Empirical Evaluation of Uni- and Bimodal Pen and Touch Interaction Properties on Digital Tabletops

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ABSTRACT

Combined bimanual pen and touch input on digital tabletops is an appealing interaction paradigm enjoying growing popularity among many HCI researchers. Due to its relative novelty, its properties are still relatively unexplored and many hypotheses emerging from intuition and extrapolations from studies about touch and other pointing devices remain to be verified. We present an empirical evaluation consisting of three experiments aimed at investigating a few important issues of pen and touch interaction on horizontal surfaces. Specifically, we examine the compromise between speed and accuracy for the two input modalities in positioning and tracing contexts, the influence of palm-resting on pen precision and bimanual coordination for pen mode-switching via postures. We report on quantitative and qualitative results obtained from these trials and discuss their potential impact on the design of pen and touch systems.

Author Keywords

Pen and Touch interaction; Digital tabletops

ACM Classification Keywords

H.5.2

General Terms

Design; Human Factors; Experimentation

INTRODUCTION

Bimanual pen and (multi)touch input on digital tabletops has received increased attention from the HCI community recently, as researchers discover the benefits of combining the two modalities enabling richer interaction possibilities. It has been generally observed that touch input through the non-dominant hand (NDH) lends itself to coarser manipulations such as panning, zooming, and moving objects on the surface, while pen interaction via the dominant hand (DH) is more suitable for precise actions such as sketching and writing [11]. There are mainly two advantages of pen and touch input being available together: in sequential interaction patterns, it enables seamless and almost instant context switches between the two modes (users are able to effortlessly transition from touch to pen actions) and in coupled bimanual operations, one modality can serve to modify the functional context of the second through parallel activation or gestural actions (e.g. placing a flat hand on the surface to constrain the pen to draw straight lines [2]).

The benefits of pen and touch interaction have materialised in a few interesting applications that demonstrate the potential of a synergistic use of the two input methods [2, 7, 10, 17, 29]. This interaction paradigm is still relatively novel and it is only very recently that commercial (and relatively costly) hardware supporting simultaneous and differentiated pen and touch have come onto the market (e.g. Perceptive Pixel [18] and Wacom [23]). The field is therefore fairly open and, notably, we observe that empirical research investigating the properties of bimanual pen and touch interaction is still relatively scarce compared to the quantity of studies dedicated to mice and other pointing devices [6, 13, 30]. We also note that most of the studies about different and potentially competing pointing methods and devices are mode-comparative by design and so do not examine the interplay of those input techniques when coexisting in a single cohesive environment [3, 15, 21, 22, 28].

In this paper, we report on an empirical investigation of certain aspects of pen and touch interaction in different contexts through a set of three user experiments, from which we derive a number of observations and lessons that we hope will inform the design of future systems and applications based on this interactive ecosystem. Our first set of experiments tackle issues that have been studied for touch and other pointing devices, and we revisit the tests and adapt them for the context of pen and touch tabletop interfaces. Concretely, we consider tasks such as widget targeting and positioning as well as shape-tracing, through which we compare direct (multi)touch input to pen and touch configurations. The difference to previous comparative studies is that, in all our pen conditions, we assume the copresence of touch, either for assisting manipulations as in our first experiment (panning and zooming the workspace), or as a possible hindrance as in our second test (palm resting causing interference). Our third and last experiment addresses problems more specific to asymmetric pen and touch interaction: bimanual coordination and synchronisation. Here we examine how effectively the NDH can change the pen's function on-the-fly via postures compared to classic button tapping on a toolbar.

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While we certainly make no claims to exhaustiveness, we believe those aspects cover important ground of the still under-explored problematics of two-handed pen and touch input and hence add to the body of work on the topic.

RELATED WORK

The problem of bimanual interaction and coordination has been widely studied in the field of cognitive sciences [20], but is also of great interest to HCI researchers wishing to exploit knowledge of cognitive and kinaesthetic processes governing human motor skills to design more intuitive NUIs (Natural User Interfaces). Following Guiard's early work on the role of the DH and NDH and the development of his kinematic chain model for two-handed action [9], many researchers have attempted to apply those findings to multitouch and more recently to pen and touch interaction.

Yee describes how a tablet PC can be augmented by a touch screen to support asymmetric pen and touch input as a way to place "both hands and the display in the same reference frame using inexpensive, portable hardware" [27]. Wu et al. propose a set of design principles for multi-hand gestures and include observations of how gesture registration by the NDH can be applied to modify the function of a stylus (e.g. to transition from writing to selecting and vice versa) [26]. Brandl et al. present the pros and cons of pen vs. touch input and lay out the groundwork for a reflection on the assignment of those two interaction modes to the DH and NDH [2]. This reflection is pursued more extensively by Hinckley et al. who, through a design study, explore the roles best adopted by each input type [11]. Their observations of people working with paper notebooks and various stationery items led them to advocate a framework of divided labour in which the unimodal pen mainly writes or inks, unimodal (multi)touch manipulates and multimodal pen and touch provide new tools.

As for applications utilising those principles, proof-of-concept prototypes have been developed to support tasks and scenarios such as sketching [10], painting [2], diagram editing [7], laying out widgets [8], equation writing [29] and active reading [17].

As mentioned above, there is still a relative paucity of solid empirical evidence to buttress many of the design principles formulated by the aforementioned authors. Brandl et al.'s maze task shows that pen+touch is superior to bimanual/ unimodal input combinations (i.e. touch+touch and pen+pen), but does not examine the individual properties of each mode further [2]. Frisch et al. conduct a user study to elicit gestures suitable for node-link diagram editing from which they obtain high-level qualitative results for the purpose of their system [7]. More recently, an evaluation by Zabramski compares mouse, pen and touch input in the context of a freehand shape-tracing task somewhat similar to our second experiment [28]. The author reports that participants using touch input performed fastest but were less accurate compared to other input methods. Another recent study by Tu et al. measures temporal and geometrical characteristics of stroke gestures when executed by the pen vs. the finger [22]. While potentially relevant for pen and touch systems, the findings concern complex single-stroke gestures, an aspect not addressed here. Finally, while not directly related to pen and touch input, Forlines et al.'s evaluation of touch vs. mouse [6] with targeting and docking tasks informed the design of our first experiment.

STUDY DESIGN AND ENVIRONMENT

When designing our evaluation and its constituent tasks, we decided to approach the problem from a low to mid-level perspective. We wanted to integrate both fine-grained per-action and per-pointer indicators, such as target pointing and tracing errors as well as higher-level aspects pertaining to user interface elements such as mode-switching and two-handed shortcuts for the design of our tasks. This choice was motivated by our belief that it is hard to generalise and provide ecological validity for measurements obtained from strictly low-level trials that focus on isolated input techniques in a heavily controlled and constrained interactive context. Similarly, it is difficult in higher-level experimental settings to validate individual design choices for more complex applications comprising several features and interaction capabilities. We therefore tried to strike a compromise between these two considerations in order to obtain meaningful results that can be of use to the community.

Following the above rationale, we devised a set of three relatively simple tasks that we thought could be performed more or less easily by users familiar with touch interfaces as well as those with less or even no experience with touch devices. For all three tasks, we created three different interaction contexts that we hereafter refer to as configurations. These configurations represent the three levels of the independent variable that is considered in each experiment (in each case, a particular interaction method).

Apparatus

As enabling hardware, we used a DiamondTouch [4] augmented with Anoto technology [1], i.e. a layer placed on the touch surface with a printed dot pattern to recognise the position of a digital pen. For the latter, we used one of Anoto's DP-301 "streaming" pens, which have the required level of reactivity for such real-time situations. This experimental platform combining a responsive multitouch tabletop with high-resolution pen-sensing technology [12] is a popular choice among researchers [2, 14, 17].

The resolution of the display was 1600x1200 which yielded a dpi value of roughly 48.

The system was carefully calibrated before each session in order to guarantee the accuracy of the measurements.

Study Design

We opted for a between-subjects design for our experiments, as we felt that people could become confused if they had to successively perform the same tasks using different interaction techniques. While imposing a logistic burden regarding the number of participants to be recruited, this choice allowed us to have volunteers carry out all three experiments in one session, where each person executed one task set to one particular configuration. This design also enabled us to use identical protocols for each configuration, hence direct comparisons were possible without randomising the particulars or orders of the subtasks, which would otherwise have been required to mitigate learning effects.

Participants

30 participants - 19 males and 11 females aged between 20 and 65 years old (median: 28 years old) - were recruited among students and staff of our department to take part in the study. Three people were left-handed, which justified our adopting a symmetrical design for our interfaces (UI widgets and shapes were mirrored about the middle vertical axis for those users).

The overwhelming majority of participants owned one or more touch device(s) such as a modern smartphone and/or a tablet computer, with only four people declaring that they did not possess such machines. No one owned a stylus-operated appliance, except for one user who said he occasionally used a special pen to write notes on his touch tablet.

Since the first three tasks had three configurations, an even assignment of those configurations to participants yielded three groups of 10 users. Before executing the actual task of each experiment, for which measurements and observations were recorded, participants were given as much practice time as they desired to become acquainted with the work to be done and the different gestures to accomplish it.

For all tasks, we recorded the time to complete it as well as the time taken to execute each individual subtask (a task constituted of 20 subtasks in each case). For each experiment, we further logged a number of task-dependent metrics that we describe in the relevant sections. These values were then summed up for all subtasks to yield a total that was included in the data set used to compare the different configurations in the analysis phase.

After each trial, users were presented with a questionnaire, in which they had to rate on a linear scale (using a slider) how easy it was for them to execute the task and report any problems they had encountered.

EXPERIMENT 1

Description

As mentioned above, this experiment was inspired by Forlines et al.'s study of direct-touch vs. mouse input [6], which somewhat departs from a traditional Fitts' law-based target acquisition test. Our goal was similarly to mimic situations encountered in graphics or publishing software where widgets need to be manipulated and placed in specific positions. Our task involved docking a draggable rectangular shape inside a given target. We merged Forlines et al.'s two experiments so that the rectangles had to be moved and resized in all cases. In our setting, however, we included a virtual sheet in the shape of a blank document (hereafter referred to as "the worksheet") in the middle of the workspace area. This worksheet could be panned and zoomed using classic multitouch gestures, a facility that is commonly available in such kind of interfaces and whose influence on the docking task we were curious to see. All shapes appeared and were to be manipulated on this designated space. Users could also drag and release the rectangles as many times as they wished.

As soon as an edge was positioned within 2 pixels (with a worksheet scaling factor of 1) of the corresponding target edge, its colour changed to green (Figure 1). Contrary to Forlines et al's experiments, shapes could only be "validated" after fully releasing them. This allowed us to measure a possible displacement-on-release effect, i.e. the slight translation of the contact point registered by the sensing hardware upon lifting the finger or pointing device. Without any smoothing or thresholding filters, this displacement can cause an object held down by dragging to move away from its target position when the finger or pointing device is released [24].

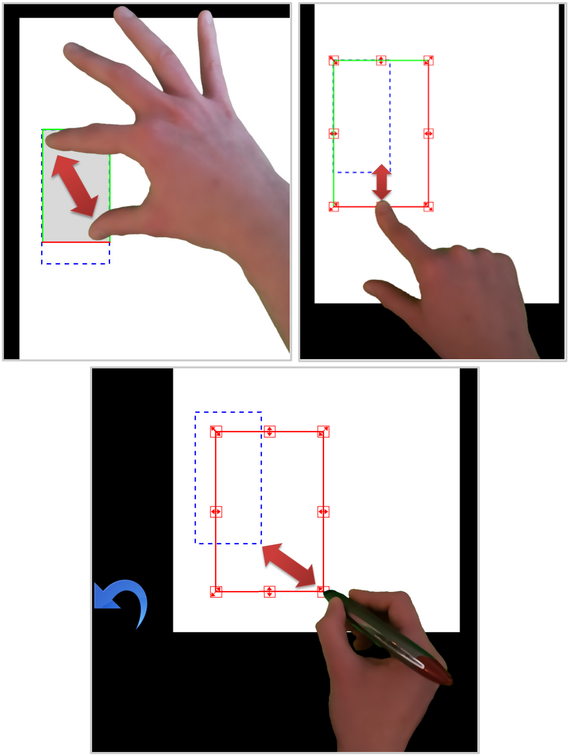

Figure 1. Positioning task with pinch-spread moving and scaling (top-left), unimodal handle manipulation with finger (top-right) and pen (bottom).

In our implementation, we defined this displacement factor as the distance covered by the contact points registered by the system t milliseconds before the finger or the pen was lifted from the surface. We chose a value of 200ms for t and recorded this displacement only for release events that led to a correctly positioned shape in order to ensure that the user was finalising a docking action. We also ensured an equal number of contact events were considered to account for the sampling rate differences between pen and touch.

In the first configuration, the rectangles had to be moved and resized using two-finger pinch and spread gestures, where the changes of the bounding box formed by the two contact points of the fingers were mapped to the affine transform affecting the position and size of the rectangle to be dragged in place (Figure 1 top left). Hence, the gesture commanded translation as well as the two independent scale factors of each axis of the dragged shape. It was left to the user whether to use fingers from the same hand or from both hands to perform the manipulations.

In the second and third configurations, rectangles were supplemented with handles along their edges and corners. These handles could be tapped and dragged with the pen (second configuration, Figure 1 bottom) or finger (third configuration, Figure 1 top right) to move the associated edges thereby scaling the rectangle. This type of widget manipulation is commonly found in graphics and design software. The handle dimensions were varied from shape to shape using three different set sizes: small (15px), middle (25px) and large (35px). The size of the handles scaled along with all objects contained in the worksheet in accordance to the latter's zooming factor. This meant that users could use the scaling feature of the worksheet to increase their targeting accuracy if they wished (but possibly at the cost of more time required to complete the task). Each set handle size was used an equal number of times for the task, specifically 6 times each for a total of 18 rectangles to be positioned.

For the configurations with handles, we recorded the number of times users missed the latter. Recalling that our target scenario is a graphic design program on a pen and touch system, we considered the situation in which the pen is mainly used for inking and direct stroke input. Therefore, in the second configuration where the pen is also used for handle manipulations, a miss caused a stroke to appear on the worksheet. To be able to resume the positioning operation, users had to tap an undo button located at the bottom left (or bottom right for left-handed people) of the workspace (Figure 1, bottom). For the third configuration, where handles were manipulated by the finger, a missed handle only caused the user to move the worksheet instead of the object, which we considered to be of lesser impact than accidental inking. Therefore, in this condition, we only registered an error without imposing additional time-consuming penalties. Because it was difficult to algorithmically differentiate an intentional worksheet pan from a handle miss, we simply observed users and manually recorded an error when it was obvious they were off target when intending to select a handle.

Results

Figure 2 shows task completion times and difficulty ratings chosen by users after performing the test. The charts show a similar pattern, with the two-finger positioning configuration (Pinch/Spread) appearing to be the most inefficient and difficult.

ANOVAs performed on these results confirmed there were significant effects in both cases ($F_{2,27} = 6.41$, $p = 0.005$ for completion time and $F_{2,27} = 14.34$, $p < 0.001$) so post-hoc Tukey tests were conducted. These tests revealed significant mean differences for completion time between Pinch/Spread and the two others ($p < 0.001$ in both cases), however no main effects were observed between the two handle configurations ($p = 0.49$). Similar conclusions can be drawn with respect to the difficulty ratings. Hence, we were not able to confirm that pen was significantly faster than touch [3].

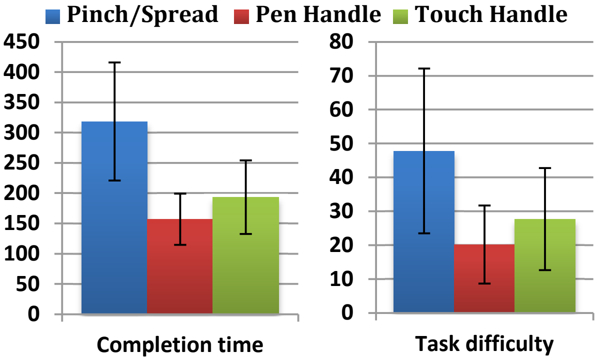

Figure 2: Task completion times (in sec.) and user ratings of task difficulty (from 0=extremely easy to 100=extremely difficult). Error bars show standard deviation values.

Digging deeper into the results and relating them to our observations of participants executing the task, we recall that especially the last docking operation was difficult for users as it required precise positioning of the rectangle edges. The displacement-on-release effect caused the rectangle position controlled by the held down finger(s) or pen to slightly move when lifting it/them up, leading to correctly positioned rectangles being misaligned after release. The average value for this displacement was evaluated at 1.18 pixels for the pen (SD=0.44) and 2.26 pixels for single-finger touch (SD=0.54), which are significantly different values, as confirmed by a t-test ($p<0.001$).

This reduced accuracy of touch and multitouch translated in increased uses of the worksheet's zooming feature. All participants of Pinch/Spread made use of it, with an average of 7.4 operations per user (SD=4.48), while 7 did for Touch Handle with 5.1 zoom actions on average (SD=4.1) and only 2 people for Pen Handle.

Our observations also showed that users tended to favour sequencing simple actions and separating degrees of freedom rather than attempting to perform one complex operation controlling several factors at a time. Many participants of the "Pinch/Spread" group said in their feedback that they would have liked to have been able to "fix" correctly placed edges so that they could then concentrate on working with the others. The configurations with single-point interaction with handles controlling only one or two edges fulfilled that requirement and users were more efficient in these conditions and felt the task was easier. Those observations are consistent with previous findings on control allocation of degrees of freedom [16].

Turning to the comparison of the handle configurations, specifically the handle targeting errors, we recorded an average of 1.6 errors for the pen (SD=1.84) and 6.2 errors for touch (SD=3.61), again with significance easily confirmed by a t-test ($p < 0.001$), which confirms previous studies reporting that pen or stylus is more accurate than touch [3]. As expected, most errors occurred for the smallest handles (68% and 80% respectively) and edges (25% and 13%). As for positioning strategies adopted by participants, we did not observe any differences, as the numbers of move and resize operations were roughly equal for both configurations (38.2 vs. 39.8 and 13.5 vs. 16 respectively).

In our qualitative feedback session, we asked participants of the pen handle group if they would have preferred to use touch and vice-versa, but generally, users of each group did not express any dissatisfaction with their assigned interaction method. Only two people in the Touch Handle condition said that a pen would perhaps have been better to hit the smaller handles, but this was less a problem of touch than a problem of the interface (and a deliberate design choice for the experiment).

We derive essentially four lessons from this experiment:

1. The pinch-spread gesture is not particularly suitable for precise positioning and hence is best reserved for coarse zooming functions of browsing windows and viewports with a single common scale for both axes.
2. The pen can also be an appropriate tool for widget manipulations, both in terms of precision/efficiency and the perspective of (some) users' preference.
3. A succession of simple operations that each controls a limited amount of degrees of freedom is preferred to one complex action that attempts to fulfil multiple operational requirements simultaneously.
4. To achieve precise positioning with touch, the displacement-on-release effect needs to be suppressed with adequate filtering and smoothing techniques. Other assisting functionality such as snap features (a suggestion made by a few participants, but contrary to the intent of this experiment), rulers and other constraint-based mechanisms [8, 25] can also be utilised.

EXPERIMENT 2

Description

In the second experiment, we considered tracing precision with the finger and the pen, a problem also crucial for drawing and design applications as well as interfaces requiring a certain level of stroking accuracy such as text input pads with handwriting recognition. We observed that among applications available for devices operated by touch only, there exist a number of sketching and freehand note-taking programs. This further motivated us to examine how the two modalities compared in such contexts. For pen tracing in particular, we wanted to determine whether not allowing resting of the palm or the arm on the tabletop surface had a noticeable influence on precision. Our three configurations were therefore: finger tracing, pen tracing with and without palm resting (Figure 3). We used simple geometrical shapes for the tests to allow users to easily execute single-stroke tracing movements with minimal cognitive effort.

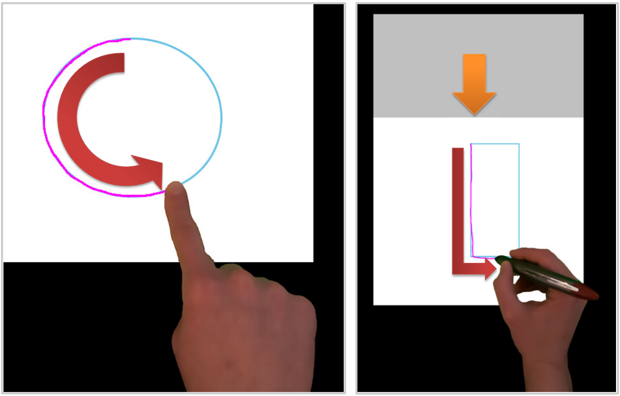

Figure 3: Shape-tracing task with a finger (left) and with the pen (right). The grey filler shows the passing time (shade emphasised in the figure for illustration purposes).

As in the first experiment, the shapes to be drawn appeared on a document-like virtual worksheet, which this time was static and hence could not be panned or zoomed. The task for the participants consisted of trying to trace over the given shapes in one stroke as precisely as possible. In the third configuration (pen tracing without palm resting), if the user touched the surface with his/her hand or arm, the background colour would change to red and tracing with the pen would be blocked until the hand or arm was lifted.

A further constraint was added to the task in that, for some of the shapes, tracing had to be performed within a specific time limit. We included these time constraints in an attempt to artificially model rapid stroking situations. To provide users with appropriate awareness of this time pressure without disrupting the tracing task, we materialised the passing time as a light grey area that gradually fills the worksheet from top to bottom (Figure 3 right). A time constraint was constructed as a function of the perimeter of the shape to be drawn, a fixed offset and a modifier. We created three time settings for the task: unlimited (i.e. no time constraint, users could take as much time as they wanted to draw over the shape), moderate and fast. Typical times for the fast setting would be less than 1.8 seconds, so users were forced to draw the shapes very rapidly, presumably with a significantly reduced ability to concentrate on precise tracing. The moderate parameter corresponded to times between 4 and 7 seconds, depending on the size of the shape to be drawn.

A series of 18 different shapes was thus generated for all configurations and, as in the first experiment, the three time settings were evenly assigned to the individual subtasks. Shapes that a user could not finish drawing within their associated time constraints (i.e. a timeout occurred while the pen was down) were repeated at the end of the set.

We calculated two precision errors for this task, a pointer-down error, which was the distance from the first contact point to the closest point on the target shape, and a shape error, which we computed as the area of the space obtained by applying an exclusive OR operation to the two areas of the target and user-drawn shapes (so that if the shape was perfectly traced, the two areas overlapped completely and therefore the error was 0). The contact point error modelled the accuracy of initial targeting of the shape by the user, whereas the shape error represented overall tracing precision for the entire stroke. Our hypothesis was that the pointer-down error would be higher for finger tracing, but that the shape errors might not turn out to be significantly different, since users could automatically adapt their tracing movement as they visualised where the stroke appeared.

Results

We consider first the global results over all subtasks, i.e. all shapes to be traced, disregarding the time constraints. Figure 4 shows users' difficulty ratings and the two errors described above.

We see that this task received a range of assessments regarding its difficulty, with average ratings for all three configurations between 40 and 50 and evidently no significant differences. In the discussion session after the task, participants who judged the experiment relatively difficult gave the time pressure imposed on them for some of the shapes as the reason for their ratings. This consideration overshadowed the differences between the three input methods and so we asked users directly how comfortable they had been with pen or finger tracing and if they would have preferred an alternative technique. While 5 participants of touch tracing said they would rather have used a pen, there were also people in the pen conditions (2 in each group), who expressed a preference for direct touch input, which somewhat surprised us. Regarding palm resting, 4 participants of the third group explicitly stated they would have liked to have had that possibility.

As for precision, the error charts of figure 4 seem to confirm our hypothesis that only the pointer-down errors would exhibit considerable disparities between touch and the two pen configurations. At first glance, it does not seem as if palm resting had any significant influence. We verify this observation and expand our analysis using the results of the tracing subtasks broken down according to their associated time settings. Figure 5 shows the separated error values.

We conducted ANOVAs on the 6 dependent measures to identify significant differences. The numeric results of those analyses and of the post-hoc pairwise comparisons (when relevant) are reported in Table 1, with significant values highlighted in bold and values close to the common α-level of 0.05 (specifically before and after Bonferroni correction) in italics.

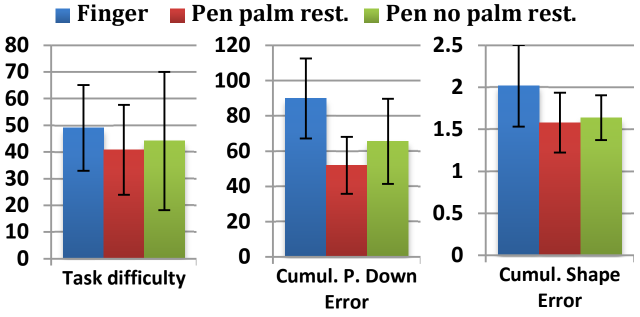

Figure 4: User ratings of task difficulty (from 0=extremely easy to 100=extremely difficult), cumulative pointer-down error (in px) and cumulative relative shape error.

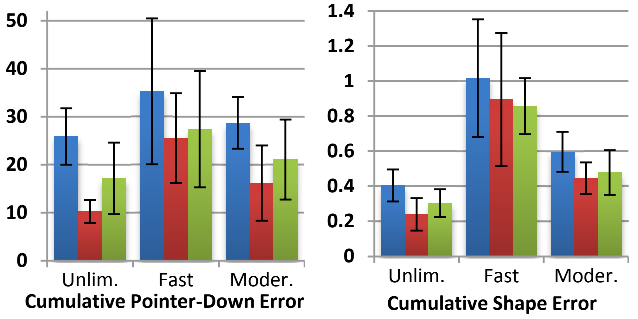

Figure 5: Cumulative pointer-down error (in px) and cumulative relative shape error for the three time constraint settings unlimited, fast and moderate.

	P.-Down Error	**Shape Error**
Unlim.	F=19.08, **p<0.001**	F=9.17, **p=0.001**
Fast	F=1.72, p=0.199	F=0.75, p=0.482
Moder.	F=7.48, **p=0.003**	F=5.13, **p=0.013**

ANOVA

	P.-Down Error		**Shape Error**	
	Unl.	**Moder**	**Unlim.**	**Moder**
Fing vs. Pr	**<0.001**	**=0.002**	**=0.001**	**0.014**
Pr vs. no Pr	*=0.030*	=0.307	=0.233	=0.790
Fing vs no Pr	**=0.005**	=0.068	*=0.040*	=0.061

Post-hoc Tukey tests

Table 1: F and p-values for ANOVAs and p-values of post-hoc Tukey tests (when applicable) for the pointer-down and shape errors in the three time-constraint settings.

The data reveals interesting results, most strikingly that there is no significant effect of palm resting on overall tracing precision. Even the pointer-down error in the unlimited time setting is not significant enough (after Bonferroni adjustment) to draw clear-cut conclusions. Furthermore, it appears that, in fast drawing contexts, finger or pen perform equally well (or rather equally badly), although the large standard deviations indicate that this varies considerably among users. We notice, however, that pen with palm-resting is always more accurate than touch input in conditions with no or moderate time pressure, which is consistent with our expectations.

If we attempt an interpretation of these results and what they could imply for pen vs. touch interfaces involving rapid tracing, opting for one or other input method has no or little consequence on accuracy (a consideration that arguably is not all that important in those types of scenario anyway). In more relaxed situations, such as artistic drawing and painting, the pen is clearly superior, even more so if those activities involve executing several short strokes rather than long freeform paths as in our task (i.e. the pointer-down error becomes a much more important factor). As for palm-resting, the influence on precision is less pronounced than we had initially thought, at least on a digital platform with all its imperfections (see Discussion section).

After establishing those results, we performed an informal experiment with a similar task using real pen and paper. We asked 6 people to trace over a set of shapes and short lines printed on two sheets (without time constraints), where they had to lift their arm while drawing for one of the sets. The results more or less mirrored what we experienced on the tabletop. The shapes were drawn relatively accurately overall in both conditions but the short lines less so (Figure 6). It seems therefore that the most significant precision discrepancy between the two conditions is the initial targeting and placing of the pen. An initial firm stand on the surface allows more precise pointing than a shaky hand making an unsteady approach. But once contact has occurred, the necessary support is established and the tracing movement can continue with relative stability, albeit with slight fluctuations and irregularities.

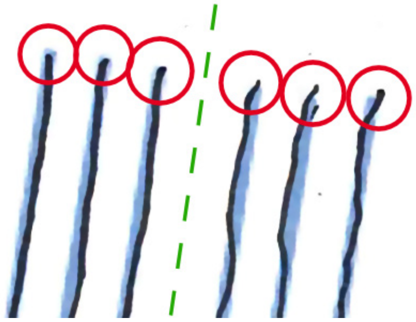

Figure 6: Lines traced on paper with arm rested on the drawing surface (left) and lifted (right). Starting portions of the line are circled in red.

We hasten to add that the ability to rest the hand or the arm on the surface while executing drawing tasks is very important for comfort and fatigue. Protracted pen use with a lifted limb causes exhaustion and pain and so we think this problem needs to be addressed if only for that reason.

To summarise our findings in this experiments:

1. Pen and touch have comparable, low precision in rapid tracing tasks.
2. Palm resting mainly affects initial targeting and pointing accuracy of the pen. Overall tracing precision is also diminished, but to a lesser extent.
3. A majority of users agree that the pen is more adequate for a tracing task. There are, however, a few people who prefer direct touch input.

EXPERIMENT 3

Our third experiment was devoted to bimanual coordination, specifically how the pen-holding DH could be affected by changing frames of reference triggered by the touching NDH, to borrow Guiard's terminology. We observed that, in most existing applications for pen and touch tabletops, pen mode-switching occurs through simple function selections or postures performed by the NDH. Most notably, the activation of pen functions through the touching hand is largely static, i.e. the switch to a different pen mode is almost never triggered by a gesture requiring a complex motion of the NDH. For their "new tools" obtained by combining pen and touch primitive operations, Hinckley et al. employ mostly tapping and holding actions for touch, while the pen can also draw strokes and drag objects [11]. This is in accordance with Guiard's kinematic model and we also followed this principle for the design of our task.

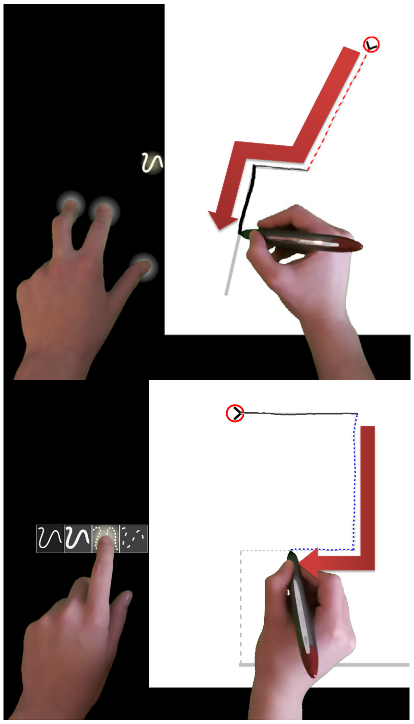

Figure 7: Bimanual coordination task with style changes controlled by postures (top) and toolbar selection (bottom).

To test people's ability to switch modes effectively, while mainly focusing on the pen-tracing task, we devised the following experiment: we asked participants to trace over a polyline, whose segments had different line styles, in a single stroke. Users had to change the style on-the-fly using the NDH to correspond to that of the segment they were currently drawing with the pen-holding DH, without lifting the latter. The goal here was less to trace over the polyline as precisely as possible, as in the previous experiment, than to execute the stroke quickly enough while correctly matching the styles of the target segments.

We adopted a similar interface to the previous task, with a static worksheet in the centre of the display on which the polyline appeared and tracing was to be performed. To keep the experiment tractable and easy to learn in a few minutes, we used four different stroke styles only: normal, dotted, dashed and bold. The three configurations that we set up controlled the way the NDH could activate the style changes. In the first two configurations, styles had to be activated using specific touch postures performed on the surface surrounding the worksheet (Figure 7 top). The difference between the two settings was that, in the first case, postures had to be maintained, i.e. fingers had to be held down to keep a non-normal stroke style selected (the normal stroke was activated by default when there was no touch contact), whereas, for the second configuration, a simple tap on the surface was sufficient to change styles (including normal style). This distinction between style selection methods was motivated by our desire to test whether quasimodes [19] were perhaps more appropriate for pen mode-switching and activation than normal tap-once selection actions.

We used the following mappings for the four different styles: one finger down for dotted, two fingers for dashed, three fingers for bold and a gentle palm press for normal style in the second tap-to-select configuration. The currently selected stroke style was shown in an icon placed close to the worksheet. For the third configuration, a classic toolbar was displayed with tappable buttons corresponding to each style (Figure 7 bottom). In all configurations, palm resting on the worksheet was allowed.

Other than the measurements common to all tasks, we recorded three important pieces of data: the total line-tracing error, the number of stroke style errors and the pen dwell time. The first quantity represented the total tracing error when attempting to draw the polyline regardless of style. It was computed by simplifying the user-traced curve into a fixed number of points and calculating the distance between those points to the closest segment on the target polyline. The second value, the stroke style error, measured how many mismatches occurred between the style of the current portion of the user curve and that of the corresponding segment of the target polyline. Specifically, we registered an error each time the distance between the current styled point on the user curve and the nearest point with the same style on the polyline exceeded a particular threshold value (this distance was infinite if the currently selected style was not present in any of the segments of the polyline). This was only done for distinct pairs of mismatched styles, i.e. no new error was logged if the next point on the user curve had the same mismatched style as the previous one.

The third quantity that we kept account of was the pen dwell time, which we defined as the amount of time the pen did not move (or moved very little) during the tracing movement and mostly occurred during pauses when the user was changing styles between segments. This time could then be compared to the total stroking time of the polyline, given the number of required style changes to trace it. A high dwell time for a stroke indicated longer periods of style change activations and more coordination effort. We suspected that we would witness higher dwell times for the toolbar configuration, where users had to momentarily shift their gaze and concentration from the tracing hand to the operating hand that had to select the correct style button on the toolbar. In the posture configurations, however, we conjectured people would remain focused on the tracing activity and trigger the different styles without looking by using the appropriate finger/palm combinations (almost as if playing the piano). If users were able to master that technique, we believed it would lead to shorter pauses between segments, yet we wondered if such rapid and unchecked switching activity might also negatively impact accuracy and hence cause the error rates to increase.

Results

Here also completion time and task difficulty results exhibit a similar pattern, with the first "Posture maintain" configuration seeming to be both the easiest and the fastest (Figure 8). ANOVAs reveal, however, that only the former has statistically significant differences, using 0.05 as the cut-off α-value ($F_{2,27} = 4.06$, $p = 0.029$ vs. $F_{2,27} = 2.76$, $p = 0.082$). Tukey tests show that the lowest p-value between "Posture Maintain" and the toolbar configuration is 0.025, which is higher than the threshold value after Bonferroni adjustment (0.017) but only marginally. We can therefore only discern a trend, but no clear general distinctions between the three configurations.

Feedback from the participants was also very diverse. For the posture configurations, people appreciated the ability to concentrate on the pen-holding hand actually performing the tracing motion, although a few users felt the need to constantly check whether the correct tool had been selected. 3 people critiqued some of the mapping choices between postures and styles (e.g. the palm posture in "Posture tap" to revert to the normal style) and 2 suggested that the visual clues to maintain awareness of the currently selected style should be improved. For the toolbar configuration, we received fewer comments relating to the input method, which is understandable considering its commonness.

The detailed tracing times and errors, reveal more telling disparities (Figure 9). The charts show that while users were mainly quicker with the posture configurations they were also more careless. Interestingly, forcing the selecting posture to be maintained in the first configuration seems to have encouraged that behaviour even more, compared to the second configuration that required only simple tapping to change the style. This is consistent with our observations of users performing the task, as we noticed that, in the first case, participants checked less often that their finger postures triggered the right style selections, compared to the other two tapping configurations. Those shorter coordination times for "Posture Maintain" are reflected in the pen dwell times, which average only 20% of the total time the pen was in contact with the surface, compared to roughly 33% for the other configurations. We think the difference between those proportions is also partly due to the fact that a retained posture sometimes only required lowering or lifting fingers (e.g. to switch from dotted to dashed style), whereas a full tapping gesture necessitated a movement of the whole hand with correct placement of the fingers.

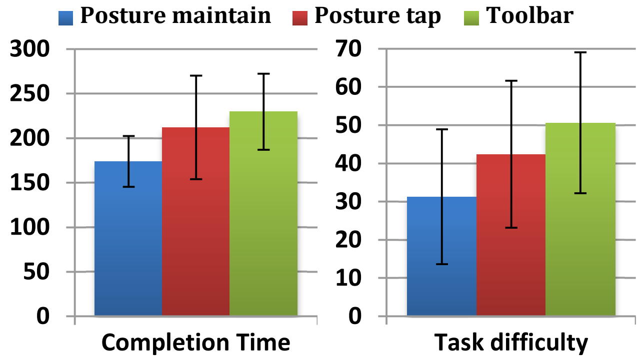

Figure 8: Task completion times (in sec.) and user ratings of task difficulty (from 0=extremely easy to 100=extremely difficult)

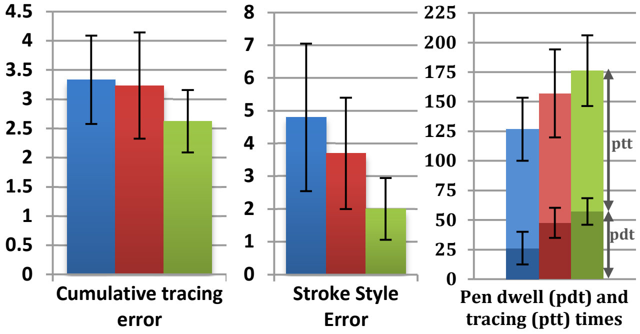

Figure 9: Cumulative relative tracing error, number of stroke style errors and pen dwell and tracing times.

Statistical tests for the three metrics confirmed main effects only for the stroke style error ($F_{2,27} = 6.74$, $p = 0.045$) and pen dwell times ($F_{2,27} = 15.75$, $p < 0.001$) (for the tracing error $F_{2,27} = 2.64$, $p = 0.09$), with post-hoc comparisons yielding significant mean differences between "Posture Maintain" and "Toolbar" for the style error ($p = 0.003$) and between "Posture Maintain" and both other configurations for dwell time ($p = 0.002$ and $p < 0001$ respectively).

We therefore learn the following from those results:

1. Pen mode-switching or function activation through postures can speed up bimanual coordination and synchronisation but at the cost of increased errors. We believe, however, that this is mainly a question of practice and postures can prove effective as functional shortcuts in bimanual pen and touch applications once the necessary finger and hand positions have been acquired. To some extent, this process can be likened to learning how to coordinate the hands when playing the piano.
2. Maintained postures encourage further speed increases and less coordination effort.
3. Adequate awareness mechanisms are needed when employing non-focused NDH interaction techniques so that users can make sure their actions produced the desired response from the UI.

DISCUSSION AND CONCLUSION

In light of our empirical results, we now take a broader view of the topic and discuss their direct and indirect implications for pen and touch systems. Essentially, we see two relevant and interrelated issues that need to be addressed to further the cause of these platforms. The first is determining the scope of the competitive advantage of pen and touch vs. unimodal paradigms, especially the currently prevailing input model of multitouch. With the proliferation of tablets, smartphones and other touch-only devices, the interactive ecosystem is heavily biased towards the latter. In this changing ergonomic context influenced by touch-operated appliances, people are gradually developing a habit of using their fingers for all kinds of interactions, including quite a few that one would think would be more adequately performed with a pen (see for example the success of the social drawing game "Draw Something" [5]). This preference was explicitly voiced by some of our participants, who declared they felt more comfortable tracing lines using direct touch than with a stylus. The majority, however, agreed that the pen is more suitable for those types of tasks. It is hard not to embrace the compelling advantages of the pen for activities such as note-taking, artistic drawing, professional design etc. But then, the question becomes: what does pen and touch bring to the table, as it were, compared to interfaces entirely commanded by a stylus?

Before attempting to answer this question we would like to bring up another reason why pen input is not earning wider mainstream appreciation and that is current hardware. Digital pens for interactive screens have the disadvantage compared to touch that people have experience with traditional writing implements and therefore expect digital counterparts to meet similar levels of precision, handiness and responsiveness. Current digital pen technology, however, is not yet up to par. Anoto pens are still very bulky and cannot be tilted beyond a certain angle for input to be detected. Response lags and insufficiently high resolutions are further problems that hamper users' natural experience on interactive displays, even, but to a lesser extent, in professional (and expensive) solutions such as those provided by Wacom [23]. Thus, it is no wonder that many commercial solutions for digital pens involve regular paper, which arguably still provides the best affordance.

At present, we think the most compelling argument in favour of pen and touch interaction is the "new tools" proposition [9]. The combination of the two modalities creates a new experience that is hard to match in a unimodal system.

In addition to what other authors have demonstrated [2, 7, 8, 10, 29], our third experiment provides a further example of increased efficiency in coordinated bimanual contexts (with a certain level of practice). The ability to rapidly trigger mode-switches and functional changes of the DH responsible for fine-grain operations via coarse-grained activations of the NDH without disrupting the user's focus on the former is an asset hard to replicate in unimodal environments.

The second issue that we wish to touch upon concerns the practical challenges posed by the copresence of pen and touch input on a single, shared interactive surface. In our second experiment, we evaluated the influence of palm-resting on tracing precision and observed that the impact was most significant on the pen's first contact point. But we would also like to raise a design question that follows from our first discussion point about the functional roles assigned to each input mode. Our first experiment showed that the pen is also very effective at performing manipulation tasks and most people do not find it incongruous. While touch is the preferred modality to perform such actions according to the accepted interpretation of Guiard's kinematic model for pen and touch interaction, what if some users would like to also be able to use the pen to activate buttons, select menus and move objects? In fact, in another test that we conducted involving a mock paint program with a toolbar whose functions could be triggered either by touch or pen, 4 participants used touch only, 5 pen only and one both to select tools. This indicates that the division of labour is not always clear-cut as far as users' preferences are concerned [7]. There are cases where touch is the only obvious possible input method, for example operations involving multipoint gestures (zooming, rotating etc.) and interactive spaces where touch and pen cause different actions to take place (e.g. on a worksheet: touch pans while pen inks). However, for clearly monofunctional areas such as toolbars, buttons, and menus, limiting activation to touch seems like an arbitrary and overly restrictive design choice. We leave it to future work to prove whether this is indeed a good decision or not.

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