Concurrent Bimanual Stylus Interaction: A Study of Non-Preferred Hand Mode Manipulation

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ABSTRACT

Pen/Stylus input systems are constrained by the limited input capacity of the electronic stylus. Stylus modes, which allow multiple interpretations of the same input, lift capacity limits, but confront the user with possible cognitive and motor costs associated with switching modes. This paper examines the costs of bimanual mode switching, in which the non-preferred hand performs actions that change modes while the preferred hand executes gestures that provide input. We examine three variants to control mode of a stylus gesture: pre-gesture mediation, post-gesture mediation, and mediation that occurs concurrently with stylus gesturing. The results show that concurrent mode-switching is faster than the alternatives, and, in one trial, marginally outperforms the control condition, unmoded drawing. These results demonstrate an instance in which suitably designed mode-switching offers minimal cost to the user. The implications of this result for the design of stylus input systems are highlighted.

CR Categories: H5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

Keywords: Mode, Bimanual, Pen, Stylus, Kinematic Chain, Symmetric, Asymmetric

1 INTRODUCTION

Interfaces with restricted input capabilities require that input be overloaded, a typical example being tablet interfaces which receive most input through an electronic stylus. The function of the stylus is commonly overloaded via software state, which creates a set of modes in the interface. To transition between modes, users are required to perform operations manipulating the state or mode of the software alongside actions manipulating application content. These mode manipulation operations have been generally recognized as costly [16]. As a result of the need for modes and the cost of mode switching in tablet input, recent work has explored potential improvements in mode-switching [5, 15, 18]. Developing improved ways to manipulate modes is an effective way of addressing the cost of mode-based interaction in limited input systems such as tablets.

The ideal mode switching technique would be a 'cost-free' mode switching technique. Mode-switching can be considered to be cost free when measurable parameters of the user's primary task are indistinguishable with and without mode-switching.

In this paper, we investigate variations on non-preferred hand (bimanual) mode-switching, in which the non-preferred hand holds buttons that control program state while the preferred hand provides gestural input with the stylus. Three variants of this paradigm are explored: the non-preferred hand action preceding the preferred hand action (as indicated by the kinematic chain model [9]), the preferred hand action preceding the non-preferred hand action, and the two actions proceeding concurrently. Experimental results show that the concurrent variant reduces total gesture time. We also show that the assumption that non-preferred hand interaction naturally precedes preferred hand interaction merits further investigation. Broader implications of this research, calling into question the nature of stylus mode switching, are raised. In particular, we note the need for an improved definition of what constitutes a single goal versus multiple goals in user interfaces and raise questions on the need for research that advocates the use of computational intelligence to manipulate mode in stylus interfaces [2, 18].

This paper is organized as follows. In the next section, we explore related work focused on mode transitions and alternatives to mode-based interaction. We then describe a simple experimental set-up to test user performance in mode-based systems. Following this, we present our experiments analyzing variants of bimanual mode-switching. Finally, we conclude by outlining some broader research questions raised by our results.

2 RELATED WORK

In this section we highlight relevant research on interaction techniques. We first focus on research on improved mode-switching. Next, we highlight recent psychology research that examines motor-control level interference.

2.1 Improving Mode Switching

Many researchers have studied variations in interaction techniques for stylus input systems that seek to fluidly allow both command and input [1, 5, 11, 15, 18]. This research can be broadly separated into research that seeks alternatives to modes versus research that seeks to improve the accessibility of software modes. Of particular interest to us is the study, specifically, of user performance in mode-switching tasks in software interfaces, i.e. improvements in the accessibility of modes. In this area, one recent study by Li et al. [15] has explored various approaches to mode switching in detail.

Li et al. explore five different techniques for mode switching. These include typical mode switching techniques that have been extensively used, i.e. use of the eraser end of a dual ended stylus, use of the barrel button on an electronic stylus, a press and hold technique similar to the Apple Newton, and use of the non-preferred hand. They also examine a pressure based technique based on work by Ramos et al. on pressure widgets [17]. In this list of mode switching techniques, we note the absence of software widgets to control modes, a result of general recognition of the fact that improvements are needed over software-based modes [16].

In their results, Li et al. note three specific things. First, the use of non-preferred hand to control program state was faster than other techniques, though not significantly faster than pressure (second fastest) or barrel button (third fastest). Eraser and press and hold were significantly slower. In error rate, stylus inversion resulted in the fewest errors, followed closely by non-preferred hand. Finally in terms of user preference, the non-preferred hand was typically preferred over other techniques.

Given the benefits of non-preferred hand interaction, further investigation into the use of non-preferred hand mode-switching is warranted. To motivate additional research, we now introduce related work in bimanual motor control.

2.2 Bimanual Motor Control

In Guiard's work on asymmetric bimanual interaction, two handed interaction is characterized as the assignment of different roles to two hands. He notes three models of bimanual motor interaction: orthogonal, where the hands are independent; parallel, where the hands are used together to perform identical, synergistic actions; and serial, where one hand precedes the other. He argues, qualitatively, that serial assembly is the most "natural" for asymmetric bimanual tasks. Following Guiard's seminal work, most systems developed to allow asymmetric bimanual interaction have followed Guiard's principle, specifically that the non-dominant or non-preferred hand sets the frame of reference and precedes the actions of the dominant or preferred hand (e.g. [8, 4, 12]).

Some research has explored the notion of asymmetric, synchronous bimanual interaction. For example, recent work by Latulipe et al. explored the use of asymmetric bimanual interaction to perform manual image registration [14]. During their trials, the non-preferred hand was used to control translation (based on Guiard's premise of frame-of-reference setting [9]), and the preferred hand controlled rotation and uniform scaling. They study the simultaneity that occurs in actions of the preferred and non-preferred hand. By assuming that interactions within 2ms are, from a motor processing perspective, simultaneous, they find that in approximately half of all interactions some dual-handed interaction occurred. On the other hand, when the time taken to switch modes is eliminated, they note that the asymmetric bimanual process takes longer than a unimanual process. Missing from their analysis was a detailed investigation of the characteristics of dual-handed interaction. Was the preferred hand cued in error during non-preferred hand interaction or was its action intentional? It remains to be seen how often deliberate, synchronous, bimanual, asymmetric interaction occurs in user interface tasks that support this form of interaction.

Psychologists have advanced the study of bimanual interaction by looking at "interference" that results from asymmetric bimanual interaction. Two recent results of note question the serial assembly of motor tasks outlined by Guiard and motivate our research in this area. First, Diedrichsen et al. [6] note that when tasks are directly cued rather than symbolically cued, interference between bimanual activities is abolished. Directly cued movements are controlled by presenting subjects with motion endpoints, whereas symbolically cued movements ask subjects to interpret and respond to a signal. In such cases, motion exhibits no difference in reaction time regardless of whether the motion is unimanual or bimanual. On the other hand, they also note that, in symbolically cued tasks, if users are given time to plan their motion, then interference effects are also eliminated.

Hazeltine et al. [10] explore this result in more detail. They note that several possible explanations exist for the lack of interference in bimanual interaction in directly cued movements: directly cued movements may not engage cognitive processes that result in cross-talk or interference; the two directly cued movements could be cognitively perceived as a single movement; or the cues themselves might allow sufficiently speedy response that cross-talk exists but has not been accurately measured due to the rapid response. By varying symbolic and direct cuing conditions, they note that directly cued movements do not engage cognitive processes that result in cross-talk. More succinctly, they note that the "limitation [is in] the ability to initiate two goal-directed behaviors at the same time rather than the ability to coordinate distinct groups of muscles." This work supports the hypothesis that bimanual interaction is limited at the cognitive level (in our heads), not at the motor level.

2.3 Open Research Questions

The implications of Hazeltine's work are significant in user interface research. In exploring bimanual interaction, there is no specific reason to require non-preferred hand initiated interaction, or sequential assembly of motor processes. Here, we explore stylus interaction, and note that altering the interpretation of a stylus gesture can occur at any point during a gesture. The research question then becomes: is non-preferred hand mode switching a separate goal from the creation of a specific gesture, or is inking of the moded gesture a single goal that simply requires the activation of two separate muscle groups, one in each hand?

In this work, we seek to address this issue by exploring two related questions. First, should mode-switching tasks be non-preferred hand initiated (i.e. should the non-preferred hand lead)? Second, should non-preferred hand mode switching actions be assembled serially with stylus gesture actions, or can performance gains be realized by allowing parallelism? Also, if parallelism results in performance gains in mode-switching actions, how should the parallelism be realized in an application interface? Should bimanual actions fully overlap, or should they only partially overlap?

It should be noted that the experimental design of Li et al. [15] does not address the research questions we pose. In their task, mode switching was an alternating task, starting with unmoded interaction and then alternating sequentially through moded and unmoded interaction, a compound task similar to tasks studied by, for example, Kabbash et al. [13]. The sequential alternation of moded and unmoded gestures gives users a chance to plan, meaning that the distinction between two-goal (resembling symbolic) vs. one-goal two-muscle-group (resembling directly cued) motion is lost. To understand the potential concurrency possible in asymmetric, bimanual, non-preferred hand mode switching, a non-planned mode switching task is required.

Finally, the notion that asymmetric bimanual interaction can overlap in time is not new (see, for example, [11, 13, 14]). What has not been explored is the nature of the overlap in non-preferred hand activated modes. Specifically, the goal of this work is understanding, at the motion initiation stage, the level of parallelism that occurs in one asymmetric, bimanual task. This question, also, is not addressed by Li et al. [15]. Li et al., in particular, note that for barrel button, late button pressing was a significant cause of errors, but that this did not seem to be the case for non-preferred hand interaction. However, in Li et al., the requirement that subjects pre-set modes, with errors resulting from delayed non-preferred hand action, may have forced subjects to explicitly separate the non-preferred hand mode initiation from the preferred hand drawing action. The question remains as to whether temporal and/or error-rate benefits might occur if the requirement of pre-mode switching were relaxed for non-preferred hand mode switch in drawing tasks. It is this question, specifically, that we seek to investigate here.

3 Experimental Design

All experiments were conducted on two identically configured Toshiba R15-S822 Tablet PCs running custom software written in C# using Microsoft's Tablet SDK and Visual Studio .NET. The task given to our subjects was a simple line cutting task derived from the pie cutting task of Li et al. [15]. Subjects were asked to draw a line beginning near one side of the display and running to the other bisecting two vertical bars. In default mode, the line drawn was a black line. In mode cued by the non-preferred hand, the line was a thicker yellow line similar to a highlight mark. Trials took ten to fifteen minutes per subject, and subjects were given $5 each for participating in the trial. The order of presentation of the lines was random. As our performance measures were based on time, participants were told to draw as quickly as possible without errors in a verbal orientation to the user trial, similar to directives in typical Fitts' Law tasks.

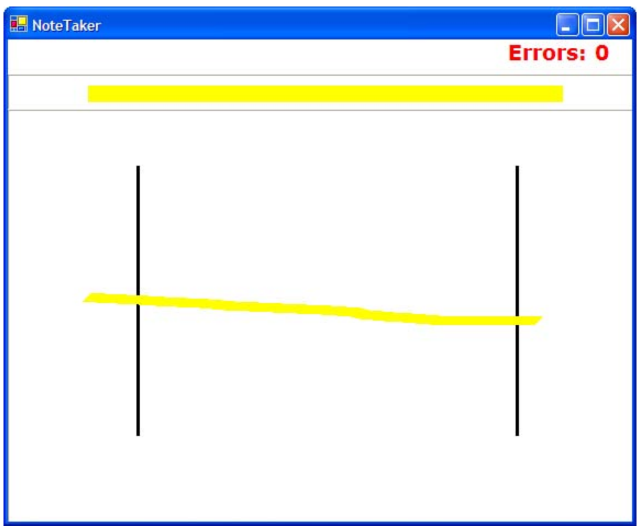

Figure 1: Drawing task.

We performed our experiment with two configurations. For pilot studies, we opened the tablet fully, and switched it into inverted landscape mode, as shown in Figure 2. The display was in front of the user, with the keyboard away from the user, 'above' the display. The display was flush against the table, and the body of the tablet elevated the 'top' of the inverted landscape display. Users could reach around the left or right side of the display to press any button on the keyboard to toggle mode. We also attached a wireless USB numeric keypad to the tablet running in tablet mode. Pressing any key on the numeric keypad toggled mode. Subjects' non-dominant hand hovered above the keyboard or keypad, and their drawing hand hovered above the display. This mimics typical drawing tasks; in typical tablet use, subjects are not required to return their hands to their lap or otherwise disengage from the physical interface between actions. Subjects typically drew slightly faster strokes with the fully open tablet versus tablet mode (360ms versus 450ms), a result of improved visibility as the tablet display was flush against the desk near them and elevated slightly at the top, similar to the way a drafting tablet angles the surface toward the draftsperson. Presence or absence of the numeric keypad versus use of the keyboard had no effect on drawing time, as subjects could hover over the keyboard or keypad with their non-preferred hand.

Figure 2: Experimental configuration for pilot studies.

3.1 Measurements

Stroke timing started as soon as the target stroke was displayed. In this way, users were not given time to plan their motion. Initiation time, defined as the time between presentation of the desired line and the first pen event, and gesture time, the time taken to draw, were recorded for each stroke. Total time for any individual stroke included the initiation time and drawing time until pen up. These intervals are shown in Figure 3.

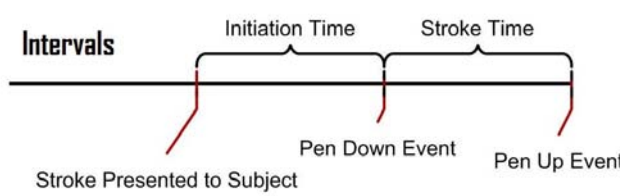

Figure 3: Time intervals recorded during our experiments were the initiation time, defined as the time between presentation of a desired stroke and pen down, and stroke time, defined as the time between the pen down event and pen up event.

The interface also recorded errors and timing of button press events. Errors occurred in two forms: mode errors and drawing errors. Mode errors occurred when subjects were either in-mode when they should not have been (in-mode errors) or when subjects were drawing in default mode when the display indicated that they should draw a moded gesture (out-of-mode errors). Drawing errors occurred when a gesture did not bisect both lines on the display. Button press/release events can occur prior to or during pen gesture event, and were measured in ticks before pen down. Button events that occur after pen down were recorded as negative numbers.

3.2 Non-Preferred Hand Mode Switching Techniques

Three non-preferred hand mode switching applications were created. The first, pre-mediated mode switching (PRE), is identical to the technique described by Li et al. [15]. Subjects are required to initiate mode switching with their non-preferred hand before gesturing with their preferred hand, as shown in Figure 4. Failure to initiate with the non-preferred hand prior to gesturing results in an error. Subjects could press and release the mode switch button with their non-preferred hand freely to alter mode multiple times prior to beginning the gesture, and mode was fixed when the gesture began. Releasing the button at any point after mode was fixed did not affect mode. The second application used post-mediated modes (POST), where the user could begin gesturing, alter the mode at will before or during the gesture, and the mode was indicated by non-preferred hand state at pen-up. We also implemented an application permitting concurrent mode switching (CON) early in the gesture. Prior to or during the first part of a gesture, subjects were permitted to alter the mode of the gesture. After a time-out, mode was fixed for the remainder of the gesture (see Figure 5). We determined the length of time for a timeout in concurrent mode switching from an initial pilot study described below.

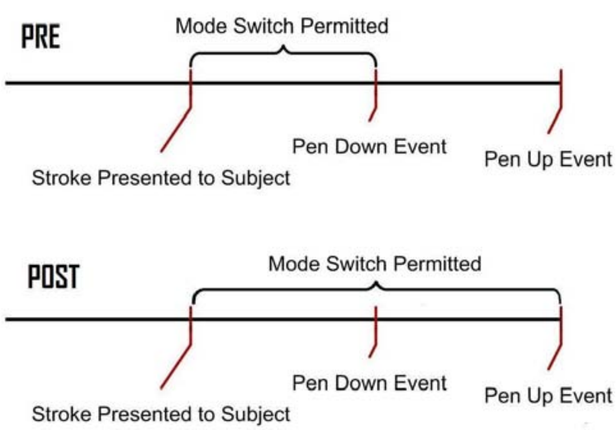

Figure 4: Pre-mediated and Post-mediated modes. In pre-mediated, to draw a moded gesture subjects must depress the button prior to beginning the gesture and hold it until beginning to draw; button state at pen-down indicates mode. In post-mediated, subjects can press the button any time before or during the gesture; button state at pen-up event indicates mode.

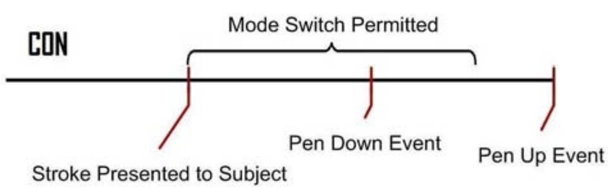

Figure 5: Concurrent mode switching. Mode can be altered during the first part of a gesture, and then is fixed.

Note that for post-mediated modes, we do not consider the time after pen up until release of the non-preferred hand. The decision to omit the time taken to lift the non-preferred hand after completion of a pen gesture was intentional. In real application tasks, a user using post-mediated mode switching could, theoretically, release the non-preferred hand after beginning a new pen gesture, thus overlapping in time the beginning of a new pen gesture with the act of fixing the mode of the previous gesture.

4 Pilot Study

We conducted a pilot study to test the assumption that natural interaction would indicate that subjects would typically begin any asymmetric bimanual task with their non-preferred hand and to tune timeout for concurrent interaction. The purpose, it should be noted, is not to force subjects to *not* initiate with the non-preferred hand, simply to see what happens when the restriction on initiating with the non-preferred hand is relaxed. In the experiment of Li et al., if subjects did not initiate with the non-preferred hand, a mode error occurred [15]. The occurrence of a mode error may have predisposed subjects to carefully initiate with their non-preferred hand.

Ten subjects, eight male and two female, eight right-handed and two left-handed, performed a within subjects experiment using pre-mediated and post-mediated modes. Subjects performed 30 gestures using each application, 15 unmoded black gestures and 15 moded yellow, a 2 technique X 2 mode repeated measures design with order of technique presentation counterbalanced. The order that moded and unmoded gestures were presented was randomized. Time was the dependent variable.

In post-activated mode, users were free to engage the mode with their non-dominant hand at any point in time. If non-preferred hand initiated interaction is "natural", one would expect that all interaction would be non-preferred hand initiated, or, at least, that moded gestures were, in a majority of the cases, non-preferred hand initiated. In fact, in 58% of all moded, post-mediated gestures, users engaged the mode *after* the gesture started. Stated another way, in over half of all moded gestures using the post technique, subjects initiated with their preferred hand, not their non-preferred hand. The median delay following start of gesture and before engaging mode was approximately 150 ms, while the average delay was 350ms.

5 Experimental Analysis of Non-Preferred Hand Interaction

Based on the results of our pilot study, the timeout for concurrent mode switching was set to 150 ms, the median timeout observed. The high average timeout resulted from the presence of outliers. Observed average gesture times were on the order of between 300 and 400 ms, so 150 ms represented approximately half the time taken for a user gesture.

5.1 Procedure

Twelve subjects, eight male and four female participated in our experiment. Each subject used the three different mode switching techniques once. Six different orderings of the three interaction techniques resulted in two users per ordering. In each condition, the interaction technique was described to the subjects. Subjects were given 10 practice gestures; seven of the ten practice gestures were moded and three were unmoded. Subjects then drew 30 gestures, 15 moded and 15 unmoded. The order of moded and unmoded gestures was a random permutation of the possible ordering of 15 moded and 15 unmoded gestures. The experimental design was 3 mode switching techniques, 2 modes per technique, i.e. a repeated measures 3 X 2 experimental design fully counterbalanced in interaction technique with random ordering of moded versus unmoded gesture. The total number of gestures collected was:
12 subjects
X 3 mode switching techniques
X 15 gestures per mode
X 2 modes
= 1080 gestures.
540 of the gestures required mode switching.

5.2 Results

Figure 6 shows total drawing times for the various mode switching techniques for all users. For moded drawing, we see mean total drawing times of 959 ms for concurrent modes, 978 ms for pre-mediated modes, and 1078 ms for post-mediated modes. Analysis of variance indicates a significant effect for interaction technique ($F_{2,9} = 5.421, p = 0.029$), ordering of techniques ($F_{2,9} = 11.859, p < 0.01$), and technique * order interaction ($F_{2,22} = 11.853, p < 0.01$). For unmoded drawing, mean total times of 968 ms, 942 ms, and 987 ms do not vary significantly ($F_{2,9} = 0.601, p = 0.57$) [1].

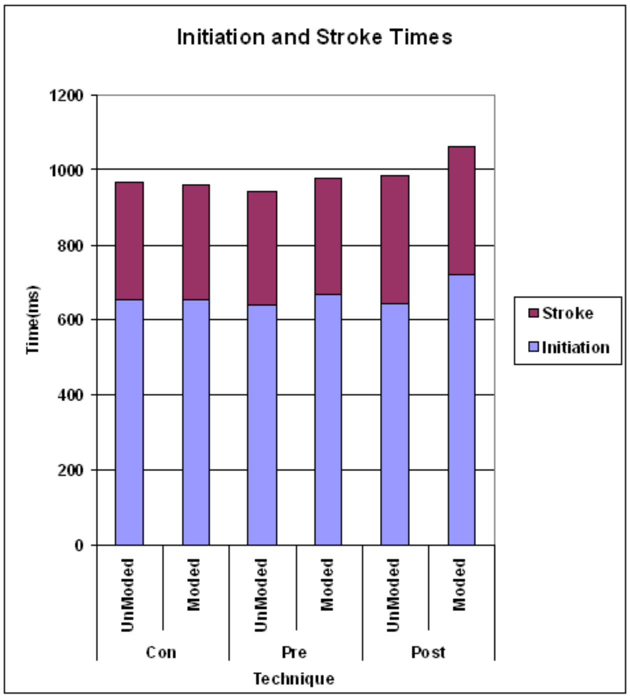

Figure 6: Moded and unmoded drawing times for CON, PRE and POST techniques.

Analyzing the effect of condition with order of conditions as a covariate is complicated by the non-linear effect order has on total drawing time ($r^2 = 0.036$). Shown in Figure 7, we see that two users are outliers. In particular, one user, user 5 (POST, CON, PRE), showed a dramatic improvement in gesture time over the course of the trial. User 5's initiation time was typical of that of other users. Another, user 7, typically initiated much slower than other users in all cases, but had gesture times that did not vary significantly from other users. While the effect of slow initiation by user 7 is of less concern (increasing within group and overall variance for all interaction techniques resulted in lower Anova scores), user 5, with the large variation in stroke time, complicates the analysis of the overall effect of technique by increasing the likelihood of post-hoc tests showing significant differences between techniques.

To consider the effect of condition on total time taken, we contrasted moded and unmoded drawing for each experimental condition. User 5 and 7 drew both moded and unmoded gestures during each of the three trial blocks, and the improvement in stroke speed of user 5 and slow initiation time of user 7 were observed for

[1] $F_{max} = 3.61 < 4.16$ and $F_{max} = 3.18 < 4.16$ respectively with 3 conditions and n-1 = 11.

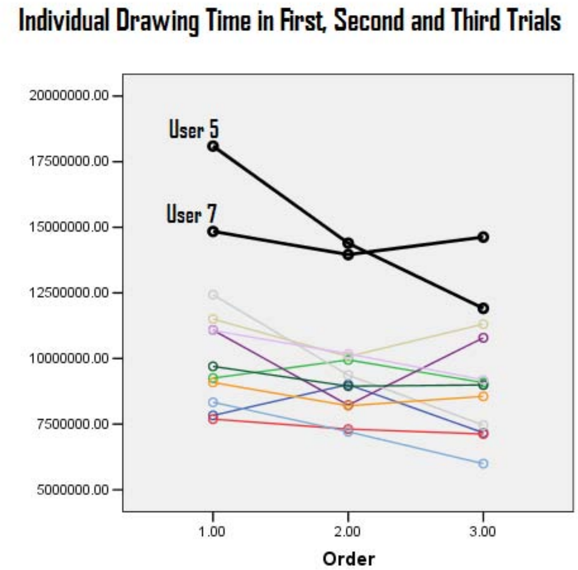

Figure 7: Drawing times for users. The x-axis indicates first, second, or third trial.

both moded and unmoded gestures. Bonferroni's adjustment for three comparisons requires observed statistical significance above (less than) 0.0167 (i.e. $t > 2.403$). For concurrent mode switching, moded drawing is actually faster than unmoded drawing, though not by a statistically significant amount ($p = 0.41$). For pre-mediated and post-mediated mode switching, contrasting the moded versus unmoded drawing from individual trial blocks, we see that moded drawing is significantly slower (PRE: $p = 0.0165 < 0.0167$ and POST: $p = 0.013 < 0.0167$ for pairwise tests).

As noted earlier, we record two time intervals for each stroke: initiation time, or the time taken between presentation of the desired gesture and the pen-down event; and stroke time, the time taken to draw the gesture with the pen. For concurrent mode switching, moded drawing is slightly faster than unmoded drawing. Examining average time of 968 ms for an unmoded gesture shown in Figure 6 and in Table 1, we see that this total drawing time is comprised of mean initiation time of 654 ms and mean stroke time of 314 ms. For moded drawing, mean initiation time is 653 ms and mean stroke time is 306 ms. Neither initiation times of 654ms versus 653ms nor stroke times of 313ms versus 306ms vary significantly ($p = 0.49$ and $p = 0.10$ respectively). We do note that the slower mean drawing time for unmoded gestures was a result of slower stroke time, not slower initiation time. Mean initiation time varied by only one millisecond for moded versus unmoded drawing.

Technique	Mode	Initiation	Drawing	Total
CON	UnModed	654	314	968
	Moded	653	306	959
PRE	UnModed	640	303	943
	Moded	669	309	978
POST	UnModed	645	342	987
	Moded	720	342	1062

Table 1: Stroke and initiation time for moded and unmoded drawing for each interaction techniques.

In contrast, when we examine pre-mediated and post-mediated modes, we see that drawing times are very similar, and that the slower drawing speeds are a result of slower initiation time. In pre-mediated mode switching, initiation times of 640 ms for unmoded drawing and 669 ms for moded drawing vary by a statistically significant margin ($p = 0.029$). Drawing times of 303 ms versus 309 ms for unmoded and moded drawing do not vary significantly ($p = 0.12$). In post-mediated mode switching, the variation in initiation time is even more pronounced (645 ms versus 720 ms, $p = 0.005$).

In pre-mediated mode switching, we note that the subject must initiate with his or her non-preferred hand. In concurrent and post-mediated mode switching, users do not necessarily need to initiate with the non-preferred hand. Of 360 post-mediated and concurrent mode switches, users' non-preferred hand engaged after their preferred hand in 37 of the gestures. However, informal observations of subjects raise some concerns. Subjects were more likely to initiate with their preferred hand in their third interaction technique than in any other (23.33% of the time, or 28 of the 37 preferred-hand initiated gestures occurred during the third block).

Table 2 shows the total number of errors made by all users in each of the conditions. A χ^2 test does not provide sufficient evidence for an interaction technique effect on error rate ($\chi^2 = 4.526, p = 0.104$ for total errors; all by-type error rates have higher p values). Qualitatively, we note that CON and PRE are approximately equal, and POST appears slightly worse in error rate.

	In-Mode	Out-of-Mode	Drawing	Total
CON	2	3	15	20
PRE	2	4	16	22
POST	4	7	23	34

Table 2: Errors by type and total errors for each interaction technique.

6 Further Analysis

The challenge in analyzing data from our user trial is a result of measurable interactions between order of presentation, technique, and user effects. We observed both skill transfer effects (two users asked whether concurrent and pre-mediated modes required any different interaction on their part) and learning effects (in their third block while using post-mediated mode switching, one user always and another often initiated with the preferred hand, noting that they could just draw a line and then decide on mode at the end of the gesture). To verify our results from our user trial, we conducted a follow-on study.

Fifteen users, three female and twelve male, were asked to perform the same task as in previous experiments. Subjects were separated into three groups (five individuals each) and used only one of the applications (a 3 X 2 mixed experimental design with interaction technique as a between groups factor, and repeated measures of moded and unmoded drawing within group). Analysis was performed to determine task completion time and error rate using the different interfaces. It would perhaps have been possible to drop the POST task, but we performed a three-way comparison of single-application use to validate our results in the prior experiment.

Figure 8 plots the time taken for CON, PRE, and POST moded gestures. To analyze moded gestures, all gestures where out-of-mode errors occurred (i.e. where a mode switch should have occurred but did not) were removed, leaving us with 203 gestures to analyze from the fifteen subjects. An ANOVA test indicates statistical significance among the total drawing times ($F_{2,12} = 10.2085, p < 0.01$). In gestures where mode switching was performed, post-hoc analysis shows that significant decreases in completion time exist when moving from POST (slowest), to PRE (middle), to CON (fastest) task completion times ($p < 0.05$ in all cases).

When comparing concurrent and pre-mediated interaction, the observed initiation times and stroke times do raise some concerns. Initiation times of 799 ms for concurrent and 870 ms for pre-mediated mode switching were observed. These times do not vary significantly ($p = 0.17$). However, stroke times of 314 ms versus 419 ms do vary significantly ($p < 0.0001$), as does total time taken of 1113 ms versus 1279 ms ($p = 0.03$). The observation that stroke time and not initiation time results in the observed slow-down may raise some question on whether interaction technique or individual differences in drawing speed resulted in improved performance for concurrent mode switching.

These concerns are offset by within subjects analysis of moded versus unmoded drawing. When comparing initiation time, stroke time, and total time for both moded and unmoded drawing for concurrent mode switching, we see no significant difference in time taken ($p = 0.49$, $p = 0.23$, and $p = 0.22$ respectively). In contrast, both initiation time and stroke time for pre-mediated and post-mediated mode switching exhibit statistically significant differences ($p \leq 0.01$ in all cases).

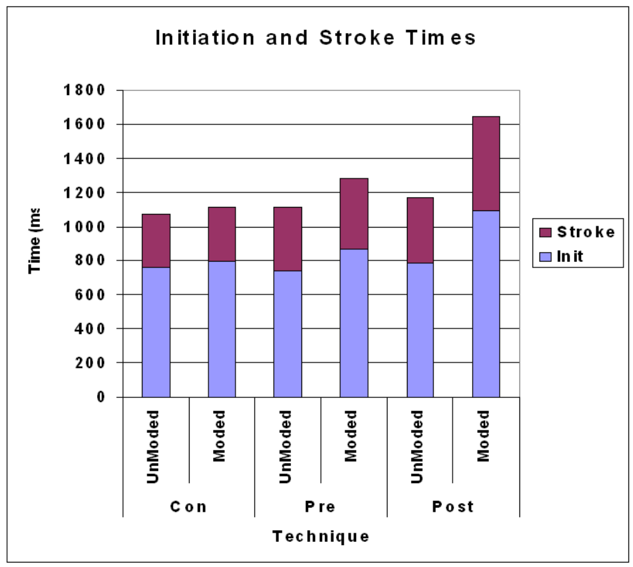

Figure 8: Gesture times for moded and unmoded drawing by interaction technique. Total time is, again, divided into initiation time and stroke time.

Technique	Mode	Initiation	Drawing	Total
Con	UnModed	762	311	1073
	Moded	799	314	1113
Pre	UnModed	736	379	1115
	Moded	870	409	1279
Post	UnModed	785	386	1171
	Moded	1094	551	1645

Table 3: Stroke and initiation time for moded and unmoded drawing for each interaction techniques.

7 Discussion

From our pilot study, we note that non-preferred interaction preceding preferred hand interaction as the "natural" form of interaction is a questionable assumption for asymmetric bimanual mode switching tasks in stylus based interfaces. In our case, we show that when the constraint that mode switches precede gesture is relaxed, the user does not necessarily pre-set modes before starting his or her interaction. Counterbalancing this evidence is the observation from our main experiments that, when concurrency could occur, users still typically initiated with their non-preferred hand. While concurrency is rare in our main experiment (only 37 of the possible 360 gestures), it should be noted that subjects interacted with three different techniques. An apparent observation that users engage the mode prior to gesturing may be a result of learning or skill transfer. The initial impulses to engage mode and begin drawing may also be simultaneous, but the shorter distance of travel for the non-preferred hand may result in an apparent overlap of modes.

In support of the simultaneity of impulse, we note that moded and unmoded drawing are very similar in speed in concurrent mode switching, with moded drawing actually outperforming unmoded drawing, though not by a statistically significant margin ($p = 0.41$). This similarity in drawing speed indicates that a claim that the action of the non-preferred hand interferes with the action of the preferred hand is highly questionable. Furthermore, when we analyze initiation time, we see that in concurrent mode switching the initiation time with and without mode switching is almost identical, while the initiation times in pre-mediated and post-mediated mode switching are longer for moded drawing than for unmoded drawing. Given our results, we can conclude that the motor impulse of the preferred hand is statistically indistinguishable despite action or inaction of the non-preferred hand with concurrent mode switching.

This does not negate non-preferred hand initiated interaction in all cases. However, it does support the observations of psychologists studying interference in motor tasks, who claim that interference does not occur at the motor control level, but at the goal selection level [7]. From our results, we see that, in cases such as the switching of modes via button pressing with the non-preferred hand, simultaneity can, and does, occur. This observation supports the hypothesis that non-preferred hand mode switching is similar to endpoint cued motion, rather than symbolically cued motion, i.e. that motor planning for the non-preferred hand mode switching operation can occur in parallel with preferred hand drawing.

A surprising result from both user trials is that slower initiation times occurred with post-mediated modes. There are two reasons that this result is unusual and merits further discussion. First, post-mediated mode switching is the most liberal of the techniques. Non-preferred hand action can occur at any time prior to, during, or at the end of the gesture just prior to pen release. Given the permissive nature of post-mediated mode switching, one would expect that motion planning and initiation of preferred hand drawing could occur prior to motion planning for the non-preferred hand. Initiation time would be shorter, rather than longer, if drawing were planned before mode switching. Second, we also note that users often initiated with their non-preferred hand, despite the post-mediated nature of the interaction. The typical style of interaction is, therefore, to depress the mode button prior to gesture, draw a gesture and lift the pen, then release the mode button. Regardless of how planning occurs, if users press the button before gesturing, we would still expect to see initiation times similar to pre-mediated and concurrent mode switching.

One possible explanation for the slower initiation time for moded drawing with post-mediated mode switching is that motion planning for both a gesture and its mode switch occurs in parallel prior to drawing. If planning for both the gesture and mode switch occurs prior to acting, then the observed increase in initiation time would be a result of an increase in the difficulty of the planning task for the subject when using post-mediated mode switching. In our first experiment, once motion began, we noted little difference in moded versus unmoded drawing times for any of the interaction techniques. In our second experiment, we noted significant differences in both initiation and stroke time. Further work is needed to fully understand the slower initiation time for post-mediated mode switching.

8 Further Research

8.1 The Kinematic Chain

The kinematic chain is a valuable model of human motion planning. It has served to explain a number of phenomena in user interaction in interfaces [9]. In the kinematic chain model, a motor is under the control of an Information Process System (IPS) that plans the activities of that motor. The model advocates serial assembly of motors in a chain, where non-preferred (left) hand interaction is planned and precedes preferred (right) hand interaction. Recent psychological research [10] [6] has called into question the serial assembly at, specifically, the motor control level. Our results provide evidence that non-preferred hand mode initiation is another instance of motor control level interaction where bimanual interference does not occur.

8.2 Characterizing Interaction

Our results lend support to the idea that non-preferred hand mode switching results in similar mental process as the default operation of not engaging mode with the non-preferred hand. Motor control for this asymmetric bimanual task does not cause measurable cross-talk for the two hands. In user interface research, this opens new potential avenues of exploration. To leverage this research, an understanding of those processes that can result in parallel motor control is needed. Addressing this problem requires a better understanding of the cognitive processes engaged in interface tasks.

To characterize those tasks for which concurrent, asymmetric interaction is possible, an understanding of what constitutes a single goal versus distinct goals for a user in a user interface is an important first step [10]. Many tasks can be modeled either as single goal tasks or as separate goal tasks. For example, the image registration task of Latulipe et al. requires subjects to perform one task, translation, with one hand and two tasks, rotation and scaling, with their other hand. When mode-switching time is removed, they note that asymmetric bimanual interaction takes longer than unimanual interaction [14]. The act of image registration is a single task, but, at the cognitive level translating versus rotating or scaling might be considered two separate goal-directed behaviors by a user performing the task. In non-preferred hand mode switching, our results provide evidence that the act of mode engagement is not a separate goal from the act of drawing a moded gesture.

8.3 Scalability

In our current experiment, we study only two-mode interaction as a precursor for more complex forms of interaction. The restriction to two-mode interaction is typical of many studies in the area of improved mode-based interaction, and is based on the need for two primary modes: a drawing mode and a command mode. One of the benefits of non-preferred hand mode switching, never explored to date, may be scalability. All five fingers can be assigned individual button modes. As well, additional modes can be assigned either through the use of multiple buttons or through the use of buttons in combination. Experiments using multiple modes are confounded by learning factors. It may be the case that, as subjects become expert with multi-mode interaction using their non-preferred hand, a rich set of modes may be accessible via effective use of the non-preferred hand to control mode switching. It may also be the case that assigning multiple possibilities to the non-preferred hand results in a multi-goal selection problem, i.e. cognitive interference.

Studying the scalability of non-preferred hand multi-mode control is an important next step in this research.

8.4 Computational Intelligence for Mode Switching

In the introduction, we define cost-free mode switching as a mode switching technique in which measurable parameters of the user's primary task are statistically indistinguishable with and without a mode switch operation. An alternative approach to enabling cost-free mode switching has used computation intelligence to analyze a user's action and the context of the action to determine the intention of the user [2, 18]. While the use of computational intelligence to infer user intention does create cost-free mode switching when intention is correctly inferred, a possibility of misinterpretation exists. In contrast, by relaxing the constraint placed on the user to pre-switch modes, our results show that it may be possible to both eliminate the possibility of misinterpretation and reduce the burden of mode-based interaction. While we can conclude that concurrent mode switching results in statistically indistinguishable initiation time, stroke time, and total time in our current experiment, more research is needed to determine whether concurrent mode switching is cost-free in dual-moded drawing tasks, or whether it simply exhibits an improvement in response time that makes moded drawing indistinguishable from unmoded drawing based on our current experimental set-up. Despite this lingering question, our results do call into question the need for computational intelligence to manipulate program state in drawing tasks that require two-moded interaction.

9 Conclusion

This paper studies techniques for non-preferred hand mode switching in stylus interfaces. It explores pre-mediated, post-mediated and concurrently mediated mode switching and notes a statistically significant decrease in moded gesture time for those users who used a concurrent mode switching technique. The time for moded gesture and unmoded gesture with concurrently switched modes is statistically similar, lending support to the ability of users to parallelize the motor processes involved in non-preferred hand mode switching.

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