Tracing and Sketching Performance using Blunt-tipped Styli on Direct-Touch Tablets

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ABSTRACT

Direct-touch tablets are quickly replacing traditional pen-and-paper tools in many applications, but not in case of the designer's sketchbook. In this paper, we explore the tradeoffs inherent in replacing such paper sketchbooks with digital tablets in terms of two major tasks: tracing and free-hand sketching. Given the importance of the pen for sketching, we also study the impact of using a blunt-and-soft-tipped capacitive stylus in tablet settings. We thus conducted experiments to evaluate three sketch media: pen-paper, finger-tablet, and stylus-tablet based on the above tasks. We analyzed the tracing data with respect to speed and accuracy, and the quality of the free-hand sketches through a crowdsourced survey. The pen-paper and stylus-tablet media both performed significantly better than the finger-tablet medium in accuracy, while the pen-paper sketches were significantly rated higher quality compared to both tablet interfaces. A follow-up study comparing the performance of this stylus with a sharp, hard-tip version showed no significant difference in tracing performance, though participants preferred the sharp tip for sketching.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces —*Interaction styles*; I.3.6 [**Computer Graphics**]: Methodology and Techniques—*Interaction techniques*

General Terms

Experimentation, Human Factors, Performance

Keywords

Sketching, evaluation, pen, paper, user study.

1. INTRODUCTION

The paperless office will likely remain a myth for the foreseeable future [19], but the increasing prevalence of smartphones and touch displays is making inroads towards replacing paper in many settings. One of the last strongholds against this development is the designer's notebook [3], traditionally a pen-and-paper medium. The paper notebook, ideally suited to the informal nature of early design sketches [8], is used for jotting down ideas and sketching design concepts. While the strengths of a digital medium, such as easy replication and composition, and persistent storage, are understood, the tradeoffs between these and the strengths of paper are not. In particular, will the move to a digital medium change the low-level performance of sketching for speed as well as accuracy?

In this paper, we attempt to answer this question by reporting on the results of a formal user study where participants were asked to both trace pre-defined shapes (Stage 1) as well as make free-hand sketches (Stage 2) using pen-and-paper compared to a digital tablet. Since direct-touch tablets remain dominant in the marketplace, we chose to use (a) the finger, and (b) the capacitive stylus with a soft, blunt tip, both used as input devices for the capacitive display tablet. In the tracing task (Stage 1), participants were asked to trace given shapes—line, circle, triangle, square, and a cross—while staying within a given tunnel around the shape. We measured the completion time for the successful trials as well as the number of failed attempts (straying outside the tunnel). In the free-hand sketching task (Stage 2), we showed participants perspective views of a cube and a cylinder, and instructed them to sketch both shapes freehand using these media. We then organized an online survey where crowdsourced workers rated the aesthetics of these sketches without knowing the medium and interface used to create them.

Our results show that tracing on tablets (with both finger and stylus) was 13% faster than pen-and-paper, a significant difference. To offset the increased speed, the pen-paper media showed fewer failures compared to the digital tablets. Tracing on the tablet with the stylus was more accurate (in terms of failures) than with the finger, indicating that the stylus is an acceptable middle ground in the choice between digital and paper media. On the other hand, for free-hand sketching, paper sketches received on average 1.7 more votes than both tablet conditions, a significant difference, while the stylus and finger conditions showed no significant difference. This suggests that paper still has an advantage for free-hand drawing.

Some of the newer tablets—such as the Microsoft Surface and the Galaxy Note Tablet—incorporate a sharp and hard-tipped stylus with increased tracking accuracy and performance. Such a device mimics the behavior of a normal pen to a much higher degree than a blunt-tipped capacitive stylus. In order to investigate how our results from the initial user study apply to such hard-tipped styli, we followed up that study with a comparison between the same blunt-tip stylus that was used for the earlier study, and a hard-tipped stylus (the S Pen on a Galaxy Note 10.1 tablet). In addition to the above mentioned task, a task of sketching a mechanical component was assigned to evaluate the performance of the stylus in

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a real-world sketching situation. Our analysis indicated no significant difference in tracing speed or accuracy between these styli, although participants preferred the hard-tipped stylus.

2. BACKGROUND

Our study focuses on the mechanics of sketching and how they translate to capacitive-touch tablets, while its outcome has potential implications towards hardware and software interfaces to support sketching on such devices. The mechanics of sketching on a tablet involve the tracing of specific paths on the interface—a combination of pointing and steering tasks. The experience of sketching, on the other hand, is a combination of developments in hardware as well as software interfaces that emulate the physical act of sketching. This section thus focuses on both these aspects: steering and tracing studies, as well as developments in HCI for design in general and sketching in particular. We also provide a brief background on the rising importance of sketching in design, which, along with the recent ubiquity of capacitive-touch tablets, motivates our study.

2.1 Steering and Pointing in HCI

Fitt's law [13] as well as the Steering Law [1] were both adapted into HCI to evaluate the performance of graphical input devices in pointing and navigation respectively. Accot and Zhai [1] first mathematically proposed the Steering Law as an extension of Fitt's Law. They also studied "steering time"—time taken to trace lines and circles of various lengths and widths, on five input devices—mouse, digital pen tablet, trackpad, and track ball [2]. They found the mouse and the tablet to show the least steering time and the highest index of performance.

Zambramski et al.'s work [30] evaluating various input methods such as mouse, finger and digital pen, showed that finger touch outperforms the other two in terms of tracing speed. Vogel and Baudisch [28] studied the issues of occlusion and ambiguity when the finger is used as a pointing device. They propose a pointing technique called "Shift" that mitigates this issue by placing a callout of the area occluded by the finger in a non-occluded area. Thorsteinsson [24] studied the possibilities and effects of using a digital tablet for drawing 3D shapes on digital and paper media in a secondary school classroom. While the pencil significantly outperformed the tablet interface, he observed that "students' skills are more important than the media [on which they draw]" [p. 206]. Zabramski and Neelakannan [31] studied the effects of pen-paper and digital pen-tablet combinations on user creativity, and found no significant differences between figures drawn on paper and digital interfaces. The Steering Law has since been extended to study the effects of corners [14] and to three-dimensions, for above-the-surface interactions such as hovering [9].

2.2 Sketching and HCI Support

The role of sketching in design has been studied extensively in both engineering and architecture [15]. Ullman [25] states the role of sketching as a means of extending the working memory of the designer. Design is a process of "reflective conversation" with materials [18, p. 154], and sketching enables a dialogue between the designer and the sketch itself, aiding this reflection [5, 21].

Since Sutherland's Sketchpad [20], there have been various graphical input devices that have been developed for use with the computer, including Computer-Aided Design (CAD). However, using CAD tools for conceptual design show that they limit the designer's thinking and cause design fixation, while sketching is more conducive to conceptual design [16, 7]. Engineering schools are thus re-introducing sketching as a creative thinking tool for design [23].

Schmidt et al. [17] review sketching among engineering students and emphasize the encouraging of the practice, both through the course and through the use of digital tools such as the Smartpen and direct-touch tablet. Sketching tools such as DENIM [12], and K-Sketch [4] were developed for early user interface design and rudimentary animation respectively. Huot et al. [6] developed a sketch-based interface builder for post-WIMP interfaces called MaggLite. MaggLite uses a mixed-graphs model which augments the regular scene graph with an interaction graph that describes interactions with the interface. These interfaces were shown to reduce the user's cognitive load and speed up development time by allowing the user to defer details, forming an interesting analogy to the "CAD vs. sketching" comparison above. Vandoren et al. [27] developed IntuPaint, a digital touch interface that uses the paradigm of a paint brush and a paint easel for a more intuitive digital painting experience. They simplify the use of complex tools and operations by incorporating physical paradigms of paint-mixing, smudging, and erasing into their digital media. There have also been considerable developments for intuitive and functional digital interfaces for sketching directed towards design and the arts [27, 26].

Yang [29] points out the need in sketching tools for critical affordances such as portability, ease of sketching, and ease of annotation that are required for the more exploratory and agile concept design stages. Developments in natural-user interfaces (NUIs) show potential of moving sketching from Jonson's [8] "low-fi" quadrant into the "hi-speed", "hi-fi" quadrant of his chart. To do this, we need to understand the constraints of both the designer's methods, and the digital media available for sketching. Through our study, we attempt to bridge this gap between digital and analog sketching media by focusing on sketching and HCI performance tasks for portable sketching media like the direct-touch tablet, and use our study to compare it with the traditional sketchbook.

3. USER STUDY

We split our experiment into two stages to study two low-level aspects of sketching: tracing and free-hand drawing, on three sketch media: pen and paper, finger and tablet, and stylus and tablet. In Stage 1 of our study, participants traced pre-defined shapes, and in Stage 2, they sketched 3D shapes. We analyzed results from Stage 1 for speed (time to complete trace) and failures (straying outside the tunnel), whereas the quality of the output from Stage 2 was assessed using a crowdsourced survey.

We chose tracing and free-hand drawing for the user study based on their importance in early design. Design students are often taught to generate ideas with quick sketches of primitive shapes, combining them to form more complex shapes (Figure 1). This motivates the sketching task (Stage 2). The final shape is then traced out on the complex shape using a marker, to differentiate it from the construction lines. This motivates the tracing task (Stage 1).

We conducted a pilot study of these tasks with a sketching expert: an industrial designer, to fine-tune parameters such as the width of the line or "Steering Tunnel". Capacitive touch tablets require at least a 3mm-wide contact area for a touch to register. We thus performed our pilot study with line widths of 3, 4, and 5 mm, obtaining quantitative measures such as time taken and number of failures, and qualitative feedback in terms of the difficulty of the task and the appearance of the traced shape. We observed that the tracing time and number of failures for a 3mm-wide line were so high as to affect feasibility of non-experts completing the tasks, while the 5 mm line width provided such a loose tolerance that the final traced shape bore little resemblance to the intended shape. A line width of 4 mm provided a good balance between the fidelity of the traced shape to the given shape and the difficulty of the task. Figure 2 shows the sizes of different tunnels as compared to the finger.

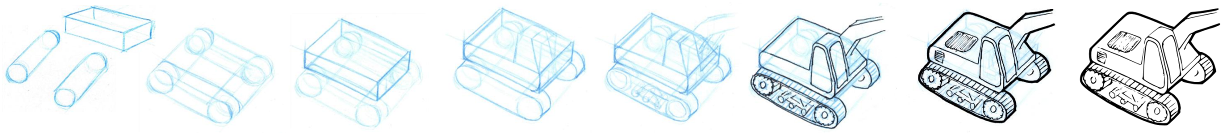

Figure 1: The sketching process as taught to students of a senior design elective course. The students are taught quick perspective sketching using primitives such as cuboids and cylinders to generate more complex shapes. The complex shapes are then emphasized by tracing over the required strokes with a marker. Figure reproduced with permission from Taborda [22].

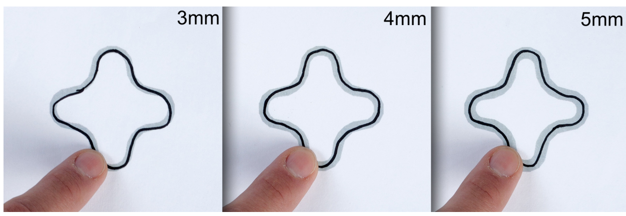

Figure 2: Steering tunnel widths used in the tracing tasks for the pilot study. Performing trials with tunnel sizes of 3, 4, and 5 mm, we found 4 mm to be the size that provided a balance between the number of failures and amount of distortion in a traced shape.

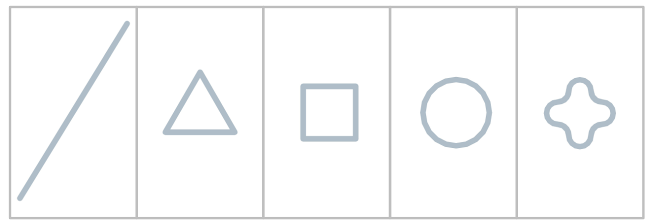

Figure 3: Five shapes used in the trace task (Stage 1): line, triangle, square, circle, and a concave shape. All shapes have the same perimeter, and were the same size both on the tablet and on paper. The line width shown for all shapes was 4 mm.

3.1 Participants

We recruited 14 paid participants (13 male, 1 female) from a senior design elective course on toy design. Participants were aged between 17 and 22 years, had normal or corrected-to-normal vision, and 13 were right-handed. They had limited or no experience of sketching or drawing on tablets, although they were proficient with using them. All participants had novice to intermediate level skill in sketching on paper. All demographics were self-reported.

3.2 Apparatus

We used a 7-inch Asus Nexus 7 as the digital tablet, and a Wacom Bamboo capacitive stylus with a 6 mm tip. To best match the tablet and stylus, we used regular sheets of paper cut to the tablet screen size, and a Sharpie marker with a 3mm tip. The setup for the study is illustrated in Figure 4 (a, b, and c), with marker and stylus sizes.

3.3 Tasks

Both stages of the study used three input and media combinations: stylus-tablet, finger-tablet, and pen-paper. For the tablets, we used an Android app specifically developed for this study. For the sake of simplicity in data (touch point) handling, this app did not implement palm rejection, which would have allowed participants to rest their hand on the tablet surface while tracing or sketching, as they would have when sketching on paper. Participants could orient the tablet or paper to their comfort.

In Stage 1 (Tracing), a trial consisted of completely tracing a pre-defined shape using the input and medium. Figure 3 shows the shapes we used: straight line, triangle, square, circle, and a rounded cross (referred to as "concave"). We chose these shapes to understand the effect of occlusion caused by the tracing finger or stylus: it was less likely to affect speed and failures when tracing simple shapes such as a line with fewer changes in direction, and more likely in the case of complex shapes. Each shape was displayed centered on the sketch medium (tablet or paper) with a random rotation and an outline thickness of 4 mm, determined in our pilot test. The participant was asked to trace the shape in a single stroke starting from any point along the outline. Straying outside the 4 mm tunnel outlining the shape counted as a failure, and caused the participant to have to redo the trial (same shape). Tracing the complete shape without leaving the tunnel was considered a success, and the completion time was recorded for that trial. In the tablet interfaces, the stroke outline turned green when successful, and red upon failure. In the paper condition, the test administrator manually inspected each trace to detect failures. In all three conditions, the administrator was present throughout to monitor the traces and ensure the required number of successful trials were completed.

In Stage 2 (Sketching), participants were asked to draw two different 3D shapes—two-point perspective views of a cube and a cylinder—using all input-medium conditions. They were shown example figures and descriptions of the desired shapes before and throughout the tasks. Participants were told to use the figures as a guideline for style only. Each participant drew three versions of each shape, and was then allowed to select the best one as their submission for that trial.

3.4 Factors

We studied the following factors in the experiment:

Medium (M) represents the input-medium combination used: pen-paper, stylus-tablet, finger-tablet.

Shape (S) represents the shapes drawn in the tracing and sketching tasks. For the tracing task, we used 5 shapes (S_T): line, triangle, square, circle, and a concave shape (Figure 3). For sketching, we used perspective views of a cube and a cylinder (S_S).

3.5 Experimental Design

Stage 1 was a full-factorial within-participants design:

	14	participants
×	3	**Media** M
×	5	**Tracing shapes** S_T
×	3	repetitions
	630	total trials (45 per participant, training excluded)

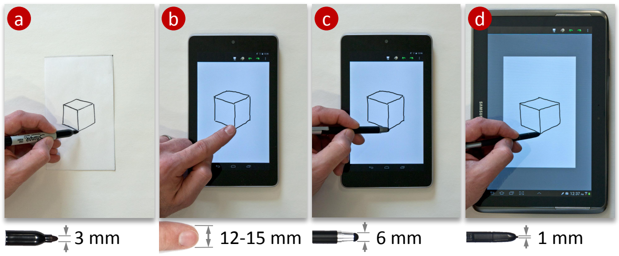

Figure 4: The media used for the main sketching study were: (a) a marker pen (overall size ø12mm × 123mm with a 3mm tip) on paper (b) a finger on a 7-inch tablet, and (c) a blunt-tip stylus (ø8.5mm × 122mm, 6mm tip) on a 7-inch tablet. The follow-up study compared (c) with (d) a hard-tip stylus (ø7.6mm × 114mm, 1mm tip) on a 10-inch tablet.

The order of both media M and shape S_T was randomly chosen. For each trial, we collected the following metrics:

Tracing Time: The time taken to completely trace a shape. In the tablet conditions, this time was measured by the Android sketching app, whereas in the paper condition, we used video recordings of the trials to measure it.

Failures: The number of tracing failures: the number of times a trace strayed outside the tunnel, or ended before the shape was completely traced.

For Stage 2, we asked participants to draw $M \times S_S = 3 \times 2 = 6$ shapes with 3 repetitions, and asked them to select only 1 shape to submit. Thus, for 14 participants, this yielded 84 submitted shapes (42 cylinders and 42 cubes). The sketches on paper were scanned in high resolution and scaled down to the same dimensions as the digital sketches. Instead of any quantitative measure, we assessed the quality of the submitted shapes using an unpaid online survey with 277 crowdsourced respondents.

Each survey consisted of 20 *shape lineups*: 10 for cubes and 10 for cylinders. With 277 respondents completing the entire survey, this yielded 5,440 individual responses. In each lineup, 5 sketches from the library of 42 submitted sketches for each shape was randomly displayed in a single row. The survey respondent was asked to choose the one sketch in the lineup that best resembled a high-quality perspective view of that particular shape. At the end of the survey, they were asked to explain their rationale for making their choices, which helped us identify incomplete responses [10]. Given this survey instrument, we defined the Perceived Quality (PQ) of a sketch as the ratio of the number of times the sketch was selected to the number of times it was shown in a lineup across all 277 surveys:

$$PQ = \frac{\text{number of times selected}}{\text{number of times displayed}}$$

3.6 Procedure

Individual participants were first given a basic background of the study, and asked to fill out an initial survey form which consisted of questions regarding the participants' demographics and past experience with sketching on tablets as well as design. The participant was then given a set of instructions for Stage 1 (Tracing) and asked to practice shape tracing before the actual tracing tasks. This practice session was conducted on the same shapes as the ones used in the actual trials on both paper as well as tablet (with and without stylus). The participant was told to take as much time as needed with practice before starting the actual trial. These times varied from 2 to 5 minutes per medium among participants. The actual trials for each medium were conducted immediately after participants practiced in that medium.

The actual trials were conducted and participants were recorded on video for later analysis of tracing times on paper. Tracing times on tablets were recorded by our Android tracing app. For the paper condition, the test administrator handed over new shapes one at a time, whereas for the tablet conditions, the software handled this automatically. After finishing all trials, participants were administered a survey asking them about their comfort and confidence using the different media.

After Stage 1, participants moved on to the sketching exercise, Stage 2. They were again allowed to practice drawing on each medium before proceeding to the corresponding trial. For each trial, the participants were given a text description of the 3D shape to draw and a blank input media. After drawing three versions of each shape, they were allowed to select one version to submit. Finally, with both shapes (cube and cylinder) finished, the participants were again given an online survey on their confidence and comfort using the different media. Each participant was paid $10 upon completion. A typical study session lasted 45 minutes.

3.7 Hypotheses

Based on the feedback we received from the industrial designer during the pilot study, we identified four major aspects that affect the performance of a user while sketching on digital medium: familiarity, parallax, occlusion, and friction.

Familiarity (A1): Most people have been trained to use pen and paper since childhood. They are, however, less familiar with touch-based surfaces, especially for sketching.

Parallax (A2): The thickness of the glass surface of the tablet results in there being a distance between the point of contact of the stylus or finger on the glass, and the corresponding "ink" mark shown on the LCD display.

Occlusion (A3): The use of finger or a large-tipped stylus as an input device results in its tip occluding the screen at the point of contact. This is different from parallax error in that the tip size obscures the "target" point on the surface.

Friction (A4): Friction between the input device and the drawing surface provides a tactile feedback that affects the user's sketching experience. The friction between paper and pen is higher than the friction between a stylus and a tablet, chiefly due to the glass surface. Friction can provide useful feedback: a lack of friction can affect the control of the user while sketching.

Based on the observations during pilot study and previous literature, we used these aspects to formulate the below hypotheses:

Stage 1 (Tracing):

H1: Tracing on paper will be faster than both digital media (stylus-tablet, finger-tablet) due to the familiarity and ease of use of pen and paper for sketching. (A1)

H2: Tracing on paper will result in fewer failures than digital media due to the higher preciseness of the pen compared to stylus (6 mm tip) and finger. (A2, A3)

H3: Among digital media, tracing with the stylus will be faster than the finger due to the higher friction and occlusion caused by the finger. (A3, A4)

H4: Among digital media, tracing with the stylus will show fewer failures than the finger due to the higher occlusion by the finger. (A3)

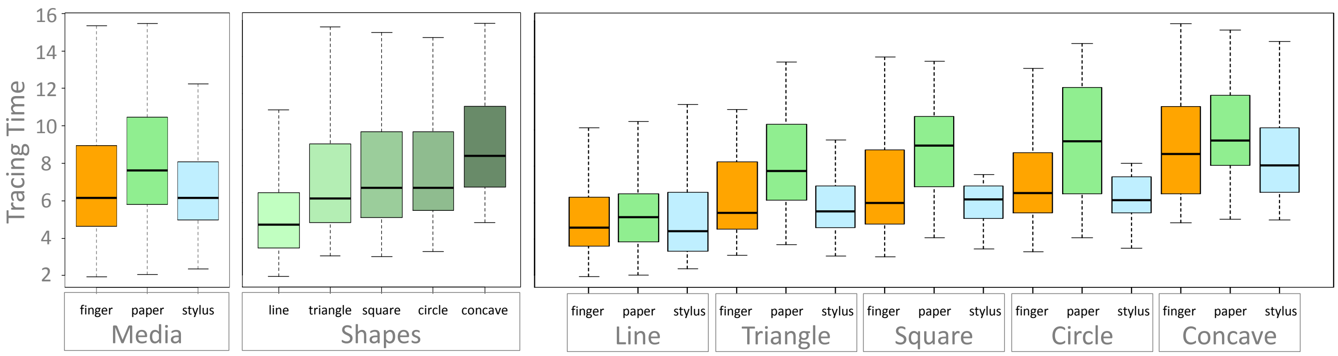

Figure 5: The boxplot on the left shows tracing times across three media: finger on tablet, pen on paper, and stylus on tablet. Tracing times for all five shapes shown in figure 3 are combined for this plot. The plot in the center shows tracing times across the five shapes as labeled, with the colors darkening from simpler shapes (line) to a complex shape (concave). The plot on the right shows tracing times across five shapes: line, triangle, square, circle, and concave, with an additional separation of the three interfaces: finger on tablet (orange), pen on paper (green), and stylus on tablet (cyan), for each shape.

Table 1: Tracing times and failures on different media.

	Tracing Times		
Medium	Mean	Std. Dev	Failures
Pen-Paper	8.58	3.76	3
Stylus-Tablet	7.27	3.77	20
Finger-Tablet	7.69	4.44	84

Stage 2 (Free-hand Sketching):

H5: Sketches on paper will score a higher PQ than the ones drawn on digital media due to its familiarity with users. (A1)

H6: Sketches drawn on the tablet will show a higher PQ when using the stylus than the finger due to the finger's higher occlusion causing less predictable marks on the tablet surface. (A3)

4. RESULTS

Below we report on the major findings for both Stage 1 and Stage 2, as well as the Steering Law analysis for Stage 1.

4.1 Stage 1: Tracing

We analyzed the tracing times using a Repeated-Measures Analysis of Variance (RM-ANOVA, all assumptions fulfilled) and found a significant effect of medium M on the tracing time ($F(2,26) = 19.52, p < .001$). No significant interactions were found. Table 1 shows mean tracing times and total failures across all three media. A post-hoc Tukey HSD test showed significant pairwise differences ($p < 0.001$) for pen-paper vs. stylus-tablet as well as pen-paper vs. finger-tablet, but not between stylus-tablet and finger-tablet.

An RM-ANOVA for shapes (all assumptions fulfilled) showed a significant effect of shape on tracing time on all media ($F(4,52) = 99.20, p < .001$). Except for Square vs. Triangle and Circle vs. Square, all other pairwise comparisons showed significant difference in tracing times ($p < .05$).

A logistic regression analysis showed a significant effect of medium M on tracing failures ($F(2,26) = 8.43, p < .001$). Failures on the finger-tablet medium were the highest for the concave shape (36), while in the case of the stylus-tablet, the number of failures were highest for the circle (7). A posthoc Tukey HSD yielded significant differences between pen-paper vs. finger-tablet ($p < .001$) and pen-paper vs. stylus-tablet ($p = .031$), but not for finger vs. stylus.

4.2 Stage 2: Free-hand Sketching

The crowdsourced survey provided the means for calculating the Perceived Quality for each sketch, reported in the results for stage 2. An RM-ANOVA of quality values showed that the sketching medium plays a significant role in the quality of sketches for the 3D cube ($F(2,26) = 5.77, p = .0084$) but not for the 3D cylinder ($F(2,26) = 1.62, p = 0.217$). The two boxplots in Figure 7 show the average perceived quality for cubes and cylinders, respectively. A posthoc analysis using Tukey HSD for the cube showed significant differences between finger-tablet and pen-paper ($p = .0067$) as well as finger-tablet and stylus-tablet ($p = .45$), but not for pen-paper vs. stylus-paper. In the case of the cylinders, we did not find any significant differences between sketches from different media.

4.3 Steering Analysis of Stage One

The Steering Law defines an index of performance (IP) that indicates the "tracing/steering time increase as a function of task difficulty" [2]. The index of performance of a medium thus represents the average tracing speed on the medium in terms of difficulty. This index of performance, calculated for each input medium, was found to be different across shapes, thus suggesting that there is an effect of shape on steering time. For tracing on a straight line, the index of performance values for the media were 7.287 sec^{-1} (stylus-tablet), 7.252 sec^{-1} (pen-paper), and 7.09 sec^{-1} (finger-tablet). For the circle, the index of performance values were 5.21 sec^{-1} (finger-tablet), 5.05 sec^{-1} (stylus-tablet), and 4.07 sec^{-1} (pen-paper).

The three media ranked in the following order for the remaining shapes: stylus-tablet, finger-tablet, and pen-paper, where stylus-tablet outperformed pen-paper by atleast 0.7 sec^{-1} in each shape. A Tukey HSD analysis of tracing/ steering time across the five shapes showed an increase in mean steering time from the line through the triangle, square, circle, to the concave shape. However, this increase was not significant between the triangle and square, and between the square and the circle. Boxplots of these tracing times broken down by medium and shape are shown in Figure 5.

5. DISCUSSION

Summarizing our results, we find the following:

- Tracing on digital media (using both stylus and finger) was faster than with the pen and paper (rejecting **H1**).
- Tracing failures on pen-paper were significantly fewer than with both stylus and finger (accepting **H2**).

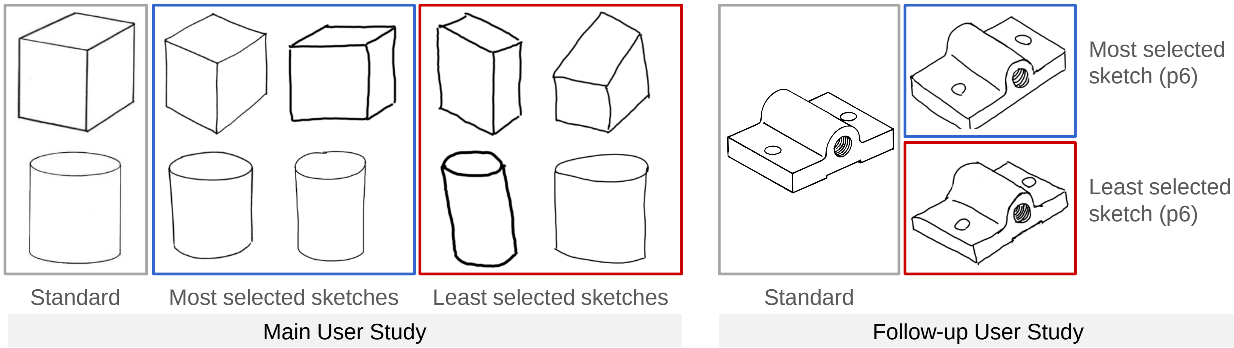

Figure 6: A sample of the sketches produced by the participants. The group of primitives on the left pertain to the main user study performed between pen-paper, stylus-tablet, and finger-tablet. The reference sketches shown to the participants in this study are shown in the gray boxes on the far left. The sketches in the blue and red boxes are the ones with the highest and lowest Perceived Quality respectively. The sketches of bearing blocks on the right were part of a follow-up study between blunt and sharp-tip digital styli. The sketches shown are by a participant (p6), whose best and worst sketches were selected by 4 independent judges.

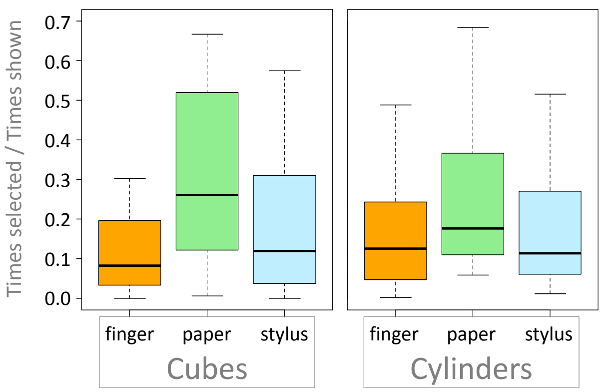

Figure 7: Quality scores of cubes and cylinders drawn with each interface. The plots show the Perceived Quality of a sketch: the ratio of the number of times a sketch is selected to the number of times it is shown.

- Tracing on the stylus-tablet medium was not significantly faster than the finger-tablet (rejecting **H3**).
- Tracing failures with the finger were marginally higher than stylus-tablet (rejecting **H4**).
- Sketches of cubes on paper showed significantly higher PQ than those made with the finger on the tablet, but not significantly higher than those made with the stylus (partially accepting **H5**).
- Sketches of cubes on the tablet did not show a significant difference in Perceived Quality between cubes drawn with the finger and those drawn with the stylus (rejecting **H6**).
- The Perceived Quality of the sketches of cylinder was not significantly different across media (rejecting **H5** and **H6**).

Our hypothesis that tracing on paper with the pen would be faster than on both tablet media was rejected, as both finger and stylus on the tablet proved to be 13% faster than pen and paper. This can partly be attributed to the friction between the pen and the paper: friction between the tablet surface (glass) and the finger and stylus are both much lower than between pen and paper, as discussed in A4 in our hypotheses. The significance of friction was something we had considered as a positive feedback which aids sketching, but is not a factor we measured in the study. This was because the frictional force varies with the pressure applied by the participant while tracing or sketching, which in turn varies between participants, the drawing implement used, and the task performed, which makes it unrealistic to generalize.

Tracing on pen-paper showed significantly fewer failures compared to both the stylus-tablet and the finger-tablet media. The failures on the stylus-tablet were lower in number than finger-tablet (Table 1), but the difference was not statistically significant. Based on participant feedback and our observations, this difference can be attributed to two main aspects. The first is familiarity with pen and paper (A1), which makes it easier to adapt to the stylus-tablet medium. The second aspect is occlusion (A3): tracing with the finger results in the finger or the hand occluding part of the shape to be traced more than when gripping a pen or stylus. Furthermore, the effect of occlusion is exacerbated with increasing complexity of the shape being traced. The effect of parallax (A2) could also contribute to the difference in failures between paper and digital media. Most user feedback cited occlusion as the reason for their discomfort with using their finger: they were not able to see exactly where the (finger) tip was on the tablet at all times. In addition, user feedback on the stylus mentioned the "squishiness" or flexibility of its tip, which made it less predictable to use.

An interesting point to be brought up here is that we are also taught finger-painting as children, but it is not a skill we continue to practice. This begs the question: how much effect would long-term training have on tracing and sketching performance? This was not a valid question earlier when pens and pencils were the more feasible and convenient media for sketching, but now with the ubiquity of tablets, is this fact likely to change in the future?

There was no significant difference in the tracing speed between the stylus and the finger on the tablet. This seems counterintuitive given the accuracy argument above. However, recall that users were not allowed errors higher than a certain threshold, and were asked to repeat the task in case of a failure. The tracing time is only recorded for a successful task. Since there were significantly higher failures for the finger in tracing, there were significantly higher number of repetitions, and this could have resulted in a learning effect that affected the steering time for the successful trial. Further experimentation is required to determine these aspects.

Observations from sketching were equally interesting. First, the results of the Perceived Quality scores varied greatly between the cube and the cylinder. Comparing the two plots in Figure 7, we can see that the cube had a more pronounced difference in scores between sketches made on paper and sketches made on the tablet, using both the finger and stylus. This could be due to the relative complexity of the perspective views of both shapes: the cube requires a better understanding of two-point perspective, while the cylinder's symmetry makes its two-point perspective the same as its isometric view. Perspective errors in the cube are also more apparent. A visual comparison of the "best" and "worst" shapes in Figure 6 suggests a broader range in the PQ of cubes than in that of the cylinders, suggesting that comparisons with more complex shapes would be needed to support this line of reasoning.

Participant feedback on the sketching tasks was skewed more in favor of paper, for reasons ranging from inadequate palm rejection on the tablets, stylus and fingertip occlusions preventing accurate intersections and alignments, and in some cases the relative weight of the tablet making it more cumbersome to turn around while tracing and sketching. Out of 14 participants in the study, 13 preferred paper for day-to-day sketching activities. As one participant succinctly concluded: "tablets may rock, but paper beats rock!"

6. FOLLOW-UP: BLUNT VS. SHARP TIPS

Our study showed that pen-paper clearly outperformed the finger-tablet medium, but less so compared to the stylus-tablet medium: Pen-paper had with fewer tracing failures than stylus-tablet, but not in tracing speed, and the PQ of pen-paper sketches were not significantly higher than those on the stylus-tablet. Two aspects affecting tracing accuracy are parallax (A2) and occlusion (A3). The combination of a blunt-tip stylus and a tablet meant that both these effects were conflated: it was unclear whether the failures were higher due to occlusion, or due to parallax.

To separate the effects of occlusion from parallax, we conducted a follow-up study with 6 paid participants (5 male, 1 female) for a comparison between two stylus-tablet media: the Nexus 7 with the soft-tipped Bamboo stylus from the earlier study, and the Samsung Galaxy Note 10.1 with its custom hard-tipped S Pen. This helped us compare the performance difference and user reaction to the different occlusions of the hard-tipped and soft-tipped styli.

The participants aged between 22 and 30, and only one of them had never sketched on a digital medium before. We used the same tracing and sketching tasks as before, but added one more sketching task: the participants were asked to sketch a bearing block, shown in figure 6. Note that the Galaxy note has a larger, 10-inch display, the effect of which we mitigated to an extent by programming the active tracing and sketching area to be the same size as the Nexus 7. With this task, we aimed to evaluate the suitability of the medium to a real-life sketching scenario. We also presented pairs of sketches made by each participant to 4 independent judges experienced in sketching, and asked them to select the better sketch. This was done partly due to the low volume of sketches (12) which did not merit a crowdsourced study, and partly to mitigate effects due to sketching skill differences between the participants.

While we could not expect any statistically significant results with a participant pool of 6, we did anticipate the hard-tipped stylus to be faster and more accurate for tracing owing to the lack of occlusion as compared to the soft-tipped stylus. For the same reason, we expected the hard-tipped stylus to produce better sketches.

Contrary to our expectations, the mean tracing time with the soft-tipped stylus (7.59 sec) was lower than that of the hard-tipped stylus (7.71 sec). In addition, the hard-tipped stylus had 15 failures, as opposed to the soft-tipped stylus's 11. An RM-ANOVA of the tracing time showed no significant difference between the two styli ($F(1,5) = 0.29, p = 0.5915$). For the tracing exercise, 5 out of 6 participants reported that they preferred the hard-tipped stylus, and all 5 reported the lower occlusion as the deciding factor. The one participant who favoured the soft-tip stylus said he felt more comfortable due to its heft, in spite of the higher occlusion. Similarly, for the sketching exercise, 4 out of 6 participants preferred the hard-tipped stylus, citing its precision as the reason, while two preferred the comfort and "larger resistance" as offering better control.

An evaluation of the judges' preferences showed that the sketches drawn with the hard-tipped stylus were chosen three times as frequently as those drawn with the soft-tipped nexus.

7. IMPLICATIONS

In this section, we offer several implications for designing sketch interfaces intended to replace paper-based sketchbooks, along with the potential advantages and disadvantages of these interfaces.

7.1 The Case for the Stylus

One of the reasons for the popularity of capacitive-touch tablets is that they do not require a peripheral input device, unlike the Personal Digital Assistant (PDA) of yesteryear. However, if we consider the relatively niche market of designers who still feel the need to carry a pocketbook for sketching and jotting down ideas, we can see the need for developing the stylus as a legitimate input device. Our hypotheses of "paper will be significantly better than the stylus" were only partially true: tracing speeds were higher in the stylus, and there was no significant increase in failures, even with the higher occlusion of the stylus. In addition, it has to be noted that for the designer, sketching is not necessarily a precise task. Sketches are supposed to be rough and ambiguous, and precise alignment of lines and corners is not a critical requirement. Observations from the follow-up study indicated that while occlusion affects tracing and sketching performance, eliminating it brings parallax to the fore. It is to be noted that parallax is really an effect of the tablet, not of the stylus. Additionally, the absence of palm rejection on the tablets made tracing and sketching less comfortable compared to the pen-paper medium. This could explain the incongruity between the poor performance of the hard-tipped stylus and the positive participant response, suggesting that comfort and familiarity rank higher than speed and accuracy.

A related point that can be argued here is our choice of using a Wacom Bamboo capacitive stylus with a soft and blunt tip as the main comparison against pen and paper. It is certainly true that much better styli with a harder and sharper tip—which more closely resemble a traditional pen—exist. First, our follow-up study focuses on exactly such advanced styli; however, the mere fact that our results hold *even* for a blunt-tipped stylus is intriguing. Second, our original intention with this work was to study the current state of pen-based computing in the world, and tablets with hard-tipped styli are still in overwhelming minority in the market.

7.2 The Digital Sketchbook: a Sketchbook++?

The pen-paper medium has the advantages of being precise, tactile, and versatile. However, there are some intangibles to consider. The industrial designer from our pilot study observed that when sketching on a notebook, she often felt a "pressure to perform", both for fear of wasting precious pages, as well as to do the (expensive) notebook "justice." The tablet is more forgiving: unwanted sketches can be discarded without any material waste. In addition, sketching on a digital notebook can be more sophisticated, with the ability to undo, duplicate and share your sketch with others.

The effects of friction pose some interesting questions that would need addressing in the migration from a paper sketchbook to a digital version. It seems that tracing on a pen and paper is more accurate, but not as fast as tracing on digital media. Are both effects due to friction? A study of muscle loading and performance similar to the one by Kotani and Horii [11] may throw some light on this.

The effects of parallax is a more pressing question that could influence the design of the next generation of portable tablets with dedicated styli. The digital tablet is still a while away from replacing the designer's sketchbook, but with recent hardware and software developments, there is potential for the gap to close rapidly.

8. CONCLUSION AND FUTURE WORK

In this paper, we have compared the performance of various input-media combinations—pen on paper, stylus on tablet, and finger on tablet—in tracing and sketching tasks. We have observed that tracing using a stylus on tablet was faster than pen on paper. The finger-tablet medium outperformed pen-paper in terms of tracing speed, but at the expense of accuracy. For the sketching tasks, the quality of the sketches were significantly higher for the ones drawn using pen-paper and stylus-tablet when compared to finger-tablet in case of more complex shapes. A follow-up study with hard and soft-tipped styli helped bring into relief the effects of parallax.

These results can help guide designers that are building the next generation of sketch-based applications. Our future work would include extending the study to explore the effects of varying tunnel widths and shapes, including the effects of the number and angles of corners. In the context of sketching for early design, this study may provide a better understanding of the performance of digital media. One more aspect we would consider is a qualitative study of the media with respect to less tangible aspects such as their effects on creativity. This would help us further understand the advantages and tradeoffs of using digital media in a design context.

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