Comparing Physical, Overlay, and Touch Screen Parameter Controls

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ABSTRACT
We present a controlled laboratory experiment comparing touch, physical, and touch + overlay (passive finger guide) input for parameter control. Specifically we examined two target acquisition and movement tasks with dial and slider controls on horizontal touch screens. Results showed that physical controls were the fastest and required the least eye fixation time on the controls, while the overlay improved performance when compared to touch alone. Speed and accuracy differences were seen primarily for dial controls; there was little difference between input conditions for sliders. These results confirm the value of physical input devices for parameter control tasks. They also reveal that overlays can provide some of the same benefits, making them a suitable input approach for certain applications where physical controls are impractical.

Author Keywords
Input; touch screen; physical control; slider; dial; knob; overlay; targeting task; movement; user study; evaluation; parameter control.

ACM Classification Keywords
H.1.2. User/Machine Systems: Human Factors; H.5.2. User Interfaces: Input devices and strategies.

INTRODUCTION
Manipulating sliders and dials is a standard way to adjust continuously varying parameters in user interfaces. There are many examples of such parameters that might be used in applications for interactive surfaces. These include adjusting zoom, brightness, contrast, or RGB color levels in an imaging application, adjusting time in a video player, or adjusting filters in a map-based search tool). We focus here on parameter manipulation tasks that require precision, plus visual attention on some output that is separated from the parameter control widget. For example, for color adjustment, the user may need fine-grained control over a color slider, and will need to observe the colored object to know when to stop. What kind of input is best for this sort of task? Are touch-based dials and sliders good enough? We compare three different input devices for parameter manipulation tasks with sliders and dials on an interactive surface: touch input alone, touch plus a plastic overlay to guide the finger, and physical input devices.

With physical electronics (stereos, sound mixers, oscilloscopes, etc.), people are accustomed to manipulating physical controls (dials, sliders, and buttons). Interaction with physical controls is natural and intuitive, can be done with little visual attention on the control, and can involve the whole hand. In contrast, although touch screens enable a whole new class of multitouch gesture interactions, there are still many interactions that involve single finger manipulation of sliders and dials. For adjusting non-spatial parameters, this form of interaction may be more intuitive and easier to learn than novel gestures. But how impoverished is single finger slider / dial manipulation compared to physical interfaces? What is the cost to visual attention, since the user has to look at the control? Can anything be done to bring back some of the tangibility of physical controls? With the ever-growing ubiquity of touch screen devices, it is imperative to ask these questions.

The well-known benefits of physical input (e.g., graspability, minimal need for visual attention) have led to substantial interest in tangible interaction with interactive surfaces. We support and encourage further research in this area. However, tangible controls are not always ideal. Tangible interfaces typically require many physical props, which could be bulky or heavy; thus they are not very portable. Props must often be supported by a horizontal surface, making them impractical for use with mobile devices and slanted or vertical surfaces. More complex props may be expensive or complicated to build.

Recently, Ullmer et al. [19] and Kincaid [11] proposed using a plastic overlay in conjunction with a touch screen, as a "guide" that contains "slotted widgets". A clear, thin plastic overlay is affixed to the touch screen. Cut-out holes in the location of digital switches, sliders, and dials serve to guide the user's finger and prevent it from straying outside of control areas. One application of such overlays is in portable electronic instruments such as oscilloscopes, signal generators, or sound mixers that would traditionally have physical controls, but that need a compact flat-form factor

ITS '13, October 06 - 09 2013, St Andrews, United Kingdom

ACM 978-1-4503-2271-3/13/10…$15.00.
http://dx.doi.org/10.1145/2512349.2512812

like a tablet or mobile phone [11]. Such tools are increasingly available as mobile device apps, making it no longer necessary to purchase a dedicated instrument for each task. We also envision overlays being used as a tangible "slap widget" interface [23] for interactive tabletops (e.g. for controlling display and filter parameters in data visualizations).

In a pilot evaluation, Kincaid [11] showed that an overlay for touch dials reduced the time required for targeting tasks when compared with touch alone. Similarly, Kulik et al. [13] showed that a touch dial + overlay ("pie slider") supported faster input than indirect manipulation of graphical sliders. We extend the work of Kincaid and Kulik et al. by asking the following questions: Do overlays provide the same benefit for sliders as for dials? How exactly does the overlay reduce parameter adjustment time for dials (is it by reducing the time to acquire the control, the time to move it, or both)? And how do overlays compare to physical dials and sliders, which have the additional characteristic of graspability? Results of our experiment demonstrate that overlays are an improvement over direct touch for dials, but that physical dials are still preferable. In addition, the overlay reduces time for dial movement but not for acquisition. In contrast, for sliders, all input techniques seem to be equally effective. Following the description of our experiment, we discuss potential applications for overlays, and design issues to consider for parameter controls in interactive surface applications.

RELATED WORK

Tangible user interfaces (TUIs) for interactive surfaces have been a popular research topic in recent years. In early work, DataTiles [16] were used in conjunction with an underlying flat panel display, as small tangible information displays and controls. More recently, a series of papers have discussed cartouches [20] or casiers [19], composable objects that serve as containers, tools, or tokens, and operate in conjunction with a touch screen device. Madgets further extended the space of tangible surface interactions by enabling the tangible widgets to be actuated [22]. Many other TUIs for interactive surfaces have been proposed, for a wide variety of applications.

Potential benefits of tangible and physical UIs are nicely summarized by Ishii et al. [9] and Ullmer et al. [21]. These include graspability, passive haptic feedback, the ability to operate controls with minimal visual attention, learnability, and potentially, the fun and intuitive nature of this type of input. For example, Fitzmaurice and Buxton [7] demonstrated that physical user interfaces with specialized shapes and dedicated functions were superior to a generic input device for a target tracking task, and suggested that graspability was a key benefit. Terrenghi et al. [18] reported that a physical lens tool was easier to learn than a graphical equivalent, though interestingly, people preferred using the touch screen because they found it more direct.

We focus here on interfaces for adjusting continuous parameter values, typically using dials or sliders. Several previous experiments have compared physical dials and sliders to other types of input, most finding benefits for physical interaction. Jansen et al. [10] showed that a physical slider was faster to acquire than a touch slider and had higher tracking accuracy. Swindells et al. [17] showed that physical sliders could be adjusted with significantly less visual attention than virtual sliders operated using a mouse or pen. Ullmer et al. [21] similarly reported that users could pay more visual attention to the screen with a TUI than a graphical interface; however, there was substantial setup time required for the TUI. Hunt and Kirk [8] found that physical sliders were more effective than virtual ones for setting parameters in a sound matching task. Similarly, Chipman et al. [4] found that a physical slider and a mouse wheel were better for scrolling tasks than a graphical scrollbar. In contrast to most other studies, Kratz et al. [12] found that a physical interface for video navigation was slower than touch interaction with a dial and slider; however, problems with the design of the physical control may have accounted for this result.

Our work expands current understanding of the benefits and drawbacks of different input techniques for interactive surfaces, by comparing traditional touch and physical UIs to plastic overlays. Many previous investigations of overlays have focused on improving accessibility for blind users [3, 14]. The interaction context is quite different in our use case because the person can still see the controls but may wish to focus their visual attention elsewhere during operation. For sighted applications, overlays first appeared in Data Tiles [16], where grooves in the tiles were used to guide pen input. More recently they have been used in conjunction with touch input [11, 13]. A commercially available overlay assists with typing on a mobile touch screen device [25].

Overlays extend the space of tangible interactions with touch screens, and theoretically, should provide some, but not all, of the benefits of other physical interfaces. In particular, they provide a guide for the finger that may make the controls easier to acquire than touch alone and should enable interaction with less visual attention than touch alone. However, they lack graspability, and the overlay does not itself store any information (e.g. in the way that the position of a physical slider stores information about the slider's value). To date there is very little empirical evidence about how overlays compare to these other input techniques. The studies by Kincaid [11] and Kulik et al. [13] (mentioned in the introduction) did not consider overlays for sliders, nor did they compare overlay and touch to physical controls.

EXPERIMENT DESIGN

We designed a controlled experiment to compare the overlay to touch alone and to physical controls (see Figure 1). Our goal was to assess specific hypothesized benefits of the overlay compared to touch, and also to see how it compared with physical controls, which we presumed should be equally good or better. We focus on basic low-level movement tasks that are the basis of all parameter adjustments. We therefore expect the results to be applicable to parameter control tasks in a wide variety of applications. In our study, the parameter controlled is the horizontal position of a cursor. This is not meant to be a realistic scenario of use; rather it is an easy-to-understand representative of a class of tasks in which the user manipulates some parameter and receives visual feedback. In many such tasks, the feedback would be visual, but not spatial in nature (e.g. manipulating R, G, and B sliders for color). To mirror such non-spatial tasks, we physically separate the controls from the feedback display, even though for our stand-in task it would clearly be beneficial to put the control in close proximity to the display or simply use direct manipulation.

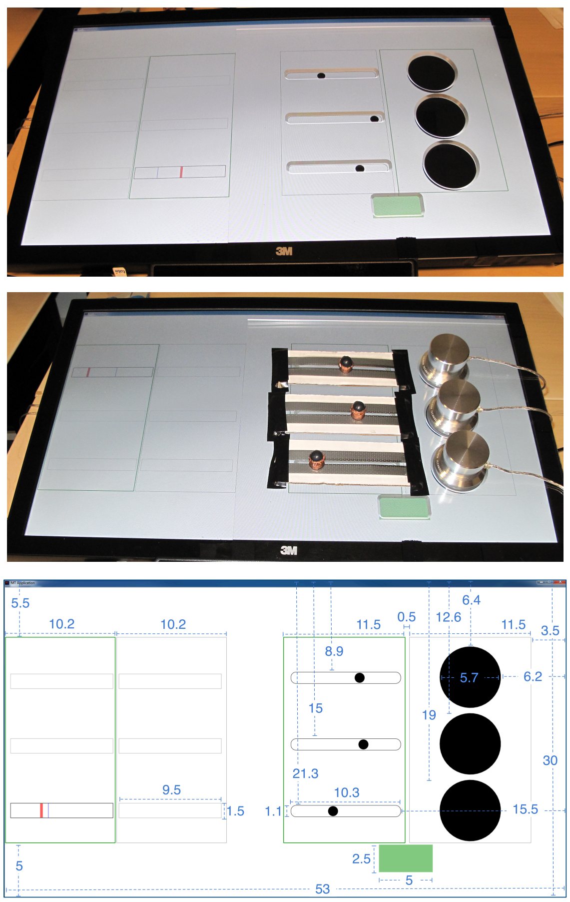

Figure 1: Conditions and Task 1 (Acquisition & Movement): Touch + clear plexiglass overlay (top), Physical (middle), Task 1 screenshot annotated with dimensions in cm (bottom).

Our experiment used a 3 conditions (touch, overlay, physical) x 3 control types (slider, single turn dial, multiturn dial) within subjects' design. The multiturn dial was used only in Task 2. Presentation order was random for control types and fully counterbalanced for conditions.

Participants

We recruited 12 right-handed adult participants (10 male, 2 female) from Agilent Laboratories. One was 18-29 years old, 2 were 30-39, 1 was 40-49, 6 were 50-59, and 2 were 60 or older. Most held a Masters or PhD degree in Science or Engineering and worked in a research capacity. One was a manager. Ten reported normal or corrected to normal vision; the other two reported that seeing the screen used in our study was not a problem. No participants reported color vision deficiencies. Experience with touch screen devices ranged from daily (4 participants) to never (1 participant) with others in-between. Participants were randomly assigned to groups who completed the conditions in different orders (two people per condition order).

Tasks

We focus on low-level movement tasks. Movement time on targeting tasks is known to vary with the width of the target and the distance traveled. In 1954, Fitts [6] quantified the difficulty of a reciprocal aiming task by defining the index of difficulty (ID) as:

$$ID = \log_2(2A/W) \qquad (1)$$

where A is the amplitude of the movement (distance) and W is the target width. Fitts also showed that movement time (MT) is linearly related to ID:

$$MT = a + bID \qquad (2)$$

where a and b are empirically determined constants. Since then, a very large number of input studies have used similar movement tasks. While there have been variations in the definition of ID, the basic relationship between MT, width, and distance has been repeatedly verified.

Our two tasks examined different aspects of control manipulation. The first task was designed to test how easy it is to acquire a control (i.e. get one's hand from another location to the control). This is important when a user needs to move their hand from one control to another to adjust different settings. The second task was designed to test practiced and repetitive movement of one control. This is important when a user operates a single control for an extended period of time (e.g. moving back and forth between two levels of a setting to make comparisons).

Task 1 – Acquisition and Movement

Task 1 is illustrated in Figure 1. It was designed to test the time required to acquire a control, and was inspired by an acquisition + tracking task used in [10]. The participant began each trial by pressing a green start button. A red and a blue bar would then appear in one of six display areas on the left side of the screen (see Figure 1 bottom left). The participant had to identify which control (out of 3 sliders and 3 dials) mapped to the live display, move their hand from the start button to the control, and then adjust the control to make the blue bar move into the red region. We used a direct spatial mapping between displays and controls (i.e. sliders controlled the left three displays and dials controlled the right three), and also showed a large green box around either the dials or sliders (whichever set should be used on that trial) to assist with control selection. For example, in Figure 1 (bottom), the user must manipulate the bottom slider, since the bottom left display is the active one. When the blue bar entered the red region, the saturation of the red area was increased as feedback. The trial automatically ended after the blue bar remained continuously in the red area for 1000 ms. Moving the bar out of the red region and then back before the trial ended was counted as an overshoot, and reset the 1000 ms timer.

For each of the conditions, participants completed a set of 18 trials: 6 controls x 3 repetitions, in random order. They were instructed to be as fast as possible. We measured the *acquisition time* (i.e. time from the start of the trial until the correct control began moving) separately from the *movement time* (i.e. from the acquisition event until the end of the trial). We also counted the number of overshoots.

Task 2 – Repetitive Movement

The repetitive movement task is illustrated in Figure 2, and was modeled after a movement task used by Mandryk and Gutwin [15]. On each trial, the participant had to move a cursor back and forth between two targets 5 times (10 one way movements), using either a slider or a dial. Participants were instructed to do these movements as quickly as possible, while aiming for 2 or fewer overshoots out of the 10 movements. A green arrow plus textual description indicated which control should be used (e.g. for the trial shown in Figure 2, the slider is the active control). Single turn and multiturn dials used the same input location but the behavior differed. The single turn dial was labeled as “fast knob”, was black in color, and took one full rotation to move the cursor from one end of the display to the other. The multiturn dial was labeled as “slow knob”, was light blue in color, and took 3 full rotations to move the same distance. The current target was always shown in red. As soon as the cursor entered the red target, the color changed to grey and the other target became red, or the trial ended.

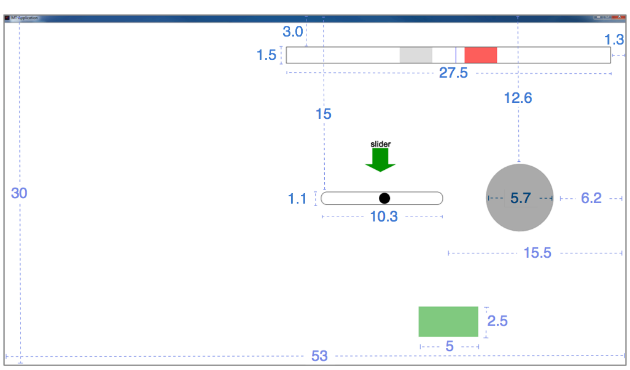

Figure 2: Task 2 (Repetitive motion). One slider and one dial were used to control a cursor that moved between grey and red targets (visible at the top of the screen). Dimensions in cm.

Each trial used one of three possible target widths (W) (25, 50, and 100 pixels) and one of three possible distances (D) between targets (200, 400, and 800 pixels). These resulted in Fitts’ ID values between 2 and 6. We used Fitts’ original method for calculating ID (see equation 1) according to the visual target width in pixels. We constructed trials from all nine combinations of widths and distances, for each of the three control types (slider, single turn dial, multiturn dial). Thus, participants completed 27 trials in each condition. Trials were presented in random order within each condition block.

Apparatus

Participants sat at a desk and interacted with a 24” capacitive multitouch display (3M M2467PW) that was oriented close to horizontal (13°). Display resolution was 1920 x 1080. Participants manipulated slider and dial controls on the right side of the screen using either direct touch or physical widgets. In the overlay conditions, a 30 x 34 cm clear plexiglass panel was fixed in place over the digital controls; it had cut outs to enable touch interaction only within control areas. In the physical conditions, physical dials were placed in the overlay’s dial slots (designed to fit precisely) and physical sliders were affixed to the overlay in the slider slots. Thus the position of physical controls was identical to touch and overlay conditions. For the physical dials, we used three Griffin Powermate devices, connected by USB. For the physical sliders, we constructed custom conductive widgets that could be detected by the touch screen. The size of the graphical circles for the dials was enlarged in the physical condition so that the color was visible around the Griffin Powermate. Input controls were at the right rather than centered on the screen to minimize blockage of eye tracker cameras by the user’s hand.

Software implementation details of the controls were carefully considered, to give each input type the best possible chance of success. Touch and overlay controls used relative rather than absolute motion. The sliders were acquired if the user touched anywhere within the slider region (including but not necessarily the black dot). This mirrors the way the touch dials work since you can touch anywhere within the dial area. After acquiring a slider or dial, the control would adjust its value based on horizontal location (sliders) or angle (dials), as long as the finger remained in contact with the screen. This occurred regardless of whether the finger strayed outside of the graphical control area, including beyond the end of a slider. This reduces the need to visually attend to the finger movement, and the need to clutch when using touch sliders (i.e. repositioning one’s hand after reaching the end of the input area). In contrast, physical sliders used absolute positioning because relative positioning is incongruent with the way physical sliders normally work. Note that relative versus absolute positioning changes the position where movement can start, but not the total distance the control must travel. For dials, clockwise motion moved the cursor to the right and counterclockwise motion moved it left.

Eye tracking data were collected using a Tobii X1Light eye tracker attached to the bottom of the display. The display angle (13°) was chosen to balance ergonomics with eye tracker requirements. Eye gaze fixations were extracted from the eye tracker data using Tobii Studio's I-VT fixation filter, with a minimum fixation duration of 60ms. We defined areas of interest (AOIs) around the input controls and the display areas, and measured the duration of fixations within each AOI.

An experimenter controlled and monitored the study from a neighboring desk containing three displays and a mouse and keyboard attached to the same machine. Custom experimental software, written in Java, was used to present trials and log timing and overshoot data.

Procedure

Participants were initially greeted and introduced to the general purpose of the study. They were positioned in a location where the eye tracker could detect their eyes, and then the tracker was calibrated using a 5-point calibration scheme. For some people, calibration failed and the eye tracker was not used.

Participants then completed six blocks of trials. First they completed both tasks for the first condition, and then repeated both tasks for the other two conditions. Conditions were in counterbalanced order. This ordering minimized the number of times the input controls needed to be changed during a study session. Participants took a short rest between conditions, while the experimenter changed the control setup. Task 2 was always done after Task 1 because it was meant to test practiced repeat movement, so Task 1 also served as practice for Task 2. Participants were allowed to practice before each block until they notified the experimenter that they felt comfortable with the task and interface. Participants began each trial by pressing a green touch screen button at the bottom of the screen. Trials ended automatically as described in the Task section.

For touch and overlay conditions, we instructed participants to use exactly one finger on their right hand. For the overlay conditions, we explicitly asked them to use the edge of the overlay to guide their finger (otherwise the condition is effectively the same as touch). For the physical condition, participants were allowed to grasp the controls however they wished, but again only with the right hand. We pointed out that the physical dials could be operated either using the whole hand or a single finger on the top or edge.

We concluded the session by asking participants to fill in a questionnaire consisting of demographic questions plus feedback on the conditions. Participants ranked the three conditions for overall appeal and for ease of completing the tasks with sliders, single turn dials, and multiturn dials.

Hypotheses

H1: Acquisition and movement times will be fastest with physical and slowest with touch, with overlay in-between.

H2: Physical and overlay will require less eye fixation time on the controls than touch.

H3: As compared to touch, overlay will be most helpful for rotary motion (dials), and especially for multiturn dials.

Analysis

Results were analyzed statistically using R. Data were first transformed to improve the fit to a normal curve (checked using Q-Q plots). We then ran repeated measures ANOVA followed by pairwise comparisons, or ANCOVA for time in Task 2. For measures that could not be transformed to fit a normal distribution, and for ranking data, we used nonparametric Friedman and Wilcoxon tests. All pairwise comparisons used Bonferroni correction. Eye tracking data were analyzed only for Task 1, because the eye tracker did not work reliably for fixations at the top of the screen, where the display was located in Task 2. Only significant results are reported.

RESULTS

Task 1 – Acquisition and Movement

There were no significant differences between conditions in terms of accuracy (number of overshoots), so we focus on time and eye gaze data.

Acquisition Time

Figure 3 illustrates that time to acquire the correct control was fastest for physical dials.

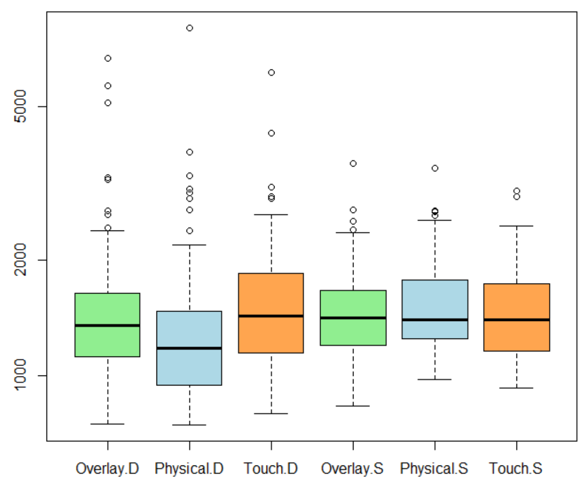

Figure 3: Boxplots of acquisition time (ms) in Task 1. S=Slider, D=Dial.

ANOVA showed a significant main effect of control type ($F(1,11)=16.6$, $p<0.002$) and an interaction between condition and control type ($F(2,22)=8.5$, $p<0.002$). There were no significant differences between conditions for sliders. Pairwise comparisons showed that only for dials, physical was significantly faster than touch ($p<0.018$). Contrary to our expectation, there appeared to be no consistent difference in acquisition time depending on the control positions (top, middle, or bottom) so this factor was not analyzed further.

Movement Time

Movement time had a significant main effect of condition ($F(2,22)=3.926$, $p<0.035$), and an interaction between condition and control type ($F(2,22)=8.4$, $p < 0.002$). Post-hoc tests showed that movement time was faster for overlay than physical with the slider controls ($p < 0.015$). There were some minor issues with the physical slider design that may account for this difference (see qualitative comments).

Eye Tracking

For each participant, we calculated the duration of eye gaze fixations in two areas of interest: an area defined around the control region (where the user manipulated controls) and an area defined around the display region (where feedback of the user's actions appeared). Figure 4 displays the percentage of fixation time on the control area relative to the total duration on both areas of interest (we call this measure PFixControl).

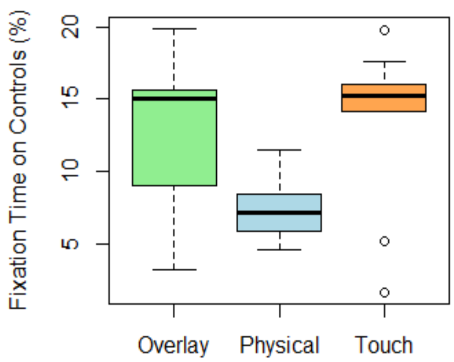

Figure 4: Percent of eye gaze fixation time on controls.

For many applications, it may be desirable to interact with controls in an "eyes-free" manner, where the user's attention focuses on the visual feedback. Thus we prefer input methods with lower PFixControl values. Figure 4 demonstrates that the physical interface achieved the lowest values on this measure. Overlay's median was very close to that of touch, but overlay was much more variable, suggesting that it was successful in reducing fixations on the controls for some people. ANOVA showed a significant main effect of condition ($F(2,14)= 4.3$, $p< 0.036$), but pairwise comparisons were not significant due to low statistical power. (Due to difficulty calibrating the eye tracker with the nearly horizontal display, we were able to collect eye gaze data for only nine participants.)

Task 2 – Repetitive Movement

Time

Each trial consisted of 10 back and forth movements. Because we were interested only in practiced movement, we discarded the first 4 movements in each set, and then averaged the time for the remaining 6. Figure 5 plots these data by Fitts' ID, along with regression lines and r^2 values. It shows that for dials, physical was fastest, touch was slowest, and overlay was in-between. For sliders, condition had no observable effect.

We analyzed the data using repeated measures ANCOVA with condition as a factor and ID as a covariate. Three separate analyses were run, one for each control type. As expected, in all three analyses, the effect of ID was significant ($F \geq 1340$, $p<0.001$). The effect of condition was significant for single turn dials ($F(2,11)=37.8$, $p<0.001$) and multiturn dials ($F(2,11)=7.0$, $p<0.005$, but not for sliders ($F(2,11)=0.3$, $p<0.8$). For multiturn dials, the movement time appears to converge for different conditions at higher ID levels, as shown in Figure 5 (right). Separate ANOVA analyses revealed that for multiturn dials, condition had only a marginally significant effect at ID 5 ($F(2, 24) =2.95$, $p<0.08$), and no significant effect at ID 6.

Interestingly, Fitts' ID did not accurately predict movement time for long distance (800 pixel) movements with multiturn dials. Our D and W combinations included three types of ID=4 trials and two types of ID=5 trials. Figure 6 reveals that of these 5 trials, those with D = 800 had longer times than other trials with the same ID; Fitts' law would predict the movement times to be the same. This effect occurred only for multiturn dials, and was consistent across all three input conditions. Separate ANOVAs revealed a significant main effect of the Distance-Width combination factor for both ID=4 ($F(2,24)=85.4$, $p<0.001$) and ID=5 ($F(1,12)=22.4$, $p<0.001$) for multiturn dials. All Distance-Width combinations were significantly different from each other at both ID levels ($p < 0.002$).

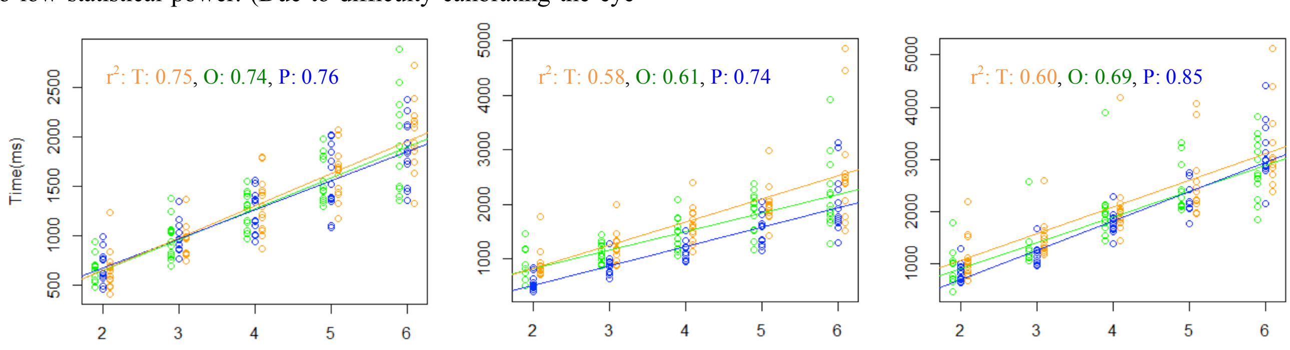

Figure 5: Average movement time in Task 2 by index of difficulty. Orange = Touch (T), Green = Overlay (O), Blue = Physical (P). For clarity, points are jittered on the x-axis to separate each series.

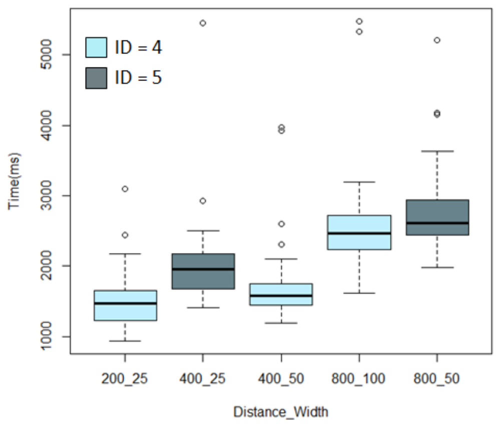

Figure 6: Movement time for ID 4 and 5 trials with multiturn dials, broken down by Distance and Width (in pixels).

Error (Overshoots)

We measured the overshoot distance on each trial (i.e. distance in pixels that the cursor moved beyond the outer edge of the target). Similar to the time data, we discarded the first 4 movements, to focus on practiced movement, and averaged the remaining movements. (Note that the last movement is also excluded because the trial ends automatically and there is no opportunity for an overshoot.) Results are shown in Figure 7.

We ran Friedman tests for each control type. Results showed a significant effect of condition for dials (χ^2= 12.7, p<0.002) and multiturn dials (χ^2= 12.8, p<0.002), but not sliders (χ^2=2.4255, p <0.3). Pairwise Wilcoxon tests showed that touch had higher error than overlay (p<0.002 single turn, p<0.05 multiturn) and physical (p<0.008 single turn, p<0.002 multiturn), for both types of dials.

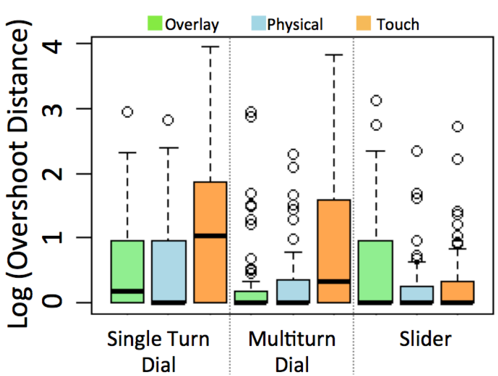

Figure 7: Error level, shown by Log of (1+ overshoot distance). Log transform is used for chart clarity.

Questionnaire Results

Participants were asked to rank the three conditions with respect to how easy it was to complete the tasks. Results are shown in Figure 8. For the sliders, there was little difference among the conditions, and these differences were not significant. For single (χ^2=8.6, p<0.02) and multiturn (χ^2=13.2, p<0.002) dials, physical and overlay were preferred. Pairwise Wilcoxon tests showed that touch was significantly worse than physical for both types of dials (p<0.04 for single turn and p<0.02 for multiturn). Touch was also worse than overlay: for multiturn this difference was significant (p<0.004) and for single turn it was marginally significant (p<0.06). Overlay and physical were not significantly different from each other. There were no significant differences in rankings of overall appeal.

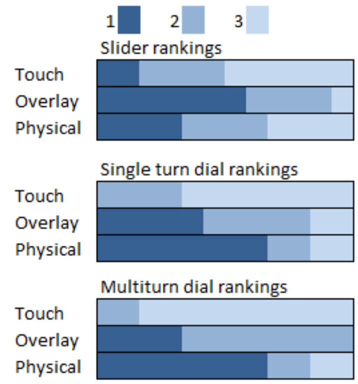

Figure 8: Ranking of the conditions for each control type. Bars indicate the number of people who assigned each rank. 1=easiest to use, 3=hardest to use.

Qualitative Comments and Observations

Participants' comments were either written on the questionnaire form, or mentioned verbally during or after the experimental tasks. These helped to explain some of the quantitative results.

When comparing touch and overlay conditions, most participants reported that the overlay was most helpful for dials. Spinning one's finger in a consistent circle is quite difficult, and without the overlay's guidance, participants found themselves going outside of the circle or across the middle, resulting in unexpected effects or variable velocity. The overlay relieved these problems. According to one person, "The slow touch knob is torture." Several participants also reported that they could remember a position on the circle (e.g. "8 o'clock") with the overlay, which was useful for the repeated motion task.

Problems with the touch and overlay conditions most often were caused by friction. Several participants reported that their fingers "stuck" to the touch surface and / or overlay. Some participants found that they could move more efficiently by touching the surface with their fingernail. Friction problems were most problematic for the dials.

Problems with the physical conditions were different for dials versus sliders. Several participants commented that the physical sliders (which used the capacitive touch surface) were not optimal. Although we were careful to design sliders that stayed in place and worked consistently, participants complained that they were wobbly and required some pressure. A few participants wanted to be able to nudge the sliders with a single finger, which was not possible with our implementation. Physical dials worked quite well for the most part, but occasionally bounced out of their slots when people did a lot of clutching (i.e. releasing the control, adjusting one's hand position, and then re-grabbing the control).

Some participants commented that they liked being able to use multiple fingers, and choose which fingers, with the physical controls. Nearly everyone initially grasped the physical dial using multiple fingers. However, in the repetitive motion task, most participants quickly transitioned to using a single finger on the physical dial, at least for multiturn trials, presumably because clutching was too slow and tedious. Two participants suggested exploring multitouch versions of the physical and overlay conditions.

DISCUSSION OF HYPOTHESES

H1: Acquisition and movement times will be fastest with physical and slowest with touch, with overlay in-between.

This hypothesis was confirmed for dials but not sliders. For dials, overlay consistently performed in between physical and touch interfaces for repetitive movement. It also fell in between for acquisition (though only physical and touch were significantly different from each other). Interestingly, based on the linear regression plot in Figure 5 (middle), we observe that for single turn dials the improvement in task time of the overlay compared to touch appeared to increase with increasing difficulty. With low ID, there was marginal difference between touch and overlay, whereas overlay was faster than touch at higher ID levels. For multiturn dials (Figure 5 right), touch was consistently the slowest, but overlay appeared to converge with physical at higher IDs.

For sliders, however, there were generally no significant differences between the conditions, suggesting that any of them are acceptable. The only exception was that the physical slider was slower than overlay for movement time in task 1, but we suspect this difference might disappear with an improved physical slider design. Participants reported that touch sliders were more natural than touch dials, and having the guidance of the overlay was therefore less important for sliders.

As we hypothesized, the overlay seems to provide some, but not all, of the benefits of a physical interface. In particular, it provides a guide that supports consistent finger motion and position sensing. These supports seem to be much more important for dial controls than sliders, probably because rotary motion is harder to control than linear motion.

H2: Physical and overlay will require less eye fixation time on the controls than touch.

This hypothesis was only partially supported. Physical had less fixation time than touch, as expected, but overlay fell in between, with the median nearly the same as touch. The greater variability in the overlay condition suggests that some people were able to reduce eye gaze fixations on the controls compared to touch, but others continued to look at the controls. It is possible that participants thought they needed to keep their finger on the black dot within the touch slider widgets (in fact you could touch anywhere within the slider) and this caused more control fixations than necessary for sliders. Low statistical power limits our ability to analyze this issue in greater depth.

H3: As compared to touch, overlay will be most helpful for rotary motion (dials), and especially for multiturn dials.

This hypothesis was supported. For dials, overlay significantly reduced both response time and error in task 2 compared to touch. Participant comments suggest that the overlay was especially important for the multiturn dials. We expected to see a similar, but smaller effect for sliders, but in fact saw no effect at all.

APPLICATION SCENARIOS

Slap widgets for parameter control: In comparison to direct touch, overlays were quite helpful for dials, and for sliders they did not hurt. This suggests that small handheld size overlays could be useful as parameter control "slap widgets" [23] on a large touch screen such as a tabletop display. The system could detect when and where the widget was placed on the screen (e.g. though tracked tags), so that placing it near a virtual object could cause the system to display parameter controls for the object.

Possible uses of such slap widgets could be to control parameters such as opacity in a drawing application, along the lines of VoodooSketch [2], or to control parameters for audio editing similar to an application by Fiebrink et al. [5]. Yet another application could be tangible queries. For instance, placing a widget near a map displaying homes for sale could enable a user to filter the search through parameters, similar to HomeFinder [24]. The concept of tangible queries was proposed by Ullmer et al. [21], but their approach required a specialized query rack and physical sliders and dials. Although our results show that physical controls support better performance (not unsurprisingly), their expense, size, and weight might make them impractical for use in many scenarios.

We note that a parameter control slap widget would need to be made of a smooth, hard material to ensure surface friction does not impede finger movement. It would also need to be held in place during finger motion, either by using the non-dominant hand or perhaps through sticky feet that temporarily affix it to the touch screen.

Mobile instruments: For the control of equipment and instruments (e.g. audio mixing boards, musical instrument tuners, oscilloscopes), our results demonstrate that physical controls should support the best usability and should be used when possible. However, there are situations in which physical controls are impractical due to their size and weight, or dedicated function. In these circumstances, overlays may be a viable alternative, since they provide some of the same benefits. Examples might include mobile instruments for use in the field, or cases where instruments are used only very infrequently, and people therefore do not wish to devote the expense or desk space to purchasing many types of specialized instruments. For these scenarios, a touch screen device (which might be simply a smart phone or tablet) could serve as many different instruments at once; changing instruments could be as simple as changing the overlay snapped onto the front [11].

GENERAL DISCUSSION AND DESIGN IMPLICATIONS

Our results should be interpreted with our specific implementation choices in mind. There are in fact many behavioral choices that must be made when implementing touch sliders and dials. We attempted to choose designs that gave the best possible chance for success to each condition in the study. However, our choices do impact the results. The following choices may be particularly important: relative rather than absolute motion, ability to acquire a slider anywhere within the control region, and ability to move one's finger outside of the control area during a movement. Results might change with different choices for how software sliders and dials work, or with a different choice of technology for the physical controls. For example, dials with momentum (i.e. dials that continue spinning on their own after the person lets go) would likely have very different performance characteristics than our implementation, and would probably reduce clutching problems with the physical dials. In addition, our horizontally oriented sliders matched the horizontal cursor movement in our output displays. It would be useful to examine the effects of a mismatch (e.g. a vertical display) and of non-spatial output, since these would likely influence performance with sliders.

With our slider implementation, one possible disadvantage of the overlay compared to touch is that it constrains movement to within the control widget. This means that if a user does not acquire the slider precisely on the indicator dot, they might need to clutch to make a long movement, whereas with the touch version they could just continue the motion outside of the slider without clutching. It is interesting that only one participant noticed and mentioned this, and it did not lead to overall inferior performance.

Based on a combination of our results and our design experience, we offer the following guidelines for the design of dial and slider control interfaces:

1. *When feasible, choose physical controls*. Ensure the physical controls are firmly affixed to some base plane so that they do not slide or shift while being manipulated. Physical controls that communicate directly with the operating system may offer more consistent and reliable behavior than passive widgets that operate via interactions with a capacitive touch screen.

When physical controls are not practical:

2. *Consider providing an overlay guide to improve interaction performance*. An overlay is particularly helpful for dials, as it supports more consistent hand motion, but nonetheless does not hurt for sliders. With practice, people may learn to reduce their visual attention on the controls with an overlay, which is not possible for touch alone. The overlay must be fixed in place to be effective (e.g. perhaps using thin rubber feet, magnets or suction cups).

3. *Implement touch sliders in a way that reduces the need for input accuracy*. In particular, accuracy requirements can be reduced by allowing the person to touch anywhere within the slider (not just on an indicator dot) and by allowing the finger to stray outside of the slider and beyond the end of the slider during a movement.

4. *Avoid long distance "spinning" with a non-weighted touch dial*, as this is an awkward interaction that is difficult to perform consistently. Consider using scrolling instead of a dial for long distance or repetitive movement tasks, or combining a dial for precise adjustments with some other input mechanism for coarse adjustments. Virtual weighted dials (that emulate momentum and friction and will continue movement on their own once started) might also be effective, though we did not test this in our study.

FUTURE WORK

In future work, we would like to explore specific application scenarios, and diversify the design space of touch and overlay parameter controls. With the overlay, we would like to examine the effect of adding detents (i.e. bumps or dips) to the edge of the overlay. These could potentially provide extra passive haptic feedback about how far the finger has traveled, but at the same time, the non-smooth surface might make sliding more difficult. We would also recommend trying different materials to find one that minimizes friction during movement. With touch parameter controls, it would be interesting to examine the effects of virtual 'weighted' dials that have momentum, explore digital "smoothing" of circular touch motions to improve reliability, and sexplore the space of multitouch gestures that could be done within virtual dials and sliders. We would also like to reexamine eye movement with these interfaces using a more robust eye tracking configuration.

CONCLUSION

We compared touch, physical, and touch + overlay approaches for parameter control on a horizontal touch screen, using dials and sliders. Physical controls were the fastest and required the least eye fixation time on the controls, while the overlay improved performance when compared to touch alone. Our results extend previous work on overlays, by showing that they provide some but not all of the benefits of physical controls, that the benefit of overlays is during control movement rather than control acquisition, and that overlays are more helpful for dials than for sliders.

ACKNOWLEDGMENTS
We thank Diane Larson and Michael Domler for their help in fabricating our overlay.

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