those found in the earlier study, and it is hard to draw conclusions based on these stated differences. There were also physical differences between Fitzmaurice's [4] generic bricks and our mouse and puck; and the visualization of the control widget and the tracked object were indirectly displayed in the earlier work and were co-located with the control widgets in this work.

Post-experiment interviews enabled us to further probe the user experience. The mouse and puck were praised for being "more precise" but this contrasted with experiences of the difficulty of actually using them when complex manoeuvres were required, such as crossing the controls over, in which case the mouse and puck would often collide. However, the lack of requirement to reach across the table when using such devices (as was present with both multi-touch and tangible conditions) arguably led to less perceived arm fatigue. Ultimately, however, users frequently praised the "better degree of control with tangibles, especially when rotating".

EXPERIMENT 2: ACQUISITION

The second experiment focuses on the acquisition stage of interaction and again compares tangible and multi-touch technologies. The experiment used a continuous tracking design similar to that used in Fitzmaurice and Buxton [5].

Method

Experimental Task

Again participants were presented with three technologies – tangibles, multi-touch, and mouse and puck. In this study participants were presented with four yellow on-screen shapes that initially sat atop corresponding blue targets. After a short countdown, the blue targets moved slowly away from the yellow shapes, following pseudo-random paths for 90 seconds (Figure 3).

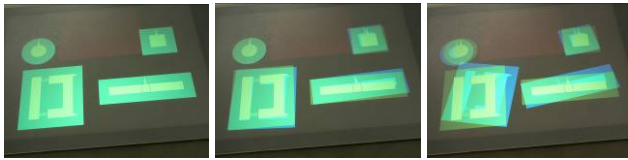


Figure 3. Moving targets (blue) and non-moving control objects (yellow) in the acquisition task

Participants were asked to keep the four yellow on-screen shapes continuously over the four blue targets and were told that for the best performance they would need “all the shapes to match the targets as closely as possible for as much of the trial time as possible”. Participants were motivated by the prospect of an extra gift voucher for the person with best performance across all three conditions. This required participants therefore to move rapidly between the four yellow shapes, i.e. regularly reacquiring them. The four targets comprised: a brick (square in shape) that could be rotated and translated; a rotor (circular) that could be rotated and translated; a ruler with an adjustable position indicator (as used in the previous experiment); and an adjustable square that could be rotated, translated and stretched. The orientation and position of each shape followed a pseudo-random path (including changes to indicator position (ruler) and size (square) as appropriate).

We again tested three different conditions (Figure 4):

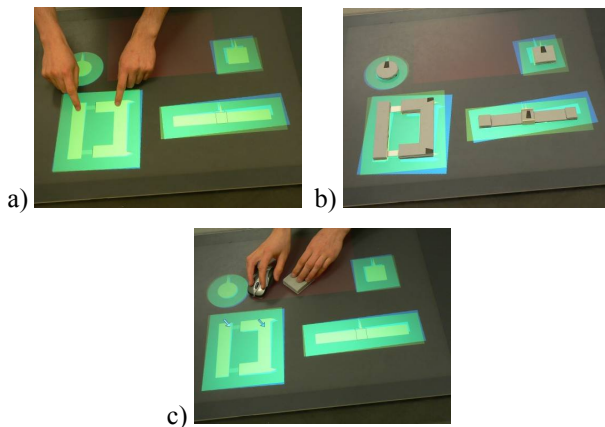


Figure 4. Acquisition task objects in a) multi-touch b) tangible and c) mouse and puck conditions

Multi-touch (Figure 4a). This was implemented as in the previous study. The square, similarly to the ruler, was adjusted by creating touch points on each substantive segment of the square and then moving the segments closer or further apart (up to set limits in either direction). Multiple fingers and hands could be used as required.

Tangibles (Figure 4b). Foam-board tangibles were again tracked using visual markers attached to their underside. The on-screen shapes followed the tangible shapes. Participants could manipulate any number of shapes simultaneously.

Mouse and puck (Figure 4c). As before, the mouse and

puck provided two pointers, each creating a touch point, activated when the mouse button was pressed. Like Fitzmaurice and Buxton [5], the mouse and puck were absolutely positioned; unlike prior work they were active only in part of the surface (shaded dark red) near the user, which was kept clear of target shapes (Figures 1 and 4c). This rectangle was displayed in all conditions to avoid bias.

Design

The experiment used a within-subjects repeated-measures design. Each of the 12 subjects matched each of 4 stimulus paths using each of the 3 input technologies: multi-touch, tangibles, and mouse and puck (independent variables). The stimulus presentation order was randomised for each technology and participant, and the technology presentation order was counterbalanced using a Latin square. We continuously measured the error between the yellow shapes and the blue targets, using a root-mean-square metric described below. We also captured overall preference, and subjective measures of comfort and ease of use for each technology. We later performed qualitative observational analysis of video records of the study tasks to determine relative handedness and predominant forms of interaction.

Participants

Participants continued from the previous experiment.

Equipment

The system was again implemented using a Microsoft Surface. Each foam-board shape had two trackable markers stuck to its underside, allowing sensing of position, orientation and, in the case of the stretchable square and ruler, size and indicator position. Again, the system ran at approximately 60fps.

Procedure

The experimenter first showed the participants a 90 second demonstration of the study task. Participants then attempted each technology in turn. For each technology, the participant completed one 90s practice stimulus, followed by a further four randomly-ordered 90s stimuli. After each technology, participants completed a questionnaire that asked them to rate the perceived comfort and ease of use of the technology on a continuous scale. Once all technologies were complete, participants completed a post-study questionnaire that asked them to rank the technologies in order of preference. The study concluded with a semi-structured interview.

Analysis

During each trial, we logged the error between the yellow shapes and the blue targets at 50ms intervals. We then calculate a single tracking error score for the trial, using a method similar to Fitzmaurice and Buxton [3]. The tracking error score is determined as the root-mean-square (RMS) Euclidean distance off target for all four target shapes and along all three dimensions (translation, rotation, and slider position):

$$Score = \sqrt{RMS_{ruler}^2 + RMS_{square}^2 + RMS_{rotor}^2 + RMS_{brick}^2}$$

$$RMS_{ruler} = \sqrt{RMS_{Trans}^2 + RMS_{Rotate}^2 + RMS_{Slider}^2}$$

$$RMS_{square} = \sqrt{RMS_{Trans}^2 + RMS_{Rotate}^2 + RMS_{Slider}^2}$$

$$RMS_{rotor} = \sqrt{RMS_{Trans}^2 + RMS_{Rotate}^2}$$

$$RMS_{brick} = \sqrt{RMS_{Trans}^2 + RMS_{Rotate}^2}$$

For a given shape in a given trial, we calculate the RMS error for each dimension:

$$RMS_{Trans} = \sqrt{\left(\sum_{k=1}^N errorTrans_k^2\right) / N} \quad RMS_{Rotate} = \sqrt{\left(\sum_{k=1}^N errorRotate_k^2\right) / N}$$

$$RMS_{Slider} = \sqrt{\left(\sum_{k=1}^N errorSlider_k^2\right) / N} \quad (\text{for ruler and square})$$

At any instant k during the experiment, $errorTrans_k$ is defined as the Euclidean distance between the centre of the yellow shape and the blue target. $errorAng_k$ is the arc length ($arclength = \theta \cdot length$) between the yellow shape and the blue target, where θ ranges from 0 to π , and $length$ is the current length of the blue target. $errorSlider_k$ is the difference in slider position or square side length between the yellow shape and the blue target. Lower scores therefore indicate more accurate tracking.

Results

Tracking error scores for Experiment 2 are shown in Figure 5. A three-way (two-tailed) repeated-measures ANOVA demonstrated a significant effect of experimental condition on RMS tracking error score ($F(2,94)=41.909, p<0.001$).

This analysis was repeated for each of the control widgets independently. There was a significant difference between input conditions for each type of control widget: the brick ($F(2, 94) = 46.692, p<0.001$); the rotor ($F(2,94)=49.589, p<0.001$); the ruler ($F(2, 94) = 13.869, p<0.001$); and the square ($F(2, 94) = 40.560, p<0.001$).

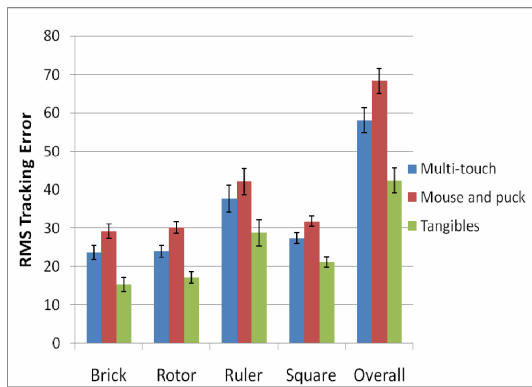


Figure 5. Average root mean square tracking error by input technology (and by control widget)

Post-hoc pairwise comparisons (using Bonferroni-corrected t-tests) showed significant differences between the three input technologies overall and at the level of each individual control widget ($p<0.01$ in each case), with the exception of a comparison between the mouse and puck and multi-touch rulers. Trends for each of the separate control widgets were consistent, suggesting reliability of results, and demonstrating that RMS tracking error was consistently lowest for tangibles, followed by multi-touch and with largest error in the mouse and puck condition.

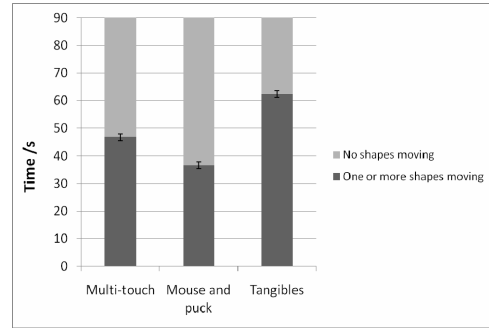


Figure 6. Proportion of idle time during Experiment 2.

We then analysed the proportion of time during experimental trials in which control objects were being manipulated (i.e. the proportion of time during which the surface was recording active interaction with a control object). Figure 6 shows the results. A three-way (two-tailed) repeated-measures ANOVA demonstrated a significant effect of experimental condition on the amount of time spent not moving any shape (“idle time”) ($F(2, 94) = 520.093, p<0.001$). All post-hoc pairwise comparisons (using Bonferroni-corrected t-tests) showed significant differences ($p<0.001$ in each case). The trends were all consistent with the error scores (i.e. less idle time matched with lower error score). This suggests that in the tangible condition, a greater proportion of time was spent actively manipulating control widgets.

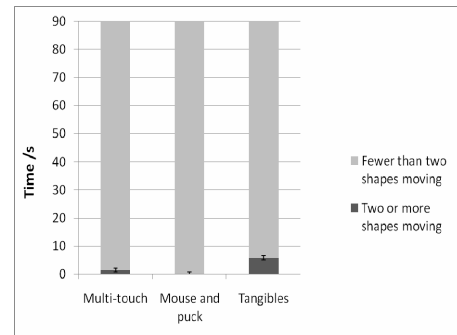


Figure 7. Proportion of experimental time with two or more control objects moving simultaneously.

This analysis was then extended to consider the amount of time during experiments in which two or more objects were moving simultaneously, to help us analyse a potential impact of bimanualism on the results. Figure 7 shows the

mean scores. A three-way (two-tailed) repeated-measures ANOVA demonstrated a significant effect of experimental condition on the amount of time with two or more objects moving simultaneously ($F(2, 94) = 84.922, p < 0.001$). Again, all post-hoc pairwise comparisons (using Bonferroni-corrected t-tests) showed significant differences between conditions ($p < 0.01$ in each case).

Note that whilst there was a significant increase in the amount of time spent manipulating multiple objects concurrently in the tangible condition, this represents an extremely small proportion of the total time in which objects were being manipulated.

As Experiment 1, participants' subjective ratings of comfort and ease of use for each of the three input technologies were also analysed using a three-way (two-tailed) repeated-measures ANOVA. For measures of comfort this showed no significant difference between the conditions. Perceived ease of use, however, was significantly affected by input conditions ($F(2,22)=5.126, p=0.015$). Only one post-hoc pairwise t-test was significant (mouse-tangible). The trends suggested that tangibles were easiest to use followed by multi-touch and then mouse and puck.

As Experiment 1, overall preference rankings were analysed using a Friedman (non-parametric) test. This demonstrated a significant difference between input technologies ($\chi^2(12)=8.667, p=0.013$). The trend was again consistent with performance results. Pairwise comparisons (Wilcoxon signed rank tests) showed tangibles significantly more preferred than mouse and puck ($Z=-2.581, p=0.01$) or multi-touch ($Z=-2.352, p=0.019$). Other pairwise comparisons were non-significant.

Video Analysis

In order to further interpret the performance data and gain a deeper understanding of participants' interactions, we analysed the video recordings of the study sessions. We coded the video data to discern predominant patterns of interaction; we then selected instances of interest for more focused analysis (e.g., interaction difficulties, unique or complex sequences of movement etc.). Our findings highlight behavioural differences between the multi-touch and tangibles conditions (the primary variables of interest).

Although the manipulation experiment allowed us to observe the fine-grained manipulation of controls, the conclusions that could be drawn seemed limited given the highly constrained nature of the task. By contrast, the acquisition experiment provided participants with much more scope to explore the interaction space and determine the most productive and comfortable forms of interaction, because the acquisition task required both fine-grained manipulation and regular reacquisition of objects. Our analysis therefore focuses on the acquisition study, but the findings are equally applicable to the manipulation study.

Our observations identify four major areas in which tangibles and multi-touch differ. We consider each in turn.

Bimanualism and Patterns of Interaction

Where others have suggested that bimanualism is promoted by tangibility, we saw a much more complex relationship. *Bimanualism* conventionally refers to two hands interacting with one object (after Guiard's discussion of asymmetric hand use with non-dominant hands framing action and dominant hands providing fine grained manipulation [8]). While we observed this conventional bimanualism (Figure 8a), we observed two further distinct interaction patterns.

Firstly, we observed both hands interacting concurrently but each hand operating an independent control widget (Figure 8b). For the purposes of this paper, we shall refer to the interaction pattern of two-handed one-object interaction as *bimanualism*; and refer to this other pattern of two-handed two-object interaction as *concurrent unimanualism*.

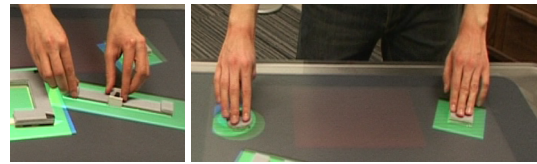


Figure 8. a) (left) bimanualism. b) (right) concurrent unimanualism

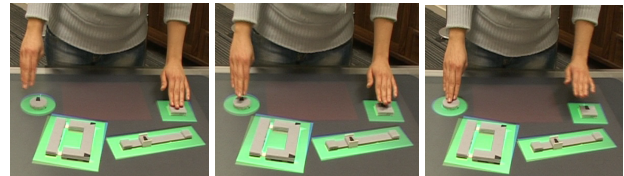


Figure 9. Lateralised sequential unimanualism (left hand operates controls on left, right hand operates controls on right, hands held hovering after use for return adjustment)

Secondly, we observed a further interaction pattern, which we refer to as *lateral sequential unimanualism* (Figure 9). In this pattern, each hand worked a separate (lateralised) area of the interface. The widgets on the left were controlled by the left hand and the widgets on the right by the corresponding right hand. Commonly, the dominant side alternated from left to right. Often a non-dominant hand would be pre-moved to hover near (or rest against) the next intended object for active control prior to acquisition. Sometimes these actions overlapped, effectively producing fleeting moments of concurrent unimanualism. Or the actions might be chained such that after manipulation for example, the right-hand did not entirely disengage from the control widget but rested against it (without active manipulation) whilst the left hand was used on another control, only to return to manipulating the right-hand object as soon as this was complete, and therefore reducing the time required for reacquisition.

We found no causal link between tangible or multi-touch interaction and participants' overall choice to use a unimanual or a bimanual interaction pattern. This questions arguments that tangibility promotes bimanualism.

We did, however, observe that participants in tangible cases were much more likely to use different interaction patterns for the simple brick and rotor controls than for the more complex ruler and stretchable square controls. In tangible cases, 10/12 participants used different patterns for simple and complex controls: 7/12 participants used predominantly unimanual interaction for the simple shapes and bimanual interaction for the complex shapes (overall 11/12 used a bimanual strategy for complex tangible controls). This contrasts markedly with the multi-touch condition, in which 11/12 participants used predominantly a single pattern for their interaction with both the simple and complex objects. In the multi-touch condition there was an even split of participants using bimanual or unimanual patterns; Figure 10 shows examples from one participant.

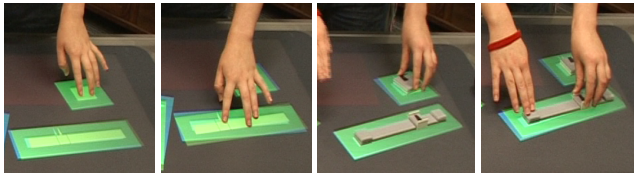


Figure 10. (left to right) a) simple multi-touch b) complex multi-touch c) simple tangible d) complex tangible

Making Contact

Beyond broad patterns of handedness, the nature of contact with controls differed by input condition. This was evident in two ways: the number of contact points with objects; and the use of object edges. We firstly consider contact points.

In the tangible condition, participants commonly used at least three contact points, even when interaction was unimanual, and often used more. A typical gesture can be seen in Figure 10c. Participants commonly used either the first three fingers of one hand, or a combination of thumb and first two fingers in a more grip-like gesture. Where three fingers and no thumb were used, participants commonly rotated objects by applying frictional forces to the top of the object (with all three fingers side-by-side; Figure 9) accompanied by an ulnar deviation at the wrist.

When bimanual interaction occurred in the tangible condition (this typically occurred when manipulating complex objects), the number of contact points was frequently as high as 7 or 8 (Figure 10d). In these cases, the left hand was commonly used as an anchor point using either a top-down friction-based pressure or a form of thumb-forefinger pinch grip, with a thumb-forefinger pinch grip used for fine manipulation of the moveable part of an object by the right-hand. Participants sometimes anchored their movements of the tangibles against the surface itself, using either fingers or parts of hands.

In the multi-touch condition, contact behaviour was very different. 11 of 12 participants used predominantly two contact points (the 12th participant used only three). In unimanual interaction this strategy almost exclusively utilised forefinger and middle finger manipulation.

Rotations were achieved by pivoting one finger around the other. Translations were achieved by movement of the whole hand (whilst retaining these two anchored contact points). When bimanualism occurred in the multi-touch condition, participants again almost exclusively used two contact points. This is similar to the multi-touch unimanual behaviour, but instead of using forefinger and middle finger, participants used the index finger of each hand.

In the multi-touch condition, we also observed the coping strategies used by participants when experiencing interaction difficulties, such as in early stages where they experimented with more complex gestural forms and more fingers. In these cases, users quickly realised a common coping strategy: if they required more control over a multi-touch object, they *reduced* the number of contact points that they had with it, as this invariably improved performance (Figure 11). This coping strategy contrasts with the way we naturally interact with tangible objects: if we wish to exert more control over a tangible object, we routinely *increase* the number of contact points. This was evidenced by the way the majority of our participants used an increased number of contact points for complex objects than for simple objects in the tangible condition.

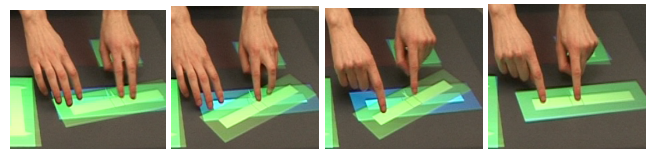


Figure 11. Reducing contacts to regain control in multi-touch

The second major difference in making contact was the use of edge information. In the multi-touch condition, participants sited their two contact points on top of the control widget clearly within the edge boundaries of the active areas of the objects. For the tangibles, however, much of the interaction relied on grip gestures in which fingers rested against salient upper edges of the shape. It is fairly evident that this provides a richer level of control, as more complex forces can be applied.

The Problem of Exit Errors

One of the most commonly observed interactional differences between the two conditions is a factor we refer to as *exit error*. This seems in part similar to observations made by Forlines et al. [7] in their discussion of contact point sizes at different points of arm extension (and has previously been briefly noted in other non-vision-based tabletop systems [1, 20]). They describe how reaching for interactive surface objects at a further distance leads to larger touch points because of the relative angle of the finger to the surface as it makes contact. Herein, however, the problem is slightly different. In the multi-touch condition, participants had difficulty disengaging from the object without causing some form of unintended extra movement. This seemed to occur regardless of the distance of the object from the participant. This is similar to Forlines

et al. [7]: the finger's contact with the surface will likely change shape as the finger is lifted, thus moving the centroid of the touch point and causing a millisecond readjustment of the overall shape.

This exit error occurred repeatedly (and significantly) for 9 of our 12 participants in the multi-touch condition and for none of our participants in the tangible condition. For one participant it evidently became so frustrating that he, presumably unconsciously, began adopting an exaggerated gestural response when he was removing contact from the surface (see Figure 12). Such maladaptive strategies to cope with exit error were significantly problematic.

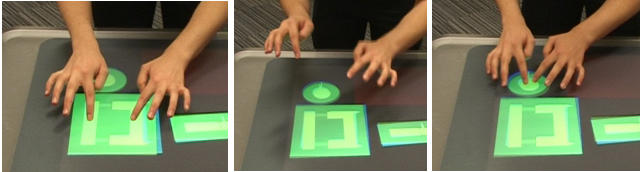


Figure 12. Maladaptive exit strategy to avoid exit error

This problem of exit error was likely significant enough to single-handedly explain the differences in RMS tracking error between the tangible and multi-touch conditions. It was clear from looking at the video data that the exit errors would have inevitably increased RMS tracking error significantly in the multi-touch condition. Nevertheless, there remains a clear difference in performance characteristics between tangible and multi-touch that cannot be explained by exit error and its impact on tracking error, namely the differences in acquisition time.

The Heterogeneity and Adaptability of Tangible Interactions

A final point concerns the extent to which participants could adapt and shape their responses to changing needs in the tangible but not the multi-touch condition.

In the multi-touch condition, we clearly saw that participants reduced the number of contact points to increase control. This seemingly led to a relatively homogenous pattern of control action (between and within subjects). Participants found one comfortable style of interaction (either unimanual or bimanual, but almost always with only two contact points) and then stuck to it, treating all control widgets similarly.

In the tangible condition, there was greater heterogeneity of handed interaction with control objects, not just between participants but within participants as well. It was common for participants to adapt their gestural response, such as adding more contact points and control for more complex objects. Furthermore, this was accompanied by a tendency towards heavy use of the cueing by leaving hands in peripheral contact with controls or hovering over them after or ahead of action, thus leaving open a rich possibility of rapid correction gestures and fleeting returns to control action as attention was shifted from control to control. This often led to complex patterns of interaction. The tangible

condition therefore promoted (or afforded) fluidity and adaptability of response, which was potentially a more successful control strategy for our interface task.

Discussion

The results of Experiment 2 demonstrated an advantage of tangibles over multi-touch. This could be due to either the ability of participants to more accurately manipulate controls in the tangible condition once acquired (as discussed in Experiment 1); or because participants were able to spend proportionally less time acquiring controls in the tangible condition (as shown in the Experiment 2 idle time analysis); or a compound effect of both.

Why might participants be able to spend proportionally less time acquiring controls in the tangible condition than multi-touch? Whilst a factor such as 'un-in-handness' [5] might explain the better performance of the tangible conditions over the mouse and puck control it does little to explain the differences between tangible and multi-touch conditions. The idle time analysis results suggest that either it is faster to acquire tangible controls compared to multi-touch or that the need to reacquire is reduced because of increased concurrent manipulation of controls. However, though we observed a significant difference in the extent to which controls were concurrently manipulated, it is proportionally so small (relative to total manipulation time) that it cannot be responsible for differences between conditions.

This suggests that it may be faster to acquire tangible controls compared to multi-touch. This is supported by the video analysis, which showed that there were more adaptive, differentiated and elaborate patterns of hand use in the tangible condition, with a subtly increased propensity for hover and hold actions in that condition. The reduced acquisition time may well then be largely due to participants' abilities to use the tactile feedback available in the tangible condition and to exploit their familiarity with grasping gestures, to foster not just better more accurate fine grained control but to be able to do this in a faster way than might be possible in the multi-touch conditions.

When comparing tracking error between tangibles and multi-touch, the video analysis would suggest that the most important factor was the exit error during the multi-touch condition. This factor alone clearly impacted the results. It has significant implications for future technology design and, as discussed above, has not previously been reported. It seems that the natural movements of hands when leaving contact with an interactive surface naturally change the shape profile of a contact point, which in turn shifts the contact's centroid location. This can then cause (sometimes significant) last millisecond adjustment of on-screen controls. This is a significant problem that must be addressed. Interactive surfaces will be severely impaired in fine-grained manipulation tasks unless alternative strategies are found, such as scaling inputs, changing temporal sampling techniques for calculating gesture end points or finding means for better surface tracking in the third

dimension. We postulate that one possible solution to this problem is “resetting” the centroid exit location to counteract the potential exit error. Specifically, this could be implemented by routinely setting the centroid exit location to be equal to the location of the centroid 100ms prior. This straightforward solution may go some way to addressing the exit error issue and would not affect input responsiveness during contact.

CAVEATS AND AREAS FOR FUTURE STUDY

Our experiments broadly replicate the work of Fitzmaurice and Buxton [4, 5] with comparable findings. Like them, we have demonstrated significant advantages for tangible controls over other inputs. We have extended their results to differentiate between tangible and multi-touch controls, and updated the results to include comparisons when the output and inputs for the interaction are co-located.

There are clear limitations to our work. The experimental control task we have chosen is somewhat limited in scope. One might argue that these fine-grained interactions are not indicative of the types of interactions that might dominate TUIs or multi-touch surfaces in the future. We do not, for instance, consider complex grouping gestures [19] or simple selection gestures like nudging. Moreover, the comparison of multi-touch and tangibles focuses on interaction with defined objects at the surface, whereas designers will also need to consider additional factors. For instance, tangibles can function as cognitive artefacts outside the interaction surface [2].

Therefore, although we have articulated our results in terms of one technology being ‘better’ than another, this finding is limited to the context of an experimental exploration of simple control widget tasks. Ultimately, TUIs and multi-touch technologies might lend themselves to different types of task, and so it is sensible to move to considering the differential affordances that such technologies offer the user, and away from the rhetoric of which might be ‘better’.

Nevertheless, in framing this experiment we hope to have made some small inroads to this process. By exploring experimentally inspired manipulations, we have begun to highlight interactional implications for multi-touch technologies, such as exit errors, limitations in contact point selection, and the reduction in adaptability and heterogeneity of action. These issues are, we believe, of importance at a much broader scale than might at first be assumed from a generic control-based task.

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