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HyperBrush: Exploring the Influence of Flexural Stiffness on the Performance and Preference for Bendable Stylus Interfaces

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Abstract. Flexible sensing styluses deliver additional degrees of input for pen-based interaction, yet no research has looked into the integration with creative digital applications as well as the influence of flexural stiffness. We present HyperBrush, a modular flexible stylus with interchangeable flexible components for digital drawing applications. We compare our HyperBrush to rigid pressure styluses in three studies, for brushstroke manipulation, for menu selection and for creative digital drawing tasks. HyperBrush yields comparable results with a commercial pressure pen. We concluded that different flexibilities could pose their own unique advantages analogous to an artist's assortment of paintbrushes.

Keywords: Deformable Devices, Pen-Based Interfaces, Digital Styluses, Creative Supporting Tools.

1 Introduction

Fig. 1. The flexible stylus HyperBrush is being bent while touching the screen, used for creative drawing (A), menu selection (B) and brushstroke width targeting task (C).

Pen-based interfaces have been used for various digital applications such as sketching, drawing, writing, and 3D modelling [9, 19, 21, 34, 48]. Research prototypes and consumer electronic products can feature additional degrees of freedom to provide a larger input vocabulary, and have exhibited positive results: tip pressure [34, 36], tilting in a direction [43], rolling with the fingers [6], or tapping the barrel [19, 40]. One can use these extra degrees of freedom to create variable brushstroke sizes [3, 15], manipulating the orientation and positioning of models, selecting items [18], and operating menus [4, 51]. The initial goal behind having additional inputs is to increase productivity, efficiency, and promote creativity [3]. Such research has attempted to simulate the experience of using non-digital tools such as the pencil [12] or paintbrush [3, 15]. While these inputs can be of great benefit to stylus-based applications, there are still some limitations posed to each. For example, pen pressure input can be difficult to control while decreasing in pressure opposed to increasing in pressure [36, 52].

We present HyperBrush, a flexible digital stylus capable of sensing bend input to be functioned as additional degrees of freedom for pen-based interfaces (**Fig. 1**). We designed HyperBrush with interchangeable flexible components that differ in flexural stiffness. Our HyperBrush measures two degrees of bend input: absolute bend—the amount of bend being applied—and rotational bend—the azimuth angle relative to the barrel of the stylus. Fellion *et al.* first introduced the concept of a flexible stylus with their FlexStylus device [15]. Their study explored stationary brushstroke width manipulation with bend input, which concluded in comparable performances to pressure input. This result paved the way for a new area of research on flexible styluses. It motivated us to further this field by evaluating the usability of bend input during simultaneous movement of the stylus. We also assessed the performance of our bend input technique on a menu selection task. We focused on measuring the effects of various flexural stiffnesses within both experiments. Finally, we investigated HyperBrush with regards to creativity, an ultimate goal. Our contributions are:

- C1: Design and fabrication of a modular flexible digital stylus with bend input capabilities.
- C2: Evaluation of flexural stiffness on bend input during menu selection.
- C3: Evaluation of flexural stiffness on simultaneous control of bend and positional input during brushstroke width manipulation.
- C4: Comparison of bend and pressure input on supporting creativity in digital drawing applications.

2 Related Work

Our research was built on different areas of stylus interfaces, grip techniques, and deformable devices. We explored prior work that has evaluated popular stylus-based input techniques such as pressure, tilt, rotation. We discussed research on pen gripping techniques that suggested contextually relevant tools and mode switching. Lastly, we examined different pen-based menu stylus, menu techniques, and deformable based interfaces.

2.1 Pen Input Techniques

Previous research explored various forms of auxiliary input such as pressure [10, 15, 34, 36], tilt [19, 43, 47], rolling [6, 19, 20], and bend [15] that are beyond tracking the

X-Y position of the pen tip on the screen [6, 49]. These additional inputs enable pen modes, selections, or tools without having to distract the users' attention away from the focus on the pen tip's position [49].

Pressure. Ramos et al. explored a multitude of widget designs that coupled pressure with change of position, scale, or angle [34]. Pressure Marks introduced pen strokes coupled with pressure for selection and action tasks simultaneously [36]. Early research has looked at the concept of changing digital brushstroke width with varying pressure; Fellion et al. compared pressure with bend accuracy [10, 15]. Research has also found that it was difficult for users to perform tasks that required a decrease in pressure levels as it compromised completion time or accuracy [9, 36].

Tilt. As opposed to pen pressure and rolling, where visualizing the change in their variability can be difficult, the tilt angle of the pen can be easily indicated by observing the physical angle of the pens barrel relative to the surface of the screen [47]. Vertical tilt angle and the azimuth angle of the pen, was found to be suitable techniques for radial menu interaction [19, 43, 47]. Xiangshi et al. also promoted that tilt can also be used to modify the width of a brush stroke from being a “hard” to “soft” brush [47].

Roll. Researchers have applied pen rolls, i.e., rolling along the barrels axis, for applications such as zooming, scrolling, rotation of objects and menu selection tasks [6, 19, 20]. While being a beneficial technique, researchers have found that it can be difficult to avoid unintentional rolling and is restricted to transverse of items to go from point A to B, which can lead to higher selection times and error rates [19, 20].

Bend. Moving beyond input techniques using rigid pens, Fellion et al. modified the stylus' design to allow flexible input [15]. As far as we know, this is the only study about bend as an input modality for styluses. FlexStylus measured both absolute and rotational deformation of a stylus and proposed grip-based, menu-based, and in-air interactions techniques. In evaluating the accuracy of bend as a variable input, they conclude that flexible input can perform similarly to pressure input for brushstroke width manipulation. However, their study did not include X-Y movement. In our work, we move knowledge forward in this domain by comparing the performance of brushstroke width manipulation while simultaneously moving in a direction for pressure and bend.

Combining Inputs. Controlling multiple auxiliary inputs, in addition to the position, can offer many benefits for pen mode switching, tasks with sequential steps, and multi-parametric selection and manipulation, [19, 49]. Xin et al. found the combination of pressure and azimuth input was best suited for multi-parametric control for writing and drawing tasks due to their loose correlation [49]. Zliding found that pressure input in combination with pen X-Y position, supports higher accuracy and performance for zooming and sliding tasks[35].

2.2 Pen-Based Menus

Most pen-based applications display their menus and tools around the edges of the screen, which can be disruptive to users workflow when interacting with, accumulating time and error [27, 28]. A *Marking Menu* is a circular contextual menu that enables users to perform selection tasks by using pen gestures and strokes in place of point-click interaction [25]. Styluses benefit from marking menus speed, efficiency, and easy learning curve for novices to become experts [27, 28]. The disadvantage is that accuracy is restricted by the number of items within the marking menu, where performance starts to decrease with more than 8 items within a level [18, 22, 43, 51]. *Tilt Menu* explored a radial menu technique using tilt input and evaluated users' performance of item location [43]. They found that items occluded by the hand resulted in poor accuracy. We used a radial menu technique with bend input similar to Tilt Menu's experiment design to explore the influence of flexural stiffness on users' performance.

2.3 Deformable Interfaces

Researchers have looked towards deformable user interfaces (DUI) as input tools to provide users with a more tactile and intuitive feeling when compared to rigid interfaces [30, 33]. Rigid interfaces also present physical constraints and limitations on how we can interact with them [45]. DUIs are often made up of soft materials that are capable of sensing physical deformation and change in shape as an input technique [7]. Utilizing objects that have the ability to twist, squeeze, rotate, or bend, introduces novel interactions that rigid interfaces cannot accomplish [7, 45]. DUIs have made its statements in gaming [14, 37, 39], accessibility [8, 13], electronic reading [46], music [17, 44], drawing [37], and mobile handheld devices [14, 16, 29, 31, 37, 41, 45] that aspire to enhance intuitiveness, expressiveness, and either augment or replace rigid interfaces.

There is to our knowledge only one existing work about a flexible stylus [15]. However, the authors did not address all research questions arising from this modality. Our work addresses the need to explore flexible styluses as a creative and expressive tool for digital painting and drawing. We further the research area of bendable stylus research by assessing how HyperBrush can be a tool to support creativity, expressiveness, and enjoyment for digital artists. We bring forth the intuitive feeling of using a physical paintbrush to the digital workflow for painting and drawing.

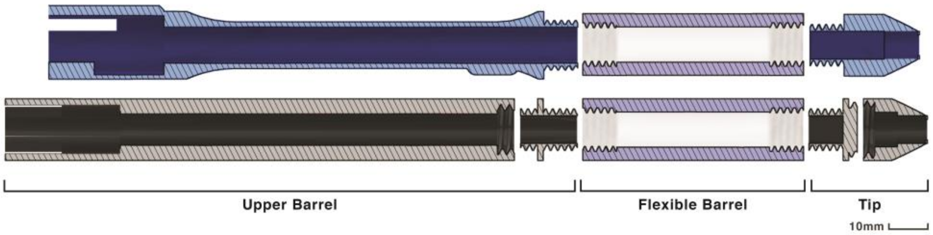

Fig. 2. Cross section model of both experiments stylus designs. Experiment 1 design (top), with a concave *upper barrel* and pseudo button that suggests orientation of the users' grip. Experiment 2&3 design (bottom) features inner screws, improving durability and modularity.

3 Apparatus Construction & Design Process

Artists rarely work with only one pen or brush. They rather have a collection of tools, which allow them to produce different stroke size, shape, intensity, colour or effects. In this idea, we were interested in the idea that 1) different flexural stiffnesses could provide artists with substantial benefits in terms of possibilities, 2) input modalities such as flexural stiffness and pressure are complementary. Therefore, we designed HyperBrush, a flexible stylus that features interchangeable components to vary flexural stiffness. We decided to have a modular design and separated our stylus into three main components that attach the *upper barrel*, *flexible barrel*, and *tip* (**Fig. 2**). Our pen design enabled swapping the flexible section, interchangeable with different stiffnesses. We discuss our construction design and how it differs from previous flexible stylus designs.

3.1 Construction Design

We used Stereolithography (SLA) printing to print at a higher quality and durability when compared to Fused Filament Fabrication (FFF) printing, which exhibited tearing and snapping while being bent. We printed both flexible/non-flexible materials using a FormLabs Form 2 [23] printer with photopolymer elastic (Elastic 50A Resin) and rigid resin (Rigid Black/Blue Resin). SLA printing made it easier to design a cavity for our bend sensor and prototype styluses for testing.

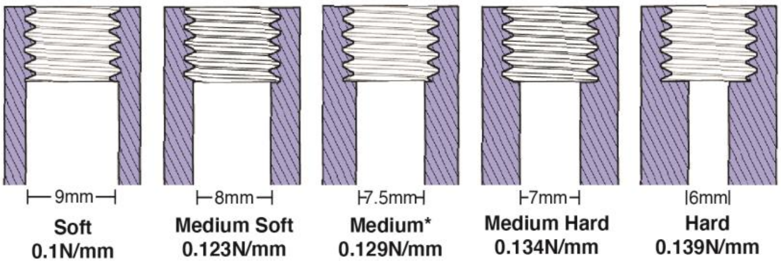

Fig. 3. Front cross section of the five flexible barrels, omitting the flexible sensor inside, with flexural stiffness measurement. Medium* flexibility was only used for studies 2&3.

Flexible Barrel. We varied stiffness by manipulating the inner wall thickness of the flexible barrel (**Fig. 3**) to maintain a uniform outside diameter of 11.2 mm. Given the photopolymer elastic material, we found that an inner diameter greater than 9 mm would reduce the durability, and less than 6 mm would not yield enough clearance for the sensor to fit. Our method supported a consistent physical outside diameter and an indistinguishable physical touch and visual difference between each barrel. We classified each flexibility as a ratio of amount of force applied per unit of deflection, known as the flexural stiffness. We calculated the flexural stiffness similarly to how a hollowed cylinder cantilever beam test is executed in engineering design [38]. The cantilever test simulated the technique of a user bending the stylus prototype during use. To vary flexibility, we recommend future prototyping to manipulate the inner wall thickness of the flexible barrel as it does not compromise any exterior design.

Top Barrel & Pen Tip. As bend gestures are directional, we choose to add a pseudo button on the upper barrel that indicated placement of the index finger to maintain a consistent roll position and reduce incidental rolling. We noticed it helped participants to maintain their grip better and reduce the amount of accidental rolling (**Fig. 2**). Our pen tip posed as the anchor point for our device during bending. We integrated a permeable rubber nib and attached a conductive wire that was threaded through the barrel of the pen carrying the electrical capacitance from the user's hand to enable X-Y input.

Two Axis Bend Sensor. We used a soft angular displacement bend sensor by BendLabs Inc. that offered high precision while rejecting most strain and noise [5]. Their sensor consisted of two capacitive flexible sensors positioned perpendicularly to one other measuring bend input from two orthogonal planes. We coupled the angle measurements to the X-Y position of our bend cursor in our bend menu study. We used an Arduino Mega [1] to communicate data from the sensor to the tablet, a Microsoft Surface [32].

3.2 Comparing HyperBrush with Previous Designs

Fellion *et al.*'s original sensing technique had four hand-made fibre-optic sensors to detect bend in two directions simultaneously [15]. We used a commercial capacitive bend sensor that provided more reliability, robustness, and precision as explained above. FlexStylus had a single flexural stiffness, unmeasured, which contrasts to our modular design purposed to interchange five flexible barrels.

4 Study 1: Bend Menu Selection

Our first study evaluated the performance and preference of flexural stiffness on a bendable stylus during menu selection. Fellion *et al.* previously introduced a bend menu interface that coupled both rotational and absolute bend to navigate through and select items in a radial menu interface [15]. Their bend menu demonstration was not evaluated, therefore we decided to use their menu interface as a medium to explore the influence of different flexibilities.

4.1 Methodology

Similar to Tilt Menu's experiment [43], we evaluated menu selection for three menu sizes with each item distributed by 90° (small), 45° (medium), and 35° (large) as well as a constant radius of 2.5 cm. We developed our testing application using Unity Engine and coupled rotational and absolute bend input to control the on-screen cursor. We programmed the absolute bend range from [0°, 45°] and rotational bend range from [0°, 360°]. Based on a pilot study, we proceeded with a Control-Display (CD) gain of 1.5.

- **Neutral Zone.** On initial touch with the screen, the menu's origin is located directly underneath the pen cursor and the state of the pen is in the neutral zone indicated as white; no current items are selected (**Fig. 4**.1).

- **Selection Zone.** Once the cursor enters the unbounded selection zone, the item underneath the cursor will highlight in red indicating that it is currently being selected (**Fig. 4**.2 & 4.3).
- **Confirmation Zone.** Items are confirmed once the user exits the selection zone by moving the cursor past the outer diameter of the desired item (**Fig. 4**.4).

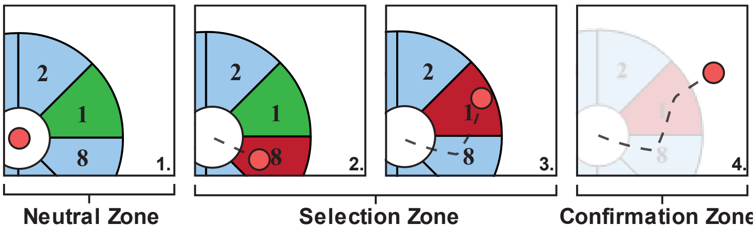

Fig. 4. Menu selection process of the cursor (pink circle) to target (green item) shown in the medium size menu. 1. Cursor starting in neutral zone. 2. Moving into selection zone (highlighted in red). 3. Navigating to target item in green. 4. Exiting on the outside radius of the target item to confirm selection.

4.2 Study Protocol

We began the experiment with a demographic's questionnaire including their experience with using digital and non-digital pens. We briefed them with a tutorial and explanation of the experiment, to allow time for training and gain familiarity with the device. The tutorial presented a random target to select, mimicking the actual experiment setup, with no repetitions involved.

We recorded participants selection time and error rate. We informed participants that we are more concerned with their performance rather than speed of task completion. Participants started the selection time by moving the cursor into the selection zone and then stopped when an item has been selected. We calculated participants error rate by dividing their total missed targets by their total overall targets. We recorded a missed target when the target item was not successfully selected by the user.

Our experiment followed a within-subject design where participants used 4 flexible pens for each of the 3 menu sizes. Each task was repeated 6 times for a total of 576 selection tasks, 4 flexibility (soft, medium soft, medium hard, hard) × (4 + 8 + 12) menu sizes (small, medium, large menus) × 6 repetitions = 576. We randomized the flexibility type, menu size and menu items to counterbalance learning effects. Study sessions lasted approximately 45 minutes.

Between each flexibility condition, we asked participants to fill a 5-point Likert scale questionnaire regarding the styluses perceived movement, responsiveness, and accuracy. At this time, we also encouraged participants to take a short break. We ended the experiment with a post questionnaire asking about their experience using a flexible stylus for menu selection and to rank their most to least preferred flexibility input type.

4.3 Hypothesis

- **H1.** We hypothesized that an increase in flexural stiffness will result an increase in error rate. Stiffer devices may take more physical exertion to bend, which could make selection tasks more difficult [24].
- **H2.** We hypothesized that the hard stylus will be the least preferred flexibility, as Kildal et al. found that users preferred softer materials as they required less effort to manipulate [24].
- **H3.** We hypothesized that the increase of the menu breadth will also increase error rate. This is supported by previous menu selection studies showing that increase in menu breadth (number of items) increases the likelihood of missing the target [4, 43, 51].

4.4 Participants

We recruited participants through email and posters. We had a total of 18 participants: 8 men, 10 women; 15 right-handed, 3 left-handed. Most participants were university students, their average age was 23 years old. None of the participants were experienced with using a bendable device. Participants received a $15 compensation for their time. The Carleton University Research Ethics Board approved this study (CUREB #111345).

4.5 Results

We first report the effects of repetition, menu size, and flexibility on selection time and following, we report the effects of the latter on error rate. We were also interested in studying the influence on item location within each menu size. Following, we discuss participants preference results and discuss findings upon their feedback.

Selection Time and Error Rate. We conducted a multi-way ANOVA across *repetition* × *flexibility* × *menu size* on selection time. Sphericity was assumed for repetition, flexibility, and was adjusted for menu size ($p < 0.01$) using Greenhouse-Geisser correction. We found a significant effect of *repetition* ($F(5, 90) = 11.7, p < 0.01, \eta_p^2 = 0.36$) and *menu size* ($F(2, 36) = 124.79, p < 0.01, n_p^2 = 0.87$) however, did not find any interaction effects. The same multi-way ANOVA across on error rate revealed a significant effect of *repetition* ($F(5, 90) = 3, p = 0.02, \eta p2 = 0.14$) and *menu size* ($F(2, 36) = 32.29, p < 0.01, np2 = 0.65$) however, no interaction effects were found.

For *menu size*, our pairwise comparison using the Bonferroni adjustment on selection time revealed a significant difference where $p < 0.01$ for each pair. This suggested that the increase in items within a menu also increased the overall selection time for participants (small: 0.88s, medium: 1.22s and large: 1.54s). We found these results to be on par with Tilt Menu and other studies which evaluated a ranking of menu sizes [42]. Our pairwise comparison for menu size on error rate found a significant difference for each menu pair where $p < 0.01$ which suggested that an increase in items within a menu also increases error rate (small: 2.2%, medium: 9.1% and large: 15.1%).

Our hypothesis (H1) assumed that an increase in flexural stiffness will yield in a decrease user's performance. However, we did not find any effects of flexibility type for both selection time and error rate (**Fig. 5**). This was interesting for us, furthermore, we discussed this factor in depth alongside with our flexibility preference results.

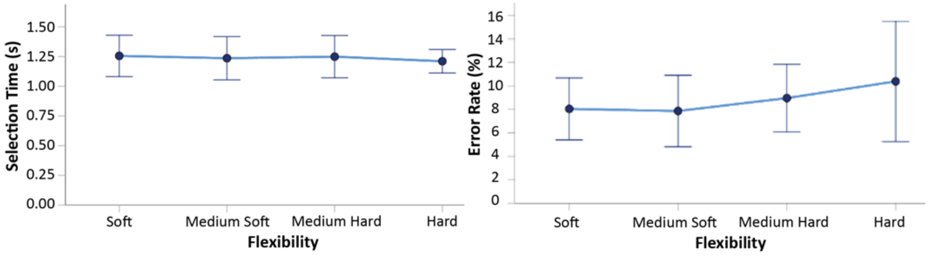

Fig. 5. Average selection time (Left) and error rate (Right) with 95% CI for the four flexibility conditions.

Item Location. We were also interested in comparing each item's selection time within its respected menu. We evaluated the right-handed participants only (n=15) to mitigate the possibility of left-hand/right-hand occlusion, similarly done by Tilt Menu [43]. Our ANOVA investigated the influence of item location on selection time and found significant differences for all three menu types: small ($F(2, 27) = 10.8, p < 0.01, \eta_p^2 = 0.44$), medium ($F(3.3, 46) = 2.7, p = 0.05, \eta_p^2 = 0.16$), and large ($F(4, 51) = 4.5, p < 0.01, \eta_p^2 = 0.24$). Across all three menu sizes, items located within the south-west region yielded the lowest selection times with relatively low error rates. Comparatively, items located south-east were more difficult to select resulting in relatively high selection times and error rates. We speculate this reasoning due to items being occluded by the user's hand in the south-east region.

Participants filled out a preference questionnaire that asked them to rank the flexibilities from most preferred to least. We had a total of $n=13$ rankings as we neglected 4 participants who misunderstood the question and only provided their most preferred flexibility. We performed a Wilcoxon Signed Rank Test on the rankings and found no significant differences. **Fig. 6** indicates that most people ranked the *medium soft* ($n=8$) and *medium hard* (N=7) flexibilities as their 1st or 2nd preferred flexibility while the *hard* and *soft* flexibilities had the most ranked 4th place ($n=5$ for both).

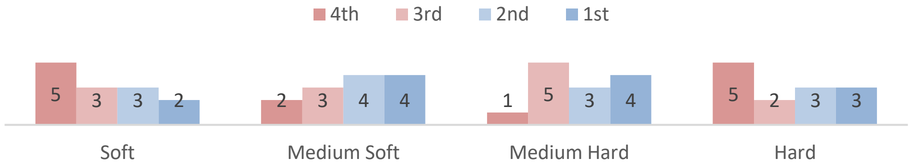

Fig. 6. Total participants ranking from most (1st) to least (4th) preferred flexibility input type.

P2, P3, P11, and P14, favoured the harder flexibilities commenting that they felt they had more accuracy, which led to fewer unintentional movements. They also stated that the soft flexibility was too difficult to be precise when making small movements. Opposingly, P1, P6, P8, and P10, argued that the soft flexibilities were more responsive and easier to control. P6 and P10, also mentioned that the soft flexibility took the least amount of physical effort to move. P5, P9, P13, and P16, preferred the medium flexibilities as they stated that it was the perfect balance between the stylus being too soft or too flexible to control.

P1, P5, P8, P9, P13, and P14, expressed that they admired the ability to quickly flick or point/bend towards an item without having to move the position of the stylus. We found this feature beneficial in a practical setting, users can quickly select items in a radial menu without having to disrupt their current pen position or mode. Interestingly, this was also found to be a feature of Tilt Menu where the user tilted the pen towards an item without having to lift off or move the stylus tip from its current position [42].

4.6 Discussion

We hypothesized that an increase of flexural stiffness may result in higher error rates (H1). We also theorized that the stiffer materials, medium hard, and hard will be the least favoured (H2). Our subjective rankings did show that many people did not prefer the hard flexibility type (n=5), moreover there was an equal amount that disliked the soft flexibility type (n=5). Being there no distinct preferred flexibility type from our analysis, we could not conclude that users favoured the softer conditions for our HyperBrush device. This means every flexural stiffness is relevant, depending on users' preference. Participants' feedback revealed that the type of task may have an influence on what flexibility users favour. Many who preferred a stiffer HyperBrush, reasoned that they felt more control over executing fine and precise movements. While others who preferred a softer HyperBrush, stated that it did not require a lot of physical strength to move and being more comfortable to use.

We hypothesized that with an increase of items within a menu will also increase error rate (H3). From our analysis, we found this was correct for error rate and selection time as well. P7, P8, P10, P14, and P17, mentioned that it was difficult to select items that were located directly underneath their hand (south-east area). We advocate that menu tools of higher importance should be mapped to items located in areas that are not occluded by the users' hand to yield in best efficiency. This is also supported with prior research on radial pen-based menus [26, 42, 50].

We point out limitations of the study. Bending our device does not require a lot of force, however, when consecutive repetitions occur, it can lead to hand strain or fatigue. We did not measure any effects of fatigue on accuracy although, it was evident from participants criticism (P1, P2, P11, and P12). We emphasize that this should be considered during the protocol planning and longer breaks between tasks should be further encouraged.

5 Study 2: Brushstroke Width Manipulation Task

Our first study explored the usability of our HyperBrush did not incorporate pen movement. Previous work compared stationary bend and pressure input for brushstroke width manipulation [15]. Our goal in the second study was to compare the ability to simultaneously control pen movement with bend or pressure input. Specifically, we measured the performance (width and movement accuracy) of controlling bend and pressure input while moving on an X-Y plane simultaneously and compared it with the Microsoft (MS) Surface Pen, which includes pressure input. Carrying on from our previous study, we also incorporate measuring the influence of flexural stiffness. For this study, we combined the medium-soft and medium-hard conditions due to our results showing no distinct differences in performance or preference.

5.1 Methodology

We investigated the influence of manipulating the brushstroke width by evaluating the user's performance on matching two target patterns: *static* and *dynamic* while moving in the given direction: North, South, East, West (**Fig. 7**). This additional factor of moving in a direction goes beyond previous work [15], to provide a more comprehensive analysis of real brushstroke patterns, which are not always left to right (i.e., east). Our intention for using two target patterns was to measure performances for holding bend position and varying the position by repetitively increasing and decreasing bend.

- **Static Target Pattern.** User moves in given direction and immediately alternates between holding the maximum width (4 cm) and the minimum width (0.5 cm).
- **Dynamic Target Pattern.** User moves in given direction and gradually alternates increasing towards the maximum width (4 cm) and decreasing towards the minimum width (0.5 cm).

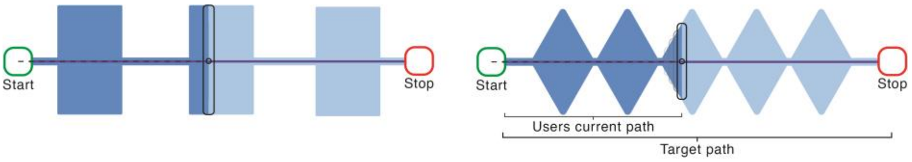

Fig. 7. Brushstroke width manipulation task with the static (left) and dynamic (right) target patterns. Illustration of a user matching their path (dark blue) to the target path (light blue), moving east. The cursor (black rectangle) indicates the current position and width size.

Before we start each task, we display the *start* and *stop* indicators outlined in green and red (**Fig. 7**). We begin the task when the user places the stylus tip within the area of the *start* indicator. We end the task when the user enters the area of the *stop* indicator and then repeats displaying the next task.

We assigned each X-Y position on the path and a brushstroke width value that essentially displayed the target path. We measured the positional accuracy by calculating the mean Euclidian Distance between the target's points and the user's points, known as Proportional Shape Matching [2, 25]. Similarly, we calculated the width accuracy as a measurement of the absolute difference from the target and user widths.

We followed a within-subject design where participants used 4 *inputs* (soft, medium, hard flexibilities, and pressure) × 4 *directions* (north, south, east, west) × 2 *target patterns* (static and dynamic) × 5 *repetitions* = 160 trials that were randomized. Between inputs, participants filled a Likert scale questionnaire regarding the input type.

5.2 Hypothesis

- **H1.** We hypothesized that the *soft* flexibility would perform better in *width accuracy* as opposed to the other flexibility conditions.
- **H2.** We suspected that when decreasing in brushstroke width, our HyperBrush would perform better than the pressure stylus in *width accuracy.*

5.3 Participants

We recruited participants through email, social media, and posters. The majority were university students with no prior experience with using flexible styluses. None participated in the first study. We had 18 participants, 10 men and 8 women: 17 right-handed and 1 left-handed. These participants conducted Study 2 and 3 in a single session (1h total), starting with the task in study 3, a creative drawing task, where they drew two illustrations, one with HyperBrush and one with a pressure pen. We chose to present them in a different order in this paper, choose to present the studies that evaluated effects of flexural stiffness sequentially (study 1 and 2) and following, discuss the creative drawing task (study 3). The study was approved by our institution's research ethics board and we provided each participant $15 compensation.

5.4 Results

We first decided to remove any effects of repetition on width & positional accuracy and conducted a Multi-Way ANOVA for both with Sphericity not violated across all factors. We found significant main effects on both width accuracy, $F(4, 64) = 13.40, p < 0.01, \eta_p^2 = 0.46$ and positional accuracy, $F(4, 56) = 22.95, p < 0.01, \eta_p^2 = 0.62$. A pairwise comparison with Bonferroni adjustment found a significant higher difference in accuracy from the 1st to all other repetitions for width accuracy and 5th to all other repetitions for positional accuracy, both at $p < 0.01$. Based on this result, we proceeded to disregard both the first and last (1st and 5th) repetitions for the following analyses as we were focusing on the learning effects of this study.

Positional & Width Accuracy. We conducted a multi-way ANOVA across *input type × direction × target type* on *positional accuracy*. We found a significant effect of *input type* ($F(3, 39) = 5.6, p = 0.03$, $\eta_p^2 = 0.29$) and *target type* ($F(1, 13) = 6.0, p < 0.01$, $\eta_p^2 = 0.68$) (**Fig. 8**). We did not find any interaction effects. We follow up with the pairwise comparison results below.

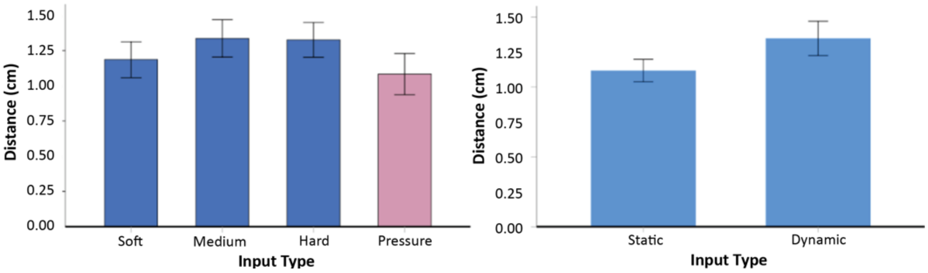

Fig. 8. Participants average X-Y distance from the target position for our three flexibilities and the baseline pressure condition (Left) and target type (Right).

Our pairwise comparison using Lowest Significant Difference (LSD) adjustment found that the Soft flexibility was significantly lower than the Medium flexibility, $p = 0.04$. The baseline MS pressure pen condition was also significantly lower than the Medium, $p < 0.01$ as well as the Hard, $p < 0.01$ flexibility types. Being that the soft flexibility also yielded in the lowest average distance as opposed to the other flexibilities, this could suggest that the soft flexibility is easier to control than the other flexibility types.

We conducted a pairwise comparison using LSD adjustment and found that the Static target averaged a lower distance and was significantly lower than the Dynamic target, $p < 0.01$. This could assume that users are more accurate with controlling the styluses X-Y position when not consistently changing the bending position of the device.

We conducted a multi-way ANOVA across *input type* × *direction* × *target type* on *width accuracy*. We did not find any main effects or interaction effects on any of the above factors on width accuracy.

Completion Time. We conducted a multi-way ANOVA for *completion time* and found a significant effect of *direction* ($F(3, 45) = 3.8$, $p = 0.02$, $\eta_p^2 = 0.34$) (Sphericity assumed) with no further interaction effects. We followed with pairwise comparison test using Bonferroni adjustment and revealed that moving in the east direction (31s) yielded in significantly lower average completion time than moving in the west direction (37s), $p = 0.04$. We also found that moving towards the north direction (32s) was also significantly lower than moving in the south (35s) and west (37s) directions where $p=0.04$ *and* 0.01 respectively.

Flexibility Preference Results. Similar to the first study, our analysis on flexibility preference did not yield significant results. Results showed the medium flexibility with the lowest preferred mean score of 1.7 while the soft and hard flexibilities were 2.3 and 2.0, respectively (**Fig. 9**).

We further discuss participants feedback and rationale behind their rankings and preferences. P8, P11, and P18, preferred the soft flexibility articulated that it was the easiest to bend because it required less physical effort consequently improving their ability to control the device. Opposingly, P1, P3, P7, and P10 argued that the hard flexibility was the easiest to control and more precise. P3 explained that the soft flexibility allowed for too much bend to be applied thus it was easier to make mistakes and overshoot targets. P6 who preferred the medium flexibility, rationed that it was the perfect medium between the two where it combined the easiness of flexing without compromising too much responsiveness.

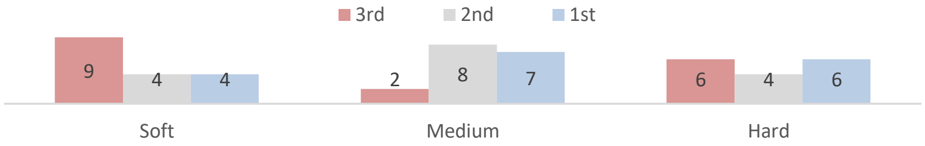

Fig. 9. Summary of participant rankings from most (1st) to least (3rd) preferred flexibility input type.

5.5 Discussion

We hypothesized that the soft flexibility would perform better in width accuracy than the other flexibility types (H1), yet we did not find any significant differences between flexibility type for width accuracy. From looking at how users perceived the performances for each flexibility, it may also be inconclusive to approximate a dominant flexibility type. Looking back at our bend menu study, we also did not find any effects from flexibility. We found these results interesting as we speculated that flexibility could depend on user's personal preference. With HyperBrush, users have the ability to interchange components to their preferred flexibility or depending on the task.

We found that participants preferred stiffer materials for tasks that require precision, such as writing. As for a softer material, drawing or sketching might be valuable here. As for drawing or sketching, we speculate that the softer material might be of value for these scenarios that require quick gestures and strokes. Commercial versions of HyperBrush could either be a set of several stiffnesses brushes, or a single brush with interchangeable parts of different flexibilities, including a rigid one.

We suspected that when decreasing in brushstroke width our HyperBrush would perform better than the pressure stylus in width accuracy (H2). Our analysis did not find any significant differences between the two input types. These results are aligned with those found in FlexStylus' study [15]. Interestingly, a few participants mentioned that the visual feedback from the curvature of our bent HyperBrush assisted with their control and accuracy during increasing and decreasing brushstroke width.

We point out the limitations of this study. Our HyperBrush had a larger pen tip surface area (28.00 mm^2) as opposed to the Microsoft Surface pressure pen (0.80 mm^2), which made it difficult for users to make very fine (small) brushstrokes. Additionally, HyperBrush's tip was made from a rubberized compressible material opposed to the matte plastic texture from the MS pen, therefore making it difficult to compare the feeling produced when drawing. We chose a larger pen tip to provide a sufficient amount of frictional force to avoid accidental slippage when bending the device. The MS pen being a commercial product, its manufacturing is precise and robust, and its pressure transfer function is thoroughly calibrated. Therefore, the comparable results of a research prototype such as HyperBrush are encouraging.

We explored a range of flexural stiffnesses for our HyperBrush, from 0.1 N/mm to 0.139 N/mm yet neither study found any influence on users' performance. Considering only that a total range difference of 0.039 N/mm (4 g/mm) could potentially be too narrow to yield any significant differences. While it would have been ideal to explore a larger range of stiffnesses, we were constrained by the thickness of the inner wall without compromising robustness of the device and fitting a sensor within its cavity. We also consider that participants also had prior exposure with using the medium flexibility during study 3 which may have an additional learning effect.

6 Study 3: Creative Digital Drawing Task

In this study, we sought to assess how our HyperBrush can be a supportive tool for users' creativity. We were also interested on how it performs compared to a commercially available pressure sensitive stylus, the Microsoft Surface Pen.

6.1 Methodology

We developed our own free form digital drawing application that supported input from both stylus types. We programmed our application using Unity Engine and coupled both absolute bend and pressure input to vary the width of the brushstroke. For instance, a larger bend or pressure input resulted in a larger brushstroke width. For the flexible input, we chose to use a single flexibility, the medium condition (0.129 N/mm), being the combination of both hard and soft extremes. This provided participant equal training between the flexible and pressure pen, while fitting within an hour-long study session.

We followed a study design similar to Aslan et al. that instructed participants to draw an illustration for both input types [3]. We instructed participants to draw two illustrations (cityscape and landscape), one per input type (bend and pressure), in which the order was reversed per participant. We gave participants 10 minutes for each illustration and was also encouraged to think aloud. We hypothesize that our participants would perceive HyperBrush to support creativity more than a pressure stylus (**H1**). To address H1, we had participants fill out a Creative Support Index (CSI) questionnaire that examined their subjective perception of how each stylus type can support the five dimensions of creativity (Enjoyment, Expressiveness, Exploration, Results Worth Effort, and Immersion) [11]. The 18 participants in Study 3 also completed study 2. They are described in section 5.3.

6.2 Results

Fig. 10 illustrates P1, P2, P4, and P9 drawings from both input and illustration types. Overall, most illustrations produced by our HyperBrush exhibited larger brushstrokes that was ideal for drawing large patches of land, grass, and sky. There was also a trend of participants drawing skies with colourful sunsets taking advantage of the gradient tool. On the other hand, the MS pressure stylus revealed drawings of smaller strokes detailing thin outlines, birds, small bits of grass, and windows.

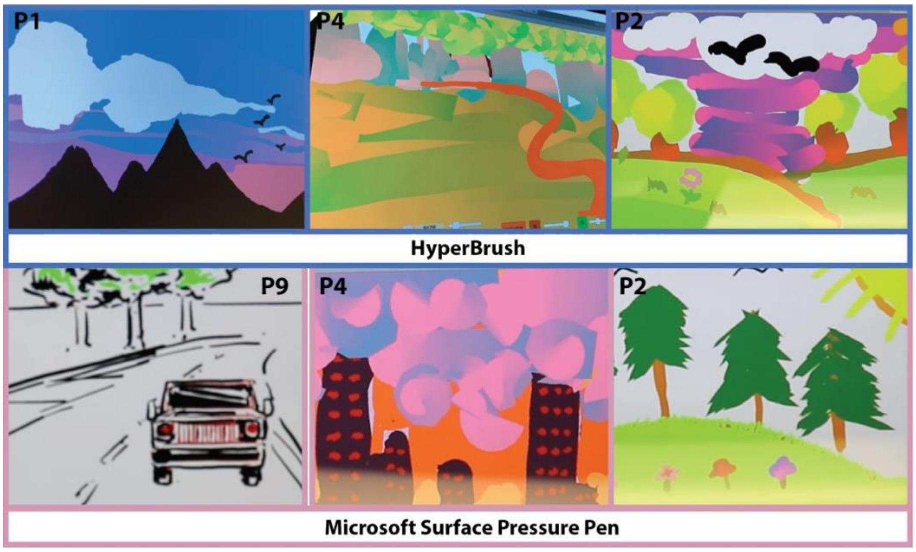

Fig. 10. Collage of participants' drawings of a landscape or cityscape from using both styluses.

P1, P2, P12, P17, and P18 expressed that the HyperBrush acted similarly to a paintbrush. We believe that this is because the flexible barrel bends in the same fashion to how the bristles on a paintbrush bends, it curves as the tool is dragged on the surface. P5, P14, and P16 also mentioned that the visual affordance from our HyperBrush helped them control the amount of bend due to being able to see the curvature as well feeling the resistive feedback from the flexible barrel.

Fig. 11. Example of P12 drawing colourful gradient clouds with using repetitive circular motions while bending and rotating the HyperBrush.

P12 commented on how they enjoyed performing a circular motion technique with both styluses, in which the gradient effect added colour depth to objects such as clouds and treetops (**Fig. 11**). P12 explained that they bent the device while directionally pointing it in a rotational fashion creating colourful gradients and visually appealing cloud like figures. P4 and others have done a similar technique while drawing their own clouds as well as treetops.

We observed that participants held the HyperBrush low on the shaft with the intention to prevent any unintentional bending and continue to use it as a regular stylus. P5 emphasized that it felt unusual gripping the HyperBrush directly over the flexible point as it felt too soft compromising a sturdy grip.

P2 and P16 expressed concerns with the difficulty of changing directions while maintaining bend input. P2 also argued that this could be a feature like painting Chinese calligraphy where directional changes can add a unique style to the size of the brushstroke width. In this case, with some experience and learning, directional changes can be used to the user's advantage to produce smooth, intentional, and artistic, variants in brushstroke width.

We calculated the CSI scores for both our HyperBrush (44.8) and the MS Pressure Pen (46.0) and yielded in similar results. We conducted a Wilcoxon Signed Rank Test for each dimension of creativity and the overall CSI score and did not find any significant differences between our HyperBrush and the MS Pressure Pen.

6.3 Discussion

We hypothesized that users would perceive HyperBrush to be a greater tool to support creativity as compared to the pressure stylus (H1). Although we did not find any differences in supporting creativity between our HyperBrush and the pressure stylus, most participants preferred our HyperBrush (n=13) over the pressure pen (n=5) as they specified that it was more enjoyable to use. We speculate the reasoning behind this is that many participants referred to our HyperBrush similar to using a digitalized paint brush. Several participants commented that the curve created from bending was almost resembling the bristles of a paintbrush being dragged against the surface. This remark motivated our choice for the name HyperBrush. However, it does not mean that our intent was to specifically replicate a brush. Users can grip the device in different ways, which offers different interaction styles, similarly to FlexStylus [15]. From our results, we found that participants performed larger and expressive brushstrokes for clouds, treetops, and skylines. As opposed to the pressure stylus, participants often performed thin strokes for outlines, windows, and birds.

The main limitation of this study is that our participants were recruited from the general population, few considering themselves as artists or experienced using digital stylus interfaces. Although we obtained valuable feedback and exceptional illustrations, a study targeted at digital artists could obtain richer feedback and results.

7 Conclusion

We presented HyperBrush, a digital stylus capable of utilizing bendable input as an additional degree of freedom for pen-based applications. We designed HyperBrush to have interchangeable flexible components so that the stiffness of the device can be accommodated to the user's preference and task. We conducted three studies to evaluate HyperBrush, one assessing the performance on a menu technique, a second comparing bend and pressure when controlling brushstroke width while moving the pen, and a third with a more complex creative task.

We observed how HyperBrush can perform similarly to a commercial MS pressure pen when it came to supporting users' creativity and controlling brushstroke width while moving. While we did not find any influence of flexural stiffness on users' performance, feedback exhibited that stiffness could be a result of personal preference. We believe that HyperBrush's variety of flexibility is analogous to having a wide selection of paintbrushes available for an artist, where each flexible brush provides their own distinct advantages and style to the artist. This is, however, still to be validated with a user study involving artists. Regarding our study about menu selection, participants found that quickly bending/flicking towards an item was a fast and effective method of interaction.

For future prototyping of a flexible sensing stylus, we recommend exploring different pen tip sizes and materials. We think that a smaller pen tip size that does not compromise the ability and control of bending could potentially expand this research field into other applications such as digital writing or object manipulation that demands precision of the pen tip. We look forward to an in-the-wild, longitudinal study with digital creative artists or designers to understand how HyperBrush could be a tool to better support their creative applications and workflow, with a comprehensive set of HyperBrush prototypes ready to go similarly to a different pencil type in a pencil case.

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