A Study on the Scalability of Non-Preferred Hand Mode Manipulation

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ABSTRACT

In pen-tablet input devices modes allow overloading of the electronic stylus. In the case of two modes, switching modes with the non-preferred hand is most effective [12]. Further, allowing temporal overlap of mode switch and pen action boosts speed [11]. We examine the effect of increasing the number of interface modes accessible via non-preferred hand mode switching on task performance in pen-tablet interfaces. We demonstrate that the temporal benefit of overlapping mode-selection and pen action for the two mode case is preserved as the number of modes increases. This benefit is the result of both concurrent action of the hands, and reduced planning time for the overall task. Finally, while allowing bimanual overlap is still faster it takes longer to switch modes as the number of modes increases. Improved understanding of the temporal costs presented assists in the design of pen-tablet interfaces with larger sets of interface modes.

Categories and Subject Descriptors

H5.2 [**Information Interfaces and Presentation(e.g., HCI)**]: User Interfaces (D.2.2, H.1.2, I.3.6)—*Interaction styles*

General Terms

Design, Experimentation, Human Factors, Performance

Keywords

Stylus, Bimanual Interaction, Mode, Concurrent mode switching, Interaction technique, Pen interfaces.

General Terms

1. INTRODUCTION

Tablet interfaces receive the majority of 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. Developing improved techniques to manipulate modes is an effective way of addressing the cost of mode-based interaction in a limited input system, such as a tablet pc.

Research by Li et al.[12] explored five different common techniques for mode switching and concluded that the use of the non-preferred hand to switch modes is the most efficient and highest-rated technique. Lank et al. [11] described and evaluated *concurrent non-preferred mode switching*, a variant of non-preferred hand mode switching that allows the user to overlap the drawing task being performed by the dominant hand with mode switching in the non-dominant hand in pen-tablet interfaces. Allowing overlap of the activity of the non-dominant and dominant hands results in a more efficient mode switch for two-mode interaction. Further, this temporal overlap of the action of the hands results in *cost-free* mode switching, mode switching where the time spent performing an unmoded gesture is statistically indistinguishable from the combined time spent for a mode switch and performing a moded gesture.

One benefit of non-preferred hand mode switching is that it can be scaled to allow for more than two modes. Tablet centric applications, such as Microsoft Journal [13], typically include multiple modes. For example, Microsoft Journal has modes for drawing, highlighting, selecting, and erasing. Flipping the tablet pen or using the barrel button permits only a default unmoded and pressed or flipped moded gesture. In contrast, the non-preferred hand can be used to control several different buttons, each of which maps to a unique mode.

In order to scale non-preferred hand mode switching several questions need to be addressed. What is the best mapping of non-preferred hand fingers to modes? Do the benefits of overlapping mode switching and drawing persist? Lastly, does allowing the overlap of mode-switch and drawing still result in a cost-free mode switch?

We examine the scalability of non-preferred hand mode switching. More specifically, we examine of effect of increasing the number of modes available to the user using his/her non-preferred hand has on task performance. We compare *pre-mediated non-preferred hand mode switching*, where the non-dominant hand precedes the action in the dominant hand, to the concurrent non-preferred mode switching, where the action of the dominant and non-dominant hands can overlap, for three and four-mode interaction. We show that

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concurrent, or overlapping, mode switching is more efficient. Further, we observe that the time savings of concurrent non-preferred hand mode switching is a result of both *parallelism*, temporal overlap in the action of the two hands, and savings in planning time. This indicates that there is a cognitive benefit to parallelism in mode switching in pen-tablet interfaces and a corresponding cost to requiring the sequencing of the two hands.

While concurrent mode switching is faster than pre-mediated mode switching, we do find that it is no longer cost-free. The action of drawing a moded gesture is slower than drawing an unmoded gesture for both pre-mediated and concurrent non-preferred hand mode switching techniques when the number of modes is greater than two.

This paper is organized as follows. First, we explore related work on non-preferred mode switching in stylus interfaces. We then describe an initial study that explores the most efficient mapping of three modes to the fingers of the non-dominate hand. Next, we describe experiments designed to test the scalability of pre-mediated and concurrent mode switching techniques. We then present results and discuss of the implications of these results to the design of pen-tablet interfaces. We conclude the paper by outlining future work in non-preferred mode switching.

2. BACKGROUND

Many researchers have studied variations in interaction techniques for stylus input systems that aim to fluidly allow both command and input [1, 3, 8, 12, 15]. Past research can be separated into research that seeks alternatives to modes, and research to improve the accessibility of software modes. Of particular interest to us in this research is the study of user performance in mode-switching tasks in software interfaces, i.e. improvements in the accessibility of modes.

In the area of user performance in moded pen-tablet interfaces, one recent study by Li et al. [12] explored five different approaches to mode switching in detail. These mode switching techniques were: the use of the barrel button on an electronic stylus; a press and hold technique similar to the Apple Newton; use of the non-preferred hand; a pressure based technique based on work by Ramos et al. on pressure widgets [14]; and stylus inversion, where the tip and eraser of an electronic stylus represent different modes. Li et al. [12] note that the use of non-preferred hand to control program state is faster than other techniques, though not significantly faster than pressure (second fastest) or barrel button (third fastest). Also, eraser and press and hold were significantly slower. In error rate, stylus inversion resulted in the fewest errors, followed closely by the non-preferred hand technique. Finally in terms of user preference, the non-preferred hand technique was typically preferred over other techniques. They conclude that, overall, non-preferred hand mode switching appears to be the best technique for selecting between two-modes in a pen-tablet interface.

Non-preferred hand mode switching is based upon a bimanual coordination model called the kinematic chain model [7]. In this model, the action of the non-preferred hand both precedes and sets the frame of reference for the action of the preferred hand. However, Diedrichsen et al. [4] and Hazeltine et al. [9] question this model for certain bimanual tasks. In particular, if the bimanual tasks are directly cued or can be structured as a single cognitive task, then the action of one hand does not interfere with the action of the other.

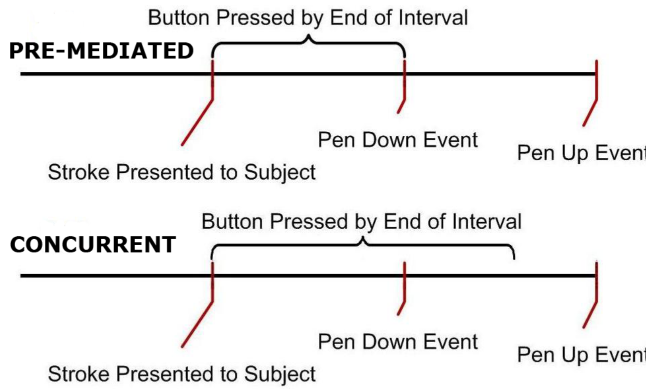

Figure 1: Pre-mediated and concurrent modes. In pre-mediated, to draw a moded gesture subjects must depress the button prior to beginning the gesture and hold it until beginning to draw; button state at pen-down indicated mode. In concurrent mode switching, the mode can be altered during the first part of the gesture, and then is fixed.

Given the benefits of non-preferred hand interaction and the work of Diedrichsen et al. and Hazeltine et al., Lank et al. [11] explored three variants of non-preferred hand mode switching: traditional pre-mediated, post-mediated, and concurrent non-preferred hand mode manipulation. Traditional pre-mediated mode switching requires action in the non-preferred hand to precede the action of the preferred hand (Figure 1). In post-mediated non-dominant hand mode switching, the action in the dominant hand precedes the mode manipulation in the non-preferred hand. The concurrent technique allows mode manipulation in the non-preferred hand to overlap the action in the preferred hand (Figure 1). By allowing the hands to work together simultaneously, Lank et al. observed that mode switching was cost-free. They conclude that the act of switching mode with the non-preferred hand does not interfere with the drawing action of the preferred hand.

While Li et al. [12] and Lank et al. [11] extensively examined two-mode interaction (unmoded and moded), tablet centric applications often offer a larger set of modes. In this paper we explore the scalability of non-preferred hand mode switching to better address such applications. In particular, we explore the use of non-preferred mode switching techniques to support the four common modes (drawing, highlighting, selecting, and deleting) found in tablet centric notetaking applications.

3. SCALABILITY OF NON-PREFERRED HAND MODE SWITCHING

The following questions arise when scaling non-preferred hand mode switching. What is the best way to map multiple modes onto the non-preferred hand? Do benefits of allowing concurrency persist as modes increase? Finally, does allowing bimanual concurrency still result in cost-free interaction? In this section, we describe an initial study to create a mapping for the non-preferred hand. Next we describe an experiment studying scalability of non-preferred hand mode switching.

3.1 Non-Preferred Hand Mapping

We performed an initial study to determine the most efficient mapping of a set of modes to the fingers in the non-preferred hand. Since the goal is to examine non-preferred mode switching for up to four-mode interaction, our initial study explores how to map the activation of three-moded gestures to the non-preferred hand.[1] Assignment of a mode to each of the fingers seems obvious, especially for the index and middle fingers. However, based on informal observation, we hypothesized that using the index and middle finger in a corded gesture, would be faster than using the ring finger.

Using custom software written in C#, subjects were presented with a number representing the desired mode. Selection of a mode was performed using a USB numeric keypad with the non-preferred hand. Modes were presented in a random order and timing information was logged from the presentation of the number to the user's selection of a mode. Modes were assigned to the non-preferred fingers as follows: the index finger was mapped to mode one, the middle finger to mode two, mode three was mapped to the ring finger and mode four was activated by using the index and middle finger simultaneously in a chorded fashion. Labels were placed on the keypad to inform the user of the mode key mappings.

3.1.1 *Procedure*

Six right-handed subjects, 4 male and 2 female, from the age of 22-28 participated in our experiment. The trial consisted of a practice block of 20 trials (5 trials for each condition) and an experimental block of 500 trials (125 trials for each condition). Before beginning participants were free to move the numeric keypad to a comfortable position.

Participants were told to select the appropriate mode as quickly as possible. To encourage speed participants were shown their fastest time in the upper right corner of the application.

3.1.2 *Results*

The results from the study are summarized in Table 1. Analysis of variance shows a significant effect for mode on task time ($F_{3,2841} = 103.236, p < .001$). Post-hoc analysis using Tukey's HSD indicates the index finger mode is significantly faster than all other modes ($p < .01$ in all cases). The middle finger mode was also found to be significantly faster than the ring and corded modes ($p < .001$ in both cases). The corded gesture was significantly faster than the ring finger ($p < .001$) which supported our initial hypothesis.

Using the results from this pilot study, we performed experiments described in the next section using umoded plus the index and middle finger for three-mode interaction and the index finger, middle finger, and corded gesture for four-mode interaction.

3.2 Experimental Design

3.2.1 *Task Overview*

The experimental task was identical to that described by Lank et al. [11]. Subjects were seated in front of a tablet computer in inverted landscape mode (Figure 3.2.1. Modes, represented by colored lines, were displayed at the top to the screen. The subjects used a numeric keypad with their non-preferred hand to activate the corresponding mode and used their preferred hand to draw a line on the tablet screen that bisected two vertical lines (Figure 3.2.1. The use of a USB number pad allowed the keys to be positioned for maximum comfort and to accommodate both right-handed and left-handed users. Experiments were conducted on two identically configured Toshiba R15-S822 Tablet PC's with an attached USB numeric keypad running custom software; the software was written in C# using Microsoft's Tablet SDK and Visual Studio .NET.

Similar to directives typical of tasks measuring human performance (e.g. Fitts' Law tasks [5], Hick-Hyman tasks [16]) users were instructed to draw their model gestures as quickly and as accurately as possible.

Condition	Time(ms)
Index Finger	501.33
Middle Finger	538.84
Ring Finger	607.95
Index + Middle Fingers	583.13
Total	557.81

Table 1: Summary of the results for pilot study.

Figure 2: Experimental setup.

3.2.2 *Measurements*

The interface measured timing for each line cutting task. Timing information started after presentation to the user of the desired mode and concluded when the user lifted the pen from the tablet surface, indicating the end of the task. The interface also logged errors and timing of button and pen events.

Errors were classified into two forms: mode errors and drawing errors. Mode errors occurred when subjects were not in the mode presented to the user. This can occur by the subject using an incorrect mode or drawing the default line. Drawing errors occurred when the drawn line did not bisect the two lines as required by the task described in Section 3.2.3.

As described by Lank et al. [11], the total time required to complete the line crossing tasks can be divided into two

[1]When a default unmoded gesture is combined with three additional non-preferred hand modes, the interface has four modes.

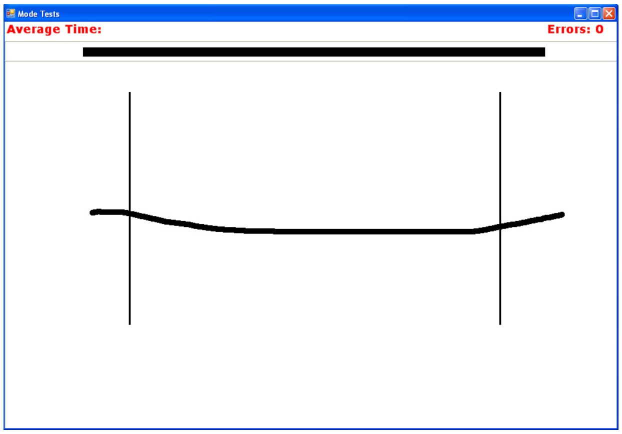

Figure 3: The experimental task performed for three and four-mode interaction.

components: initiation time and stroke time. Initiation time is defined by the time between presentation of the desired line color and the beginning of the gesture in the preferred hand (pen down event). The stroke time is defined as the time from the pen down event to the pen up event. Total time is the summation of the initiation time and stroke time.

In this paper, we further decompose initiation time into three subcomponents: the cognitive cost of deciding the appropriate action and planning the tasks (T_c), the motor cost of activating the mode with the non-preferred hand (T_m), and the time between the mode switch and the initiation of the pen gesture (T_{int}). The resulting decomposition is shown in equation 1. Due to the difficulty of measuring T_m and T_c individually, we present the data as $T_c + T_m$ which represents the time from the presentation of the desired line color and the first mode switch. T_{int} is measured as the time from the mode switch to the pen down event. Since the concurrent technique allows overlapping of the mode switch and beginning the pen gesture, it is possible for T_{int} to be negative in the concurrent technique.

$$TotalTime = T_c + T_m + T_{int} + StrokeTime \quad (1)$$

3.2.3 Hypotheses

In examining the scalability of non-preferred hand mode switching, our goal was to test the following hypotheses:

H1 Concurrent mode switching outperforms pre-mediated mode switching as the number of modes increases.

H2 The time savings observed by concurrent mode switching can be shown in T_{int}.

H3 No time savings should be observed in $T_c + T_m$ for concurrent mode switching.

H4 Concurrent mode switching remains cost-free regardless of the number of modes.

Lank et al. [11] observed a significant time benefit for their concurrent technique, however, it may be that this benefit is a result of unique characteristics of two-mode interfaces. Hence, H1 is designed to test whether this benefit for the two-mode case for concurrent mode switching is observed as the number of modes increases. It is possible that the cost of goal selection outweighs any benefits associated with allowing overlap in mode switching and drawing.

It is unclear whether the benefits of concurrent non-preferred hand mode switching is a result of allowing temporal overlap in the action of the two hands, called parallelism [4], or whether there is a cognitive benefit to concurrent interaction. Hypotheses H2 and H3 aim to address this question. H2 examines whether there is benefit from parallelism in motor activation. If the benefit is due to parallelism, then it would be expected that T_{int} would be less for concurrent than for pre-mediated modes. T_{int} might be negative in the concurrent case, with mode switch occurring after pen down. We had the preconceived belief that the planning time and the time executing the mode switch, i.e. that $T_c + T_m$, are the same for both concurrent and pre-mediated mode switching. We hypothesize that planning is no easier for either task. As well, the actual mode switching task is identical and should consume the same amount of time for muscle activation. Finally, we assume that subjects seek to perform this mode switch immediately as they start their action. However, it is also possible that with the concurrent technique subjects are more likely to wait to switch modes and therefore, $T_c + T_m$ is greater for concurrent interaction. Hypothesis H3 will validate whether this is the case.

Lank et al. [11] determined that task time was statistically indistinguishable in the concurrent mode switching case, regardless of whether a mode switch occurred. If this remains the case for a more complex interface with additional assignments of behavior to the pen, as indicated by hypothesis H4, then non-preferred hand mode switching is the ideal mode switching technique since it consumes no statistically observable time.

To test these hypotheses, we used the timing information reported by Lank et al. [11] as a baseline for the two-mode case and examined both three-mode and four-mode interfaces.

3.2.4 The Experiment

Fourteen subjects, 9 male and 5 female, between the ages of 22-38 participated in our experiment. Two subjects were left-handed, twelve were right-handed. The experiment consisted of eight sessions split over two days. Each day users were asked to use two applications. The first application required the user to use only 3 modes: default, blue, and green. The second application required four-mode interaction. Subjects used each application for one practice session and one experimental session. Each session consisted of 20 unmoded gestures and 20 gestures for each of the possible modes. To counterbalance the order of techniques, subjects were randomly split into two groups. On the first day, the groups used either the traditional pre-mediated technique or the concurrent technique. On the following day, the groups switched techniques so that each group used both techniques by the end of the two days. In each session, the interaction technique was described to the participants. The total number of gestures collected for the three-mode application was:
14 subjects
X 2 mode switching techniques
X 20 gestures per mode
X 3 modes
= 1680 gestures.
1120 of the gestures required mode switching.

Mode	*Technique*	*Initiation*	*Stroke*	*Total*
Unmoded	Traditional	612	293	901
	Concurrent	577	258	829
Index	Traditional	784	312	1082
	Concurrent	651	287	927
Middle	Traditional	761	308	1064
	Concurrent	689	284	953

Table 2: Summary of results for three-mode interaction in ms.

The total number of gestures collected for the four-mode application was:
14 subjects
X 2 mode switching techniques
X 20 gestures per mode
X 4 modes
= 2240 gestures.
1680 of the gestures required mode switching.

Therefore, over the two days 3920 gestures were collected of which 2800 required mode switching.

4. RESULTS

4.1 Three-mode Interaction

Summary for three-mode interaction is displayed in Table 2. Analysis of variance on total time of the task shows a significant effect for the mode presented to the user ($F_{2,718} = 24.64, p < .001$), the mode switching technique used ($F_{1,718} = 27.30, p < .001$), and the order that the subject used the technique ($F_{1,718} = 6.37, p < .05$). For unmoded drawing, the concurrent technique was significantly faster than the traditional technique ($F_{1,252} = 10.78, p < .001$). The concurrent technique was also significantly faster than the pre-mediated technique for the index finger ($F_{1,227} = 13.64, p < .001$) mode and for the middle finger mode ($F_{1,239} = 5.45, p < .05$).

Post-hoc analysis using Tuckey's HSD shows that unmoded gestures where significantly faster than moded gestures within each technique ($p < .001$ for each technique). There was no significant effect within each technique resulting from the finger used to change modes.

Below we further break down the time taken to perform a task into the two components described in section 3.2.2: initiation time and stroke time.

4.1.1 Initiation Time

Analysis of variance indicates a significant effect for technique ($F_{1,718} = 22.17, p < .001$), mode ($F_{2,718} = 25.57, p < .001$), and technique*order ($F_{1,718} = 45.90, p < .001$).

As mentioned in section 3.2.2, initiation time can be broken down into two parts, the decision and planning cost plus the mode activation cost ($T_c + T_m$) and the time between the mode switch and the initiation time of the pen gesture (T_{int}). Figure 4 shows the results from the decomposition of moded gestures by technique. Individual examination of the traditional and concurrent techniques for the effect of mode on $T_c + T_m$ and T_{int} shows no significant difference between modes. However, for $T_c + T_m$ there was a significant effect for technique ($F_{1,12} = 9.98, p < .01$) and order*technique ($F_{2,11} = 34.39, p < .001$). There was also a significant effect

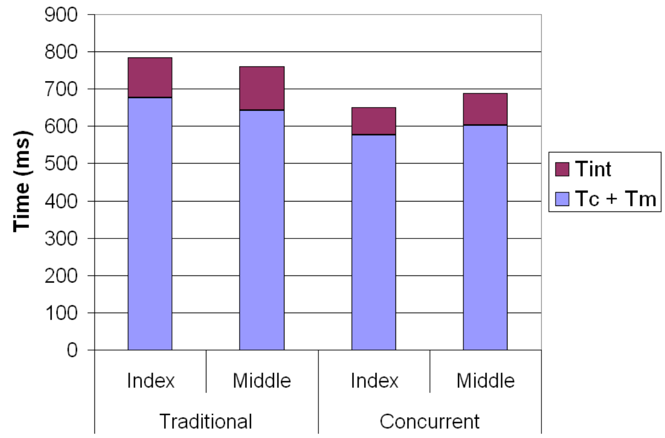

Figure 4: Initiation times by mode for three-mode interaction

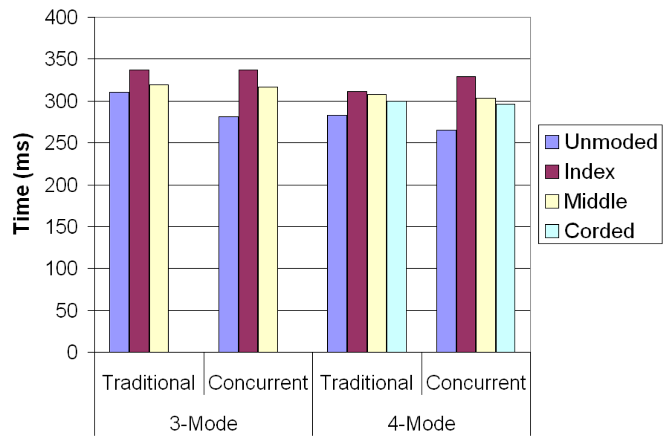

Figure 5: Mean stroke times for three-mode and four-mode interactions by technique.

for technique on T_{int} ($F_{1,12} = 13.01, p < .01$) as well as an ordering effect ($F_{1,12} = 10.77, p < .01$).

4.1.2 Stroke Time

The summary for the mean stroke times are shown in Figure 5. Analysis of variance shows no significant effect for mode, technique, or order on stroke time.

4.1.3 Error Rates

The overall error rates for the traditional technique and concurrent technique where 14.3% and 14.8%. The error rate for drawing errors between the pre-mediated technique (9.8%) and the concurrent technique (9.5%) was relatively similar. The error rate for mode errors was also similar between techniques with an error rate of 4.5% for the pre-mediated technique and 5.2% for the concurrent technique.

4.2 Four-mode Interaction

Figure 6 displays the total drawing times for four-mode interaction. The total mean time to complete the tasks for the pre-mediated technique was 1031ms compared to 952ms for the concurrent technique. Analysis of variance shows a strong effect for technique ($F_{1,12} = 21.21, p < .001$), mode

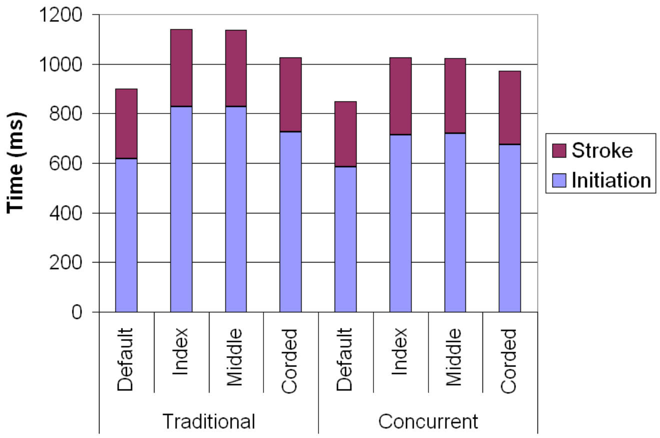

Figure 6: Total Drawing times for the four-modes.

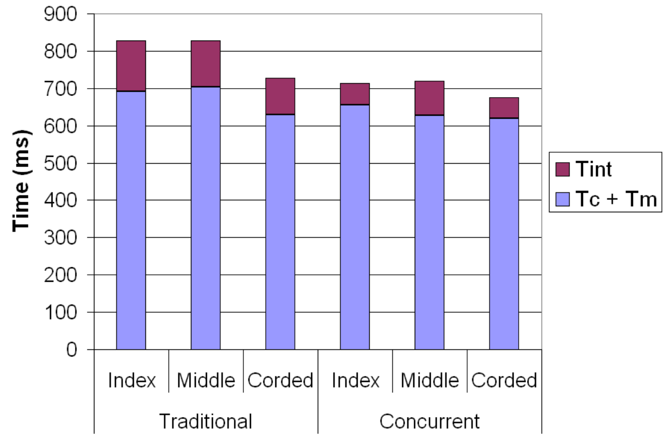

Figure 7: Initiation times for the four-modes.

($F_{3,10} = 29.46, p < .001$), and technique*order ($F_{2,11} = 41.27, p < .001$).

For unmoded drawing, we observe mean total times of 884ms for the pre-mediated technique, and 832ms for the concurrent technique. Analysis of variance shows an effect for technique ($F_{1,12} = 6.123, P < .05$). Analysis also shows an effect for technique in all moded drawing. For the index finger mode, the mean of the total task time for the concurrent technique (1004 ms) was significantly faster than the 1109ms mean of the pre-mediated technique ($F_{1,12} = 4.773, p < .05$). For the mode requiring the middle finger, the concurrent technique was also found to be significantly faster with a total time of 988ms compared to 1093ms for the traditional technique ($F_{1,12} = 7.52, p < .05$). The corded mode selection, created by using both the index and middle finger simultaneously, also resulted in the concurrent technique being significantly faster than the traditional technique ($F_{1,12} = F5.59, p < .05$) with means of 948ms and 1013ms.

4.2.1 Initiation Time

Analysis of variance on initiation time showed a strong effect for mode ($F_{3,10} = 32.60, p < .001$), technique $F_{1,12} = 19.16, p < .001$), and a technique*mode ($F_{4,982} = 3.31, p < .05$). Mode interaction within each technique was limited to unmoded versus moded drawing. In both the pre-mediated and concurrent traditional technique, Post-Hoc analysis showed unmoded drawing to have significantly faster initiation times than the index finger, middle finger, and corded gesture modes ($p < .01$ for each mode in each technique).

The decomposition of initiation time into $T_c + T_m$ and T_{int} is shown in Figure 7. Post-Hoc tests show no significant difference of modes within the traditional and concurrent techniques. However, analysis of variance between the two techniques shows a significant effect for condition in both $T_c + T_m$ ($F_{1,12} = 8.92, p < .05$) and T_{int} ($F_{1,12} = 19.00, p < .001$) with the concurrent technique out performing the traditional pre-mediated technique.

4.2.2 Stroke Time

Analysis of variance between the two techniques shows an ordering effect ($F_{1,12} = 8.86, p < .05$) and technique*order effect ($F_{2,11} = 8.86, p < .01$). However, technique alone did not have an effect on stroke time. Post-Hoc analysis of mode within each technique also shows no significant differences between stroke time.

4.2.3 Error Rates

The overall error rate for the traditional pre-meditated mode switching technique was 10.5%. The error rate for drawing errors was 7.3% and 3.2% for mode errors. The concurrent technique's overall error rate was 11.3% with a drawing error rate of 6.4% and a mode error rate of 4.8%.

5. DISCUSSION

Our experiments are designed to test four hypotheses, specifically:

H1 Concurrent mode switching outperforms pre-mediated mode switching as the number of modes increases.

H2 The time savings observed by concurrent mode switching can be shown in T_{int}.

H3 No time savings should be observed in $T_c + T_m$ for concurrent mode switching.

H4 Concurrent mode switching remains cost-free regardless of the number of modes.

In this section, we examine each of these hypotheses in light of our experimental results. Next, we analyze some of the implications of these results for future work. Hypothesis H1 was designed to determine whether relaxing the requirement that non-preferred mode switching occur before drawing was beneficial as the number of modes increased greater then two. When we examine the results of both the 3-mode and 4-mode experiments, we see that a statistically significant time savings still results from permitting parallelism. As shown in figure 4 and 7, allowing parallelism results in users initiating the start of their gesture approximately 10% faster.

Hypotheses H2 and H3 were designed to determine why the temporal benefits are observed for the concurrent non-preferred hand mode switching technique. This analysis was not performed for the two mode case in Lank et al. [11]. Hypothesis H2 tests whether there is a time savings that results from relaxing the requirement that the action of the pen must follow the mode switch. With the concurrent technique, the user has increased permissiveness to begin the

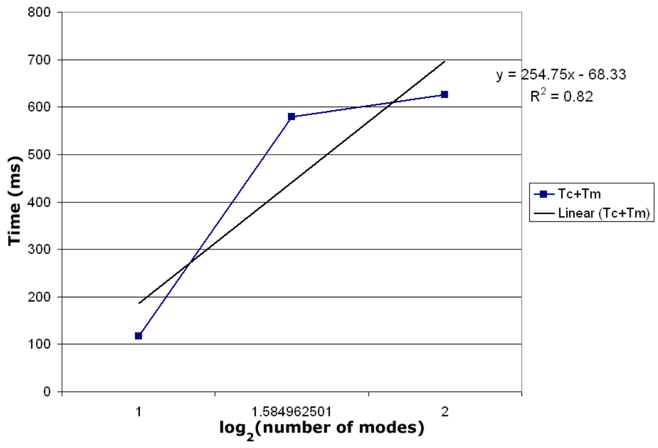

Figure 8: $T_c + T_m$ for concurrent non-preferred mode switching as the number of modes increases.

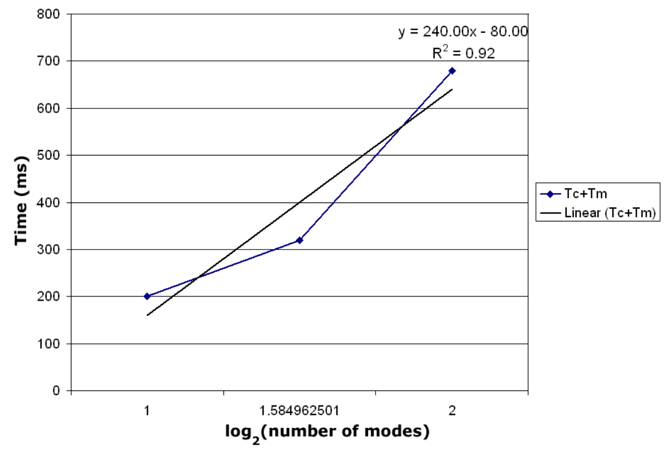

Figure 9: $T_c + T_m$ for traditional non-preferred mode switching as the number of modes increases.

gesture before preforming a mode switch, thus, we expect a decrease in the time between mode switch and the start of the gesture, T_{int}, for the concurrent technique. In our results, for both the three and four-mode interfaces there exists a statistically significant reduction in T_{int}, indicating that the user is taking advantage of this increased permissiveness.

The conclusion for H3 contradicts our preconceived belief of the outcome. Since mode switching can occur after pen down, we expect $T_c + T_m$, the planning time and the muscle contraction time, for the two techniques would be similar; or $T_c + T_m$ would be greater in the concurrent case. The latter belief is a result of participants not rushing to complete the mode switch task when they can wait. However, this is not what we observe. Instead, we observe that $T_c + T_m$ is less in the concurrent case, meaning that the time to plan the overall action and the time to switch modes is less for concurrent mode switching than for pre-mediated mode switching.

In considering this result of the concurrent technique there are two interpretations: it is easier to plan or the user is able to press the buttons faster. Since there is no difference in the muscle task preformed by the non-preferred hand the latter interpretation is unlikely. Therefore, the only possible explanation is that T_c is less in the concurrent technique, i.e., that it is easier to switch modes in the interface when parallelism is allowed. This is a significant result. Because this is a temporally constrained task, we conclude, as do psychologists [9], that the result of improved timings are the direct result of a task with lower cognitive cost, i.e. one for which the planning can be performed more efficiently.

Hypothesis H4, if supported, would indicate there is no cost associated with switching modes in interfaces up to the four-mode case. In essence, it would demonstrate that, for temporally constrained tasks, the mode switch operation does not require cognitive planning and, if parallelism is allowed, does not result in time penalty as a result of muscle activation. However, hypothesis H4 is not supported by our observations. In both the three and four-mode cases, we see a temporal cost associated with mode switching in the concurrent case, that is the concurrent case is no longer cost-free.

When we compare $T_c + T_m$ for three versus four modes in the concurrent case, the average values are 558ms for three and 627ms for four modes. In the pre-mediated case, average values are 648ms for three and 667ms for four modes. Based on Bonferroni-corrected paired t-tests, these differences are statistically significant ($p < 0.01$ in both cases). As number of modes increases, we see an increase in the time taken to activate modes. Below we use the Hick-Hyman law [10] as a way to describe the differences required for a given task as the number of modes available increases.

6. FUTURE WORK

The Hick-Hyman law states that given a set of n stimuli where each stimuli is associated in a one to one relationship with n choices, the time to make the appropriate response to the stimulus is represented by

$$RT = a + blog_2(n), \tag{2}$$

where a and b are empirically determined constants. The Hick-Hyman Law has been traditionally used to predict movement and reaction time in cascading menus [2]. It may also be applicable to mode switching, by allowing us to predict how increasing the number of available modes effects initiation time.

If mode switching follows Hick-Hyman we would expect that given n number of modes, the response time (RT) to select a mode should increase in a logarithmic fashion. In our line bisecting tasks, $T_c + T_m$ are the only non-constant terms within interface technique. There is no effect on T_{int} based on number of modes. If Hick-Hyman predicts response time then $RT = T_c + T_m$ based on number of modes. While we would expect that the initiation time recorded by the tasks to increase in a logarithmic fashion, our dataset from this experiment only contains 2 data points ($n = 3$ and $n = 4$). However, in our previous work [11], we studied two-mode interaction. We incorporate the initiation times reported for two-moded interaction using the raw data of the previous experiment in [11] to extract $T_c + T_m$.

Figure 6 (pre-mediated) and Figure 5 (concurrent) show data from [11] combined with data from the experiments described in this paper. Using the two-mode case from [11] and our date from experiments in this paper, the figures suggest that mode switching follows the Hick-Hyman law ($R^2 = .92$ for the traditional technique and $R^2 = .82$ for the concurrent technique). However, as the number of data points is still small this correlation is only tentative.

As a result of this early correlation, we plan to extend the number of modes beyond four using ring and pinky fingers and more complex chords. Analyzing this data in light of the Hick-Hyman law may allow the development of a cognitive model of decision cost for mode-based interfaces in pen-tablet systems.

7. CONCLUSION

This paper studies the scalability of non-preferred hand mode switching, and demonstrates the benefits of parallelism, shown in [11] for the two-mode case, extend to three and four modes. Analysis of our experimental data indicate that:

1. Concurrent mode switching outperforms pre-mediated mode switching as the number of modes increases.
2. Time savings occur both in the time taken to activate a mode with the non-preferred hand and in the time between non-preferred hand action and the start of a gesture in drawing interfaces.

Taken together these results suggest that the cost of activating a mode is lessened when the actions of the hands can be parallelized.

In previous work, we showed that non-preferred hand mode switching was cost-free when parallelism was permitted, i.e., that moded and unmoded gestures were statistically indistinguishable. In this work, however, we see that as the number of modes increases, the time taken to initiate modes increases. We also observe that the initiation time for moded gestures is longer then the initiation time for unmoded gestures. Preliminary results indicate that the temporal cost of increasing the number of modes may correlate with the Hick-Hyman Law.

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