Comparing Parameter Manipulation with Mouse, Pen, and Slider User Interfaces

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Abstract

Visual fixation on one's tool(s) takes much attention away from one's primary task. Following the belief that the best tools 'disappear' and become invisible to the user, we present a study comparing visual fixations (eye gaze within locations on a graphical display) and performance for mouse, pen, and physical slider user interfaces. Participants conducted a controlled, yet representative, color matching task that required user interaction representative of many data exploration tasks such as parameter exploration of medical or fuel cell data. We demonstrate that users may spend up to 95% fewer visual fixations on physical sliders versus standard mouse and pen tools without any loss in performance for a generalized visual performance task.

Categories and Subject Descriptors (according to ACM CCS): H5.2. Information interfaces and presentation: User interfaces− interaction styles, input devices and strategies, evaluation/methodology. H.1.2. User/Machine Systems: Software psychology. I.3.6. Methodology and Techniques: Interaction techniques.

1. Introduction

Exploring data in applications such as medical imaging often requires a user to manipulate many parameters to see different portions of the data, see the data from different perspectives, or to find a desired result. If a final image is known a priori, there's typically little need for human exploration instead of an automated process to perform a set of data manipulations. However, more often, the desired views of the data are unknown and the process of exploring different views through parameters is more important than obtaining a final image. Moreover, the combination of parameter settings that will achieve a desired new data result is rarely obvious. Experimenting with a range of display options and queries may provide insight not possible with static images alone [Rhe02]. Adjusting parameters in these situations requires frequent control manipulation to enable exploration of alternatives.

We present an experiment comparing mouse, pen, and physical interfaces (sliders) for a parameter manipulation task. Prior research (e.g., Crider et al. [CBS*07]) reported qualitative benefits of physical controls, such as physical sliders, knobs, and buttons, over graphic controls for parameter manipulation in some visualization applications. Our goal was to *quantify* these differences, if they occur, and deduce the reasoning behind them.

Compared to physical controls, graphic controls manipulated through pen and mouse interfaces are less expensive and more flexible (e.g. mappings of functions to controls can be changed dynamically, and controls can be hidden). Furthermore, mouse and pen interfaces are often the best choice where clear mappings are know, such as the (x, y) position of an object [JSMM94]. However, physical controls have potential interaction advantages:

- Bimanual interaction: physical controls allow use of two hands, potentially allowing two parameters to be manipulated simultaneously [BM86, HYA*08].
- Graspability: physical controls can be easily grasped, potentially reducing acquisition time [FB97].
- Visual attention: physical controls may be easier to move with less visual attention [CBS*07, HPGK94].

Because control adjustments take place frequently, these differences could provide substantial benefit over the course of a higher-level task.

1.1. Task Choice

Our experiment involved a color matching task. Participants adjusted four slider controls to alter the appearance of a color swatch until it matched a target color. Each control adjusted one parameter in a perceptually linear color space.

We chose this particular color matching task to carefully meet two objectives. We sought a task that was:

- Representative of parameter manipulation in other high dimensional data exploration tasks.
- Effective for measuring correctness.

Color matching is representative of data exploration tasks for several reasons: it involves manipulating several parameters in no specified order; some parameters have more intuitive effects than others, and some parameters are conceptually independent where as others are conceptually related. In particular, we used the CIE L*a*b* color model. In this model, lightness could be easily understood and independently manipulated, but yellow-blue and red-green parameters were less intuitive, and their effects were difficult to mentally separate. Measurable correctness was important for experimental control. In many parameter manipulation tasks, ‘good’ combinations are identified subjectively by the user. However, we needed an objective way to evaluate correctness, so we could determine when a task was complete. The CIE L*a*b* color model provided clear, consistent data manipulation paths and end points (i.e., color matched within a specified tolerance). This perceptually linear color model also enabled us to determine a distance between any color and the target color.

2. Application Scenarios

Parameter manipulation is a common task in many visualization applications. For example, volume rendering of 3D medical image data produces a 2.5D image, where some tissues are displayed semi-transparently so that other tissues may be seen underneath. These colors and transparencies, as well as other rendering options, are set interactively through a series of controls such as sliders. Several visualization interfaces have been designed to support exploration tasks with medical data, including parallel coordinates style [TPM05] and spreadsheet style [JM01] interfaces. Physical user interfaces have been used in the medical domain to adjust 3D parameters such as the position and orientation of a slicing plane [HPGK94] as well as 1D parameters such as pre-determined transparency functions [CBS*07]. Here we focus on 1D parameters that can be adjusted through physical or graphical sliders.

Similarly, for visualizations of non-spatial data, users often want to filter the data through dynamic queries [AWS92]. In this method, a user drags query sliders that filter information based on each dimension in a multidimensional data set. For example, to search for a house to purchase, a user may set parameters such as the number of bedrooms desired, desired distance from a location such as a workplace, desired cost, and so on, as demonstrated in HomeFinder [WS92]. These parameter values are not simply set once and then ignored, but are dynamically updated to change the query and to understand the variation in data values (in this example, the range of homes that are available).

Related parameter manipulation tasks also occur in many other applications. In scientific simulations, users need to adjust input parameters (e.g., finding input parameters to optimize a fuel cell’s design). In computer graphics, users set display parameters (e.g., to adjust the way an object appears when lit). Similarly, Hartmann et al. [HYA*08] presented the idea of “tuning” application variables at runtime, enabling programmers to rapidly compare code alternatives to facilitate software prototyping.

Prior research in visualization [CBS*07] suggested using physical sliders to manipulate visualization parameters, citing potential for increased visual attention on the screen, interaction benefits such as bimanual control, as well as more screen space for the visualization (since physical controls do not take screen space). However, these proposed benefits have not been tested empirically.

3. Related Research

Indirect interface devices such as a mouse require a user to perform many sub-steps in order to manipulate a graphic control. These include acquiring the mouse with one’s hand, moving the mouse cursor to acquire the graphic control, and then adjusting the control [FB97]. Although these steps are simple, they may require visual and cognitive attention, breaking the flow of a user’s primary task [CBG04]. Direct physical input devices may reduce the need for some of these interface manipulation steps [UHJ03]. Physical interfaces offer potential benefits of graspability, bimanual control, and visual attention as described above. Previous researchers have focused more on performance than visual fixations on user controls; so, our related research discussion has an emphasis on explicit performance work.

Specialized physical input devices have been shown to outperform equivalent graphical widgets for several applications. For example, Fitzmaurice and Buxton [FB97] demonstrated that physical or “graspable” user interfaces with specialized shapes and dedicated functions were superior to a generic input device for a target tracking task. Another example is Arsenault and Ware’s [AW00] observation of a 12% performance improvement when participants contacted objects in a virtual reality Fitts Law tapping task. In a graspable user interface, physical objects are tightly coupled to graphic objects in a virtual scene. We distinguish this from our work, where the physical interfaces adjust parameters affecting the scene, rather than directly representing scene objects.

Parameter control tasks have also been shown to benefit from physical interfaces. Hunt and Kirk [HK99] conducted an experiment comparing physical and virtual sliders for setting sound parameters. Participants achieved better results on a target sound matching task using physical sliders. Similarly, Chipman et al. [CBG04] compared a physical slider, a graphical scrollbar, and the mouse wheel for two scrolling tasks. Both physical interfaces performed better than the graphical scrollbar, with the mouse wheel being superior for searching and the physical slider being superior for reciprocal tapping.

We focus on tasks where a user manipulates a moderately sized set of parameters that affect a visual display. Within this domain, Crider et al. [CBS*07] and Hartmann et al. [HYA*08] qualitatively suggested that a mixing board interface consisting of physical slider controls may offer advantages over graphic slider controls manipulated with the mouse.

Our work extends previous research by (i) comparing control handling performance and visual fixations, and (ii) examining a parameter manipulation task that is more similar to typical tasks in visualization. In contrast to previous work, our experimental task requires users to judge a single visual output affected by all controls. Moreover, the effect of a control on the output is not always easy to predict. In addition, we employ eye tracking to examine how different interface devices affect visual attention, since maintaining ones eyes on the screen may be more important in visualization than in some other computer applications.

4. Goals

We studied control handling and visual fixation patterns in the context of a representative parameter manipulation task. Specifically, our experiment…

- Compared the eye fixations, a measure of visual attention, that participants took to conduct a challenging task using mouse, pen, and slider user interfaces.
- Determined how much less participants handle controls during 'easy' tasks vs. 'difficult' tasks.
- Compared control handling times and distances moved when participants work with mouse, pen, and slider.

5. Experiment Design

This section describes our experimental design. The main factor of user interaction (UI) had 3 conditions: mouse, pen, and physical slider. Each of these UIs controlled a four-parameter color space that is described in more detail below. We sought a non-trivial task requiring exploration and attention where we could measure eye gaze fixations, task completion time, and parameter distance traveled.

5.1. Participants

Twelve paid participants (5 female, 7 male) each took approximately one hour to complete the experiment. Their ages ranged from 18-25 years ($M = 21.3$, $SD = 2.2$). Each participant had normal vision, or corrected to normal vision with contact lenses, and was required to pass an Ishihara color-blindness test [IK77] to qualify as a participant.

5.2. Tasks

Participants performed a color matching task; they manipulated physical or graphical controls to adjust a color until it matched a target. The task apparatus is illustrated in Figures 1 & 2. The left and right quadrants of the color circle displayed a constant target color for the duration of the trial; whereas, the top and bottom quadrants of the color circle changed according to each participant's actions with each user interface (mouse, pen, and slider). The background was chosen to convey consistent transparency and relative color information within the color quadrants. Straight edges of each color quadrant intersected the diagonals of a 20 x 20 grid checkered grid such that half the edge overlapped white and half the edge overlapped black. A black background surrounded the checkered grid.

Color Space

Target colors were randomly generated from a perceptually linear three-parameter CIE LAB (or, CIE L*a*b*) color space [McL76] and a one-parameter linear transparency (t) scale. L*, a*, and b* parameters had low to high values according to International Commission on Illumination standards (i.e., CIE; Commission Internationale de l'Eclairage). t traversed a typical 8-bit transparency scale. These parameters are summarized below. L* values ranged from black to white; a* values ranged from green to magenta; b* values ranged from blue to yellow; and, t values ranged from transparent to opaque. Parameter ranges were restricted such that all parameter combinations mapped to a viewable color on the visual display. Specifically, $L^* \in [35, 70]$, $a^* \in [-15, 20]$, $b^* \in [-15, 20]$, and $t \in [110, 250]$. In other words, instead of the broadest color space, we sought a combination of (L^*, a^*, b^*, t) that would (i) be faithfully rendered on the visual display, and (ii) result in a color that was as perceptually linear to its neighboring parameters as possible.

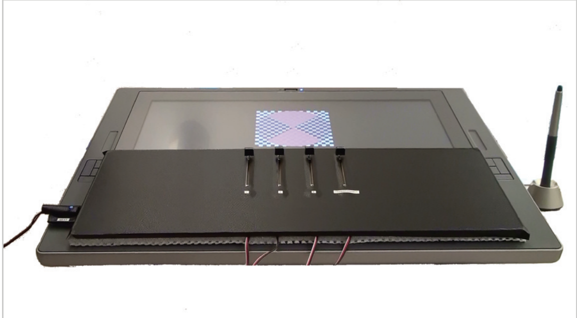

Figure 1: *Color matching task apparatus. The physical slider board was removed for Mouse & Pen conditions.*

CIE LAB colors were processed for display using a two-step conversion process. First, CIE LAB values were converted to CIE XYZ values. Second, CIE XYZ values were converted into gamma-corrected RGB values that could be displayed on our sRGB calibrated display.

Equipment Layout

Participants sat at a desk in a dimmed experiment room. They interacted with a 21" Wacom Cintiq 21UX interactive pen display set at a 20° inclination as shown in Figure 1. The desk height and chair were both adjusted to comfortable positions for each participant before the experiment. A mouse was positioned next to the tablet and could be adjusted to a comfortable position. Four physical sliders and a 'next trial' button were implemented using Phidgets [GF01]. Each slider was placed within a custom built acrylic frame wrapped in a black matte vinyl coating. The sliders and graphical display were updated every 16.7 ms with < .1 ms variation between updates using a PC running Microsoft Windows Vista. The display was set to a 32 bit sRGB color mode with known CIE LAB transformation matrices, and operated at 1600 x 1200 pixel resolution. Eye gaze and fixations were measured with a

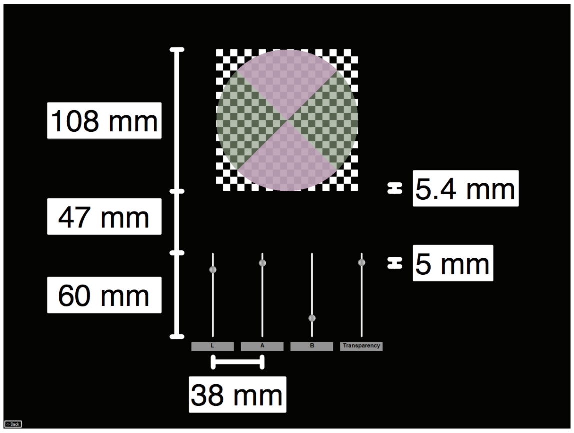

Figure 2: *Color matching task display layout for all conditions (Mouse, Pen, and Slider).*

Locarna PT-1 eye tracker operating at 30 frames / second and capable of 1° accuracy. Eye tracking data was recorded at 320 x 240 pixel resolution, and we defined an eye fixation as 10 frames (333 ms) of eye gaze within a 25 pixel radius. Figure 2 illustrates the layout and dimensions of the color circle and parameter controls. The physical controls for the slider had the same layout dimensions, width, and range of motion as their graphical counterparts used for the mouse and pen conditions. Additionally, off-white stickers were affixed to the tops of the physical sliders to match the 'look' of their graphical counterparts.

Study Design

We used a completely counter-balanced, within-participants design for the three conditions of UI: mouse, pen, and slider. Each participant performed 10 trials for each UI condition for a total of 30 trials.

Participants performed six training trials before the experiment. Two trials of each UI condition (Mouse, Pen, and Slider) were presented in the same order as the participant would experience during the actual experiment. In addition to training each participant, these trials plus counter-balanced ordering reduced the possible influence of learning effects in the subsequent experimental trials.

The same set of target colors were used for each UI condition, and the presentation order was randomized. Randomization virtually eliminated the chance that a participant would remember a particular color, while re-use of the same set of 10 colors eliminated bias towards a particular condition. For example, any slight perceptual difficulty differences while matching a particular color would be equally experienced for each of the three conditions (mouse, pen, and slider).

A color was considered matched when the L*, a*, b*, and t values were within ±5, ±5, ±5, and ±35 units, respectively. Intuitively, these tolerances represent bounds that were barely differentiable.

The controls were chosen to span a range of parameter difficulty. The controls were labeled L, A, B, and Transparency, respectively. L*, a*, and b* dimensions were foreign to all participants and extremely difficult conceptually segment; but, the concept of transparency was well understood by all participants and easy to conceptually segment compared to the other parameters.

Refer to our accompanying video for additional information on our experimental design and apparatus. In summary our design had…

- One factor *user interface* with 3 conditions (UImouse, UIpen, and UIslider)
- Four measures *time to match* (tmatch), *time traversing all controls* (tcontrol), *distance moving all controls* (dcontrol), and *number of eye fixations* (Nfix).

Participants interacted with four controls for L*, a*, b*, and t that we define as cL*, ca*, cb*, and ct, respectively.

5.3 Procedure

Participants were seated at a desk in front of a display as shown in Figure 1. They conducted the following steps:

1. *Color blindness screening*: Participants identified a set of 8 Ishihara color samples presented on the graphical display to screen for common color vision deficiencies such as red-green and blue-green color blindness.

2. *Eye tracking calibration*: Participants were fitted with the eye tracker glasses, then asked to successively fixate on centers of a 3x3 grid rendered on the experimental display.

3. *Training*: The experimenter described the study to the participant from a pre-defined script and answered any questions raised by the participant. Next, the participant performed six color matching trials – two for each condition of mouse, pen, and slider. These tuples were presented in the same order as the participant would experience during the experiment. The participant was free to adjust the sliders in whatever order or manner s/he desired until the adjustable color quadrants matched the target color. Each trial began when the participant pressed a graphical 'next trial' button (pen and mouse conditions), or a physical 'next trial' button (physical condition). Trials ended automatically once all sliders were set correctly, within a tolerance of 1/7 (14.2%). Participants could grasp and manipulate each user interface widget as they pleased, and they could iterate towards a target color using any strategic combination of user interface movements. Participants were not instructed to perform bimanual manipulation when handling the sliders; however, they were not prevented from using bimanual manipulation for the training or actual trials.

4. *Trial Completion*: Participants performed the same color matching technique as the training phase with a new set of target colors. 10 trials were successively performed for each of the three experimental conditions. Asking participants to have a short rest between conditions minimized fatigue during the experiment.

5. *Eye tracking drift check*: After completing all the experimental trials, participants repeated the calibration described in step 2. This calibration was used to check for calibration 'drift' that could be caused by the eye tracking glasses being bumped or adjusted during the study.

6. Results

We first performed Q-Q plots to test our data distributions. We observed linear Q-Q plots for lognormal transforms of measures tmatch, tcontrol, and dcontrol, and a linear transform of measure Nfix. Lognormal transformations were therefore applied to the time and distance measures before performing the appropriate statistics. For the statistical results, *M* denotes Mean, *Mdn* denotes Median, *SD* denotes Standard Deviation, *d* denotes Cohen's *d* measure of effect size, and *p* denotes level of significance. We use the typical *d* thresholds of d = .2, .5, and .8 for small, medium, and large values denoting importance of effect sizes [Coh88]. Statements of significance take into account Bonferroni corrections to a $p < .05$ significance threshold. For ANOVA results, we used the Huynh-Feldt correction when Mauchley's Test of Sphericity was violated.

If a participant moved two (or more) sliders at the same time (i.e., bimanual manipulation), movement times and distances for each slider were added together. This procedure provided conservative slider handling data that is consistent with time and distance data from the mouse and pen interfaces. Only 107 s out of 2157 s of slider movements were recorded simultaneously. Thus, only an average of 5.2%, with a 95% confidence interval [3.1%, 7.2%], of movement time contained bimanual manipulations. Three of the twelve participants chose to not use bimanual manipulation at all when handling the sliders. Because of this low incidence of bimanual manipulation, we focus our results and analyses on user control handling and visual fixation for each of the three user interface conditions: mouse, pen, and slider.

6.1 Differences between UI Conditions

We observed large visual attention differences between UI conditions. Figures 3 & 4 show the number of visual fixations per participant on the color wheel and each of the UI controls, respectively. Figure 5 compares the total number of visual fixations on the UI control region for the mouse, pen, and slider conditions.

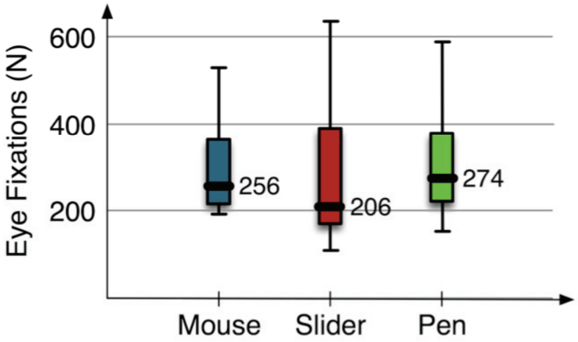

Figure 3: *Boxplot Visual Fixations on Color Target.*

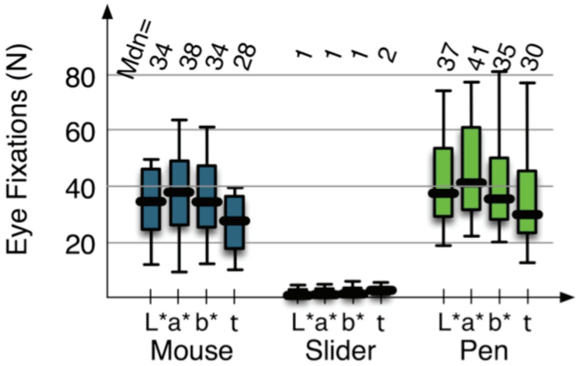

Figure 4: *Boxplot Visual Fixations on each UI Control.*

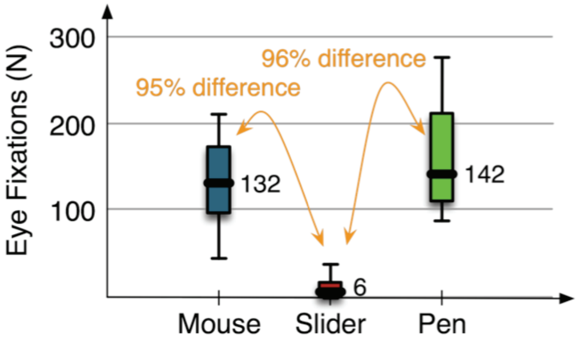

Figure 5: *Boxplot Visual Fixations on UI Control Region.*

We did not observe significant differences between UI conditions for visual fixations on the color target. However, large and significant differences were observed for fixations on the four UI controls. A repeated measures ANOVA (3 UI conditions x 4 slider controls) revealed significant main effects of UI ($F(2,22)=49.5$, $\eta_p^2=0.82$, $p<0.001$) and control ($F(2.2,24.2)=5.4$, $\eta_p^2=0.33$, $p=0.01$), and a significant interaction between UI and control ($F(5.4,58.9)=4.1$, $\eta_p^2=0.27$, $p=0.002$). Pairwise comparisons revealed that UIslider was significantly different from both UImouse and UIpen ($p<0.001$), but UIpen and UImouse were not significantly different from each other. Significant differences between specific controls, and the interaction between controls and the UI condition are discussed in the next section below.

In summary, highly significant differences were observed for the total number of visual fixations per participant on the UI control region for UIslider-UImouse and UIslider-UIpen as shown in Figure 5.

Despite these large visual attention differences we did not observe significant differences in overall task performance. Figure 6 shows total times participants took to match the target color. Although UIslider was faster on average, this difference was not significant.

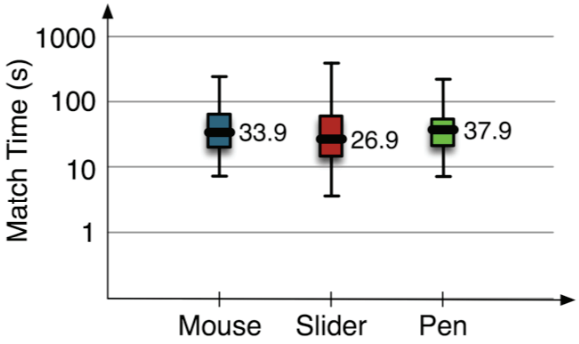

Figure 6: *Boxplot Match Times(s) for each Control*

6.2 Control Difficulty

The four color manipulation parameters (L, a*, b*, and t) were not equally easy for participants to adjust. This resulted in differences in the number of visual fixations, control handling time, and control handling distance.

Visual Fixations

Figure 4 shows that the number of visual fixations on each of the four slider controls differed, and that the amount of this difference also varied depending on the UI condition. Overall, pairwise comparisons revealed that ca* was significantly different from ct ($p=0.008$).

For UIpen, significant differences were observed between ca*-cb* ($p=0.03$) and ca*-ct ($p=0.023$). For UImouse, significant differences were observed for ca*-ct ($p=0.046$) and cb*-ct ($p=0.032$). For UIslider, significant differences were observed only for ca*-ct ($p=0.032$).

Total Control Handling Times

Figure 7 shows total times participants took handling each control for UImouse, UIpen, and UIslider conditions. A repeated measures ANOVA (3 UI conditions x 4 slider controls) revealed a significant main effect of control ($F(2.4,26.2)=10.5$, $\eta_p^2=0.49$, $p<0.001$). Pairwise comparisons showed that cL* was significantly different from ca* ($p=0.024$), cb* ($p=0.015$), and ct ($p=0.012$). Other pairwise differences were not significant.

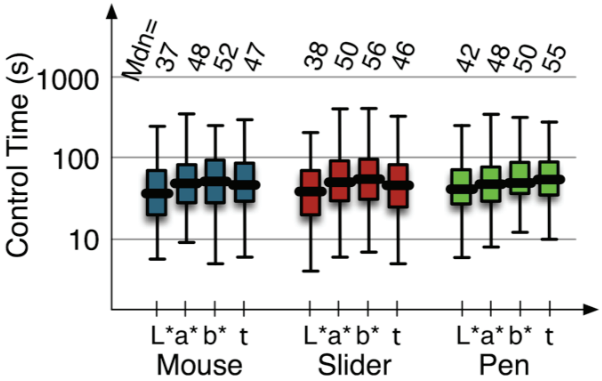

Figure 7: *Handling Times(s) for each Control.*

Total Control Handling Distances

Figure 8 shows total distances participants took handling the controls for UImouse, UIpen, and UIslider conditions. A repeated measures ANOVA (3 UI conditions x 4 slider controls) revealed only a significant main effect of control ($F(2.1,22.7)=49.6$, $\eta_p^2=0.82$, $p<0.001$). Pairwise comparisons showed significant differences between cL*-ca* ($p=0.002$), cL*-cb* ($p=0.001$), cL*-ct ($p=0.003$), ca*-ct ($p<0.001$), and cb*-ct ($p<0.001$).

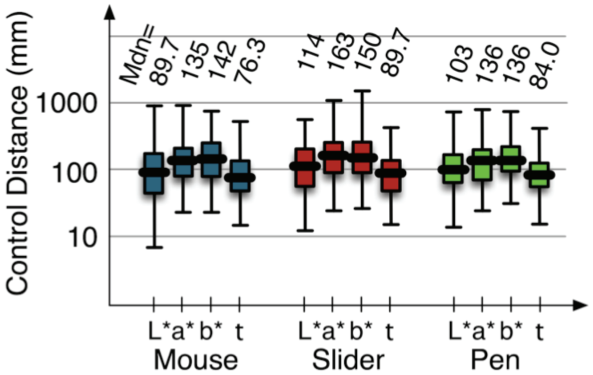

Figure 8: *Travel Distances (mm) for each Control.*

7. Analysis

Table 1 summarizes the key relationships between the results. Parameter manipulation tasks typically involve some parameters that are conceptually separable from others, and therefore intuitively easier to understand than parameters that are conceptually interdependent. This difference was modeled in our color matching study. We conjectured that controls cL*and ct would be easier to deal with than ca* and cb*. This is because L* and t deal with dimensions that are easier for participants to mentally segment – L* represents darkness and t represents transparency. Thus, these controls manipulate an easy-to-chunk dimension. Conversely, a* and b* are multi-colored elements that are not typically 'chunked' along a single dimension by most people. The green / magenta and blue / yellow scales associated with a* and b* are much more difficult to distinguish. Consequently, L* and t represent 'easy' controls and a* and b* represent 'difficult' controls.

We can gain an intuitive sense of how much the different UI conditions differ compared to individual slider settings. As shown in Figure 7 and Figure 8, there is more variation between the time and distance traversed with the individual sliders than between UImouse, UIpen, and UIslider conditions. We define UIslider as 'Physical' because the sliders physically 'project' from the display. Conversely, we define UImouse & UIpen as 'Graphic' because the sliders are represented by flat 2-D graphics on the display. UImouse & UIpen represent indirect and direct user interfaces, respectively.

Table 1: *Summary of Differences between Individual Controls ('Easy': cL*, & ct vs. 'Difficult': ca* & cb*) and UI Conditions ('Graphic': UImouse & UIpen vs. 'Physical': UIslider)*

	'Easy' vs. 'Difficult' Control	'Physical' vs. 'Graphic' UI
Handling Time	Δ	≈
Handling Distance	Δ	≈
Match Time	N/A	≈
Eye on Target	N/A	≈
Eye on Control	Δ	ΔΔΔ

Legend

≈	Similar
Δ	Slight Difference
ΔΔ	Moderate Difference
ΔΔΔ	Very Large Difference

The following analyses do not discuss differences between bimanual and unimanual handling because such a small percentage of slider control handling involved bimanual manipulation. We observed that participants appeared to focus attention on one particular dimension at a time during the color matching tasks. This observation is consistent with the notion that bimanual manipulation often involves one hand as a 'support' while the second hand actively performs an action. By contrast, moving two sliders simultaneously in a parameter manipulation task would require people to think about the effects of two parameters at once, which may be very difficult. Our results suggest that offering bimanual control does not offer much benefit for parameter manipulation tasks.

7.1 Visual Fixation Differences

We observed large differences in visual attention between the mouse, slider, and pen conditions. About the same number of visual fixations were observed on the color target (slightly less for the slider control, but not significantly less). Since participants moved similar distances and took similar times moving controls for each UI condition, the similar numbers of eye fixations on the color target for each condition are what we would expect.

Conversely, we observed huge differences in visual fixations on the slider control vs. the mouse and pen controls. These data, combined with the similar performance data, suggest that people needed much less visual attention when using the slider vs. the other controls. For example, Figure 5 shows a large 95% difference in the number of eye fixations between the mouse and slider conditions, and a similarly large 96% difference in the number of eye fixations between the pen and slider conditions. Furthermore, these differences had large effect sizes ranging from *d* = 2.94 to *d* = 3.60. These effect sizes represent over 90% non-overlap between the UIslider and UImouse & UIpen conditions [Coh88]. While one might intuitively expect a person to visually fixate on a mouse or pen more than a slider, these data provide quantitative understanding of the scope of these differences.

These results suggest that physical user interfaces such as sliders can free visual attention away from tools such that a user can spend up to 20 times more relative visual fixations on their primary task. This finding could be important for visualization tasks in time and safety critical environments such as vehicles, operating rooms, and military theaters. We further expect that this effect will be more pronounced for novice users. For example, Law et al. [LAK*04] found that novice subjects focused substantially more visual attention on a laparoscopic surgery tool compared to expert surgeons in a targeting task.

7.2 Impact of UI Device on Task Performance

Despite the large visual attention differences, we observed similar overall task performance between the UIslider, UIpen, and UImouse conditions. Participants spent similar times and distances traversing the controls for each of the conditions, and took similar amounts of time to perform a color match. Although a 20 – 30% median improvement in match times was observed for UIslider compared to UImouse and UIpen, this difference was not statistically significant.

These results suggest that, using a physical control such as sliders, one can maintain more visual attention on the display without significantly jeopardizing control manipulation performance. If anything, our results suggest that performance may slightly improve even though participants require up to 20 times fewer visual fixations. This is supported by the observation that participants spent more of their visual fixations on the color target compared to the controls (see Figures 3 and 5). Cognitively understanding how parameters affect the visual display, plus individual differences, appeared to have a larger impact on overall performance than the input device.

The color task was designed to model representative parameter manipulation tasks, and to provide a conservative range of task difficulty, which was supported by the high variability in match times both within and between participants seen in Figure 6. Our results indicate that physical controls enable users to better maintain visual attention on the screen during such tasks, but that this is not a major factor influencing overall performance. Nonetheless, we conjecture that future studies involving a greater number of participants (i.e., greater statistical power), would result in statistically significant improvements in task performance for physical controls. In addition, maintaining visual attention on the display may play a larger role for visualization displays more complex than our simple color display, and may be especially important in time and safety critical environments.

7.3 Impact of Easy versus Difficult Controls

Our results support our conjecture that cL* and ct represent separable ('easy') controls whereas ca* and cb* represent interdependent ('difficult') controls. Although the differences in time and distance in Figure 7 and Figure 8 do not visually appear large, this is primarily due to the logarithmic scale required to perform the statistics. Up to 50% differences in median times and distances were observed between the 'easy' and 'difficult' controls. Furthermore, these differences had medium to large effect sizes ranging from *d* = .6 to *d* = 1.59. Thus, our study results cover a range of user interface control difficulties that people are likely to experience when viewing and interacting with visualizations. More important, the observed handling time, handling distance, and visual fixation differences between easy and difficult controls suggest that the intuitiveness of a control impacts overall performance. Finding an intuitive mapping between input parameters and their effect on the visualization is therefore critically important.

8. Applications and Extensions

The following discussion explicitly summarizes how our results might be applicable for other user interfaces and applications.

User interfaces

The pen interface in our study is conceptually between a mouse and physical slider. The major difference between the mouse and the other devices is that input with the mouse is indirect. The major difference between the pen and physical sliders was that the pen required handling graphical controls on the display like the mouse rather than grasping controls that protrude out of the screen. With the physical slider, the graphic and haptic feedback are more tightly coupled during parameter manipulation than with the pen or mouse interfaces. Consequently, we might expect similar results to those presented in this paper from other physical controls with similar properties as the sliders. Such controls include other one-dimensional interfaces such as buttons and knobs. Also, many two- and three-dimensional controls have similar properties (e.g., interactive props such as the neurosurgical interface described by Hinckley et al. [HPGK94]).

These physical controls have typically been used to directly modify objects in a graphical scene instead of manipulating more abstract concepts such as our color matching task's display parameters.

Applications

We studied a color matching task that is representative of the high-level concept of interacting with a parameter space. This includes 'classic' areas such as audio mixing and video games, where physical controls are commonly used, but also more abstract applications where their use is currently limited. Examples include adjusting visual display parameters for graphics and visualization applications (e.g., setting lighting or material properties to modify appearance of objects in an architecture rendering), parameter tuning for software prototyping and algorithm implementation (e.g., finding optimal default zoom settings for a geographic information system), and adjusting input parameters for scientific simulations (e.g., choosing hydrogen and oxygen mix ratios to optimize fuel cell performance).

9. Future Work

Future work should be performed in two main areas. First, comparisons of different physical user interfaces other than sliders should be performed. Second, future studies should compare differences within specific applications, then compare these results to more general, abstract tasks such as the color matching task described in this paper. These studies could include situations where the controls were further away, or the visualization was a different size. Such studies might influence the relative performance of certain controls.

In addition, future studies of parameter manipulation could consider bimanual interaction in greater detail. In our study, participants rarely moved two physical sliders simultaneously; however, they may have occasionally held two sliders at the same time, reducing the need to acquire them. Future studies could compare these and other potential advantages of bimanual interaction.

10. Conclusions

We have demonstrated that users may spend up to 95% fewer visual fixations on physical sliders versus standard mouse and pen interfaces without any loss in performance for a representative visual performance task. We observed levels of significance less than p = .001 and effect sizes representing over 90% non-overlap between slider vs. mouse & pen user interfaces. Additionally, users maintained these results across a large range user interface control difficulty. These results strongly suggest that users performing high cognitive load tasks may free much of their visual attention from mouse or pen tools if they use slider tools instead. These results are applicable to both direct manipulation and abstract parameter handling tasks.

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