PhantomPen: Virtualization of Pen Head for Digital Drawing Free from Pen Occlusion & Visual Parallax

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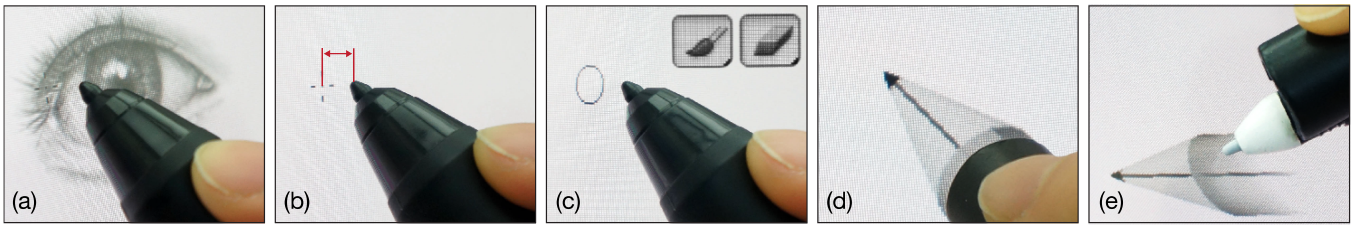

Figure 1: Problems of direct pen input: (a) pen occlusion that covers portions of drawing, (b) visual parallax between a physical pen tip and mouse cursor due to display glass thickness, and (c) hidden pen information such as pen type, color, and thickness, which is not intuitively perceived on the digital canvas. PhantomPen solves these problems by replacing the physical pen head with a virtual pen displayed as if connected to the pen barrel from the user's perspective (d), while an actual pen tip, hidden by the pen barrel, delivers tactile feedback (e).

ABSTRACT

We present PhantomPen, a direct pen input device whose pen head is virtualized onto the tablet display surface and visually connected to a graspable pen barrel in order to achieve digital drawing free from pen occlusion and visual parallax. As the pen barrel approaches the display, the virtual pen head smoothly appears as if the rendered virtual pen head and the physical pen barrel are in unity. The virtual pen head provides visual feedback by changing its virtual form according to pen type, color, and thickness while the physical pen tip, hidden in the user's sight, provides tactile feedback. Three experiments were carefully designed based on an analysis of drawings by design professionals and observations of design drawing classes. With these experiments that simulate natural drawing we proved significant performance advantages of PhantomPen. PhantomPen was at least as usable as the normal stylus in basic line drawing, and was 17 % faster in focus region drawing (26 % faster in extreme focus region drawing). PhantomPen also reduced error rate by 40 % in a typical drawing setup where users have to manage a complex combination of pen and stroke properties.

ACM Classification: H5.2 [Information Interfaces and Presentation]: User Interfaces–input devices and strategies.

General terms: Design, Human Factors

Keywords: pen, occlusion, parallax, visual feedback.

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INTRODUCTION

The pen is intuitive, fast, and unconstrained, and has been the tool of choice for artists and designers for a long time. Today, the traditional tool has been digitalized and enables designers to work in ways that were previously impossible. The digitalized device, in conjunction with commercially available software, offers convenient functionalities such as copy, undo, save, diverse colors and textures, and transcends the analog pen in many ways.

Direct pen input technology is evolving to faithfully reproduce the analog pen. However, such a pursuit has made the digital pen a victim of a physical flaw of the analog pen (Figure 1a). Furthermore, the digital technology has generated a new set of problems that were not found in the analog pen (Figure 1b&c).

In this paper we present a new input technique that overcomes the shortcomings of the analog pen and also fixes the new problems of the digital pen. Such improvements will increase drawing performance, and especially so for drawing requiring precise pen control.

By conducting a literature survey and observing drawing classes, we identify the problems of direct pen input in a digital drawing context (Figure 1a~c). To solve these problems we present PhantomPen, a new direct pen input technique that overcomes the limitations of the conventional analog pen and state-of-the the art direct pen input (Figure 1d&e). Then we design and implement a prototype system to evaluate the drawing performance. Three experiments that closely reflect the real drawing context are designed and conducted. The results show that PhantomPen can be applied to the actual drawing situation and improve the drawing performance.

PROBLEMS OF DIRECT PEN INPUT

Pen occlusion and parallax have been reported as major defects of direct pen input [6, 7, 18, 26, 29, 30], but few directly solved the problems. Along with these problems, hidden pen information has also been a problem when drawing. We divided these problems into three categories, defined each of them, and analyzed the conventional approaches to solve them.

Pen Occlusion

When using a direct input device, the hand or the pen can cover certain portions of the display [29]. The hand may cover a larger area than the pen. However, the area occluded by the pen is highly probable to contain important information since it is near the pen tip, where the interaction occurs. The occlusion can be especially problematic in selecting a small UI element or drawing small features.

A common approach to solve occlusion is to shift and magnify information covered by the hand or pen [18, 27, 28]. However, such callout techniques may occlude other visual information in the vicinity. In addition, when the callout is displayed in a vacant, non-occluded area [27], it may place additional load on the user's cognition as the location of the callout changes each time.

Another approach may be to make the styli thinner. However, professional-grade styli require higher precision sensors that are usually larger and thicker [30], so it is difficult to do so without sacrificing the performance.

Visual Parallax

Visual parallax is the difference between the apparent locations of the stylus and the mouse cursor. The parallax error, even a few millimeters of it, can present difficulties to the user in interaction [15]. The main cause of the parallax is the thickness of the protective glass of the display. For example, the thickness for Wacom Cintiq 21UX, which is widely used by design professionals, is about 2 mm. In addition, the coordinate information of the stylus comes from internal coils [30], and there exists a possibility of miscalibration.

One might think that an indirect input device can remove the error caused by the parallax, but it has eye-hand coordination issues. With an indirect input device, movement of the stylus is separated from that of the cursor, making it difficult for users to naturally match the two movements. This is because people tend to aim the target first with their eyes and then move their hand towards the target [11]. On top of that, indirect pen input is slow compared to direct pen input [6], thus it is hard to say that indirect methods are proper solutions for the visual parallax.

Another approach is to minimize the thickness of the glass of the display [15]. An alternative, thinner material can reduce visual parallax [25]. While these efforts can certainly help reduce visual parallax, the tablets that are currently available employ a solid protective glass panel to withhold pen tip pressure, and we expect visual parallax to persist for a while.

Hidden Pen Information

An analog drawing tool has only one set of properties, such as color and thickness, and exhibits its properties through its appearance. On the other hand, a stylus serves various functionalities as a universal apparatus, often without explicitly exhibiting relevant information [5].

Pen information is usually shown in peripheral panels scattered throughout the digital canvas. In this case, users have to frequently displace their line of sight away from the interaction region and search for the panel to obtain the pen information. Such displacements of the line of sight may impair work efficiency [9]. To minimize searching, the current pen status can be shown utilizing a large box and distinctive color coding [22]. However, such an emphasis cannot account for the problem of displacement of the line of sight.

Pen information can be displayed near the pen tip using simple display widgets activated by any one of: pen gesture [8], pen tilting [24], pen rolling [2], and pen projection [21]. These methods can display related information near the pen tip not to displace the line of sight, but information is hidden when the widgets are not activated.

Recent graphics software such as Autodesk SketchBook Pro delivers tool information, such as size, shape, color and transparency through the cursor. However, each tool has its own specialized visualization convention, and there can be confusion over some tool types as they unavoidably share the same cursor convention. While these cursors can be useful, they are limited because they are simplified 2D symbols that must not distract the user from the content, resulting in information visualization not as intuitive or as holistic as the actual analog tools.

The pen device itself can provide pen information with the aid of external modalities such as haptic feedback [17], or light and sound [14]. However, these means provide only ambiguous information about the status of the pen.

DIGITAL DRAWING WITH DIRECT PEN INPUT

Most of the problems identified for direct pen input above are from artificial experimental setups. To better understand the user's natural and unconscious behaviors in practical drawing, we observed drawing classes in an Industrial Design Department at a university.

Drawing Class

The drawing classes consisted of 50 students and lasted for 16 weeks. Students were taught from elementary line drawing to 2D product rendering. The last 2 weeks of the lecture were about digital drawing using tablet displays. The 15th week was an ice breaking period to familiarize the students with the tablets. During the 16th week the students were asked to draw complicated product sketches with the skills they had learned using Wacom Cintiq 21UX tablets, Autodesk SketchBook Pro and Adobe Photoshop. We frequently observed and interviewed the students in and out of the classroom.

Observations

Our first observation revealed that effects of pen occlusion were more problematic in digital drawing. When drawing on paper, students frequently rotated and displaced their sheets using the non-preferred hand. Experts also rotated and displaced their sheets when drawing [4, 19]. However, as a student commented, students "don't move the tablet from the fixed position, because the [Wacom Cintiq 21UX] tablet is too heavy."

Without being able to freely rotate the canvas, students tried to minimize the occluded area by bending their wrist in an arch shape with their pen tip still touching the screen. Such a behavior, also reported by other researchers [26], can increase fatigue during drawing. However, the students simply considered soreness of wrist a "byproduct of hours of drawing."

Because the tablet could not be rotated very easily, students dealt with occlusion by zooming in on an area of interest. However, when working in the magnified state, the overall structure of the drawing became harder to recognize [3]. In addition, when zooming in/out the students pressed hotkeys on the keyboard. Such actions drew the students' attention to the keyboard, distracting them from the actual drawing task.

One interesting observation is that students did not try to avoid occlusion by moving their head. Their occlusion avoidance effort was largely reliant on movements of their wrist and arm. The students almost fixed their head in a position in which they could view the whole screen.

Visual parallax between the cursor and the pen was the other source of complaint in the digital drawing classes. Students who were skilled at using mouse devices to perform graphic tasks pointed out that "the distance between the pen tip and the cursor gave awkward feelings compared to the mouse." Since drawing often requires accurate positional selection [19], some students said that they could draw better by "focusing on the cursor" while drawing small features. However, when not drawing small features, the students "focused on the pen tip." Such an alternation of focus has also been reported by other researchers [6].

In our observation, important pen attributes were not effectively conveyed. For instance, when using pen and eraser tools alternately, students mistakenly erased when they meant to draw because the cursors were the same in shape for both tools. These kinds of mistakes did not occur when the students used analog drawing tools such as color pencils and markers. One annoyed student suggested that "the cursor should contain indicative information about the pen attributes." In addition, other students found it "distracting" that all the information panels were scattered across the screen.

PHANTOMPEN

From the observations above, we discovered that the problems of direct pen input are closely related to the physical form of the *pen head* and the information covered by it. Thus, we judged that we could start to address the three problems of direct pen input – pen occlusion, visual parallax, and hidden pen information – by rethinking the pen head.

Virtualization of Pen Head

We implemented PhantomPen by replacing the head of the stylus with a real-time rendered virtual pen head. With the shape of the pen head rendered to be aligned with the pen barrel in the user's line of sight, and with a hidden pen tip (Figure 2a), it provides visual feedback as well as tactile feedback. PhantomPen addresses the problems of direct pen input:

- By replacing the physical pen head with a virtual pen head, the physical obstacle is removed from the user's perspective (Figure 2b).
- By coinciding the virtual pen tip with the drawing plane, visual parallax is eliminated (Figure 2c).
- By rendering a real-life appearance of the tool, important pen attributes are visualized in the user's focus region, in real time (Figure 2b&c).

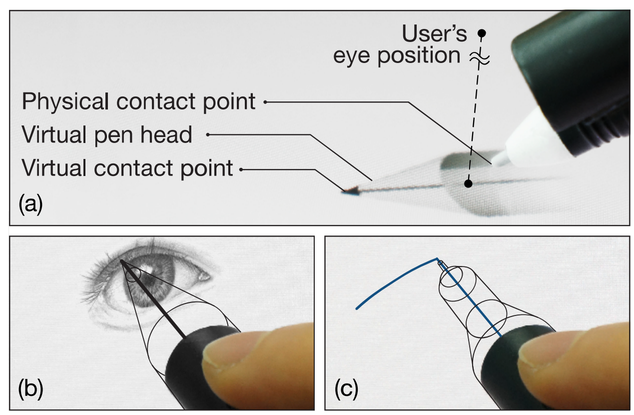

Figure 2: PhantomPen's components (a); virtual pen head does not occlude drawing (b); its virtual tip coincides with the drawing plane, and delivers pen attributes such as pen type, thickness, and color (c).

Geometric Model

The visualization of PhantomPen (Figure 3) changes according to the user's eye position $\boldsymbol{e} = (E_x, E_y, E_z)$, the position of physical contact point $\boldsymbol{p} = (P_x, P_y, 0)$, and the pen tilting direction $\boldsymbol{t} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$ with respect to the frame of reference $\{\boldsymbol{o}, \boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}\}$ on the tablet display. The tip location $\boldsymbol{q}$ of PhantomPen on the screen is:

$$\boldsymbol{q} = \boldsymbol{p} + \boldsymbol{d}$$

where $\boldsymbol{d} = (-R\cos\varphi/\cos\theta, -R\sin\varphi/\cos\theta, 0)$, and a point $\boldsymbol{r}$ on the axis of PhantomPen is projected onto the tablet display surface as follows:

$$\boldsymbol{r}' = \boldsymbol{r} - \frac{\boldsymbol{r}\cdot\boldsymbol{k}}{\boldsymbol{u}\cdot\boldsymbol{k}}\boldsymbol{u}$$

where $\boldsymbol{r} = \boldsymbol{q} + L\boldsymbol{t}$ and $\boldsymbol{u} = (\boldsymbol{r} - \boldsymbol{e})/\|\boldsymbol{r} - \boldsymbol{e}\|$.

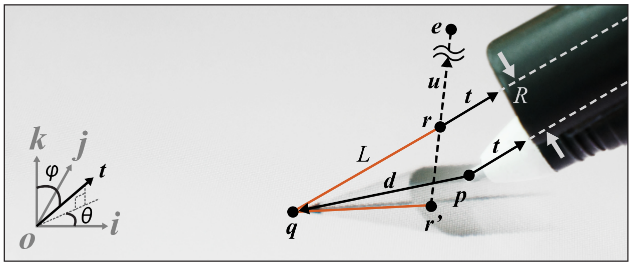

Figure 3: Geometric model of PhantomPen.

PROTOTYPE

We implemented a prototype as a proof of concept to evaluate the drawing performance. We explain the prototype in terms of pen barrel design, sensing of pen status and eye position, and virtual pen head visualization.

Pen Barrel Design

Tactile Feedback

A sense of the pen tip touching physical objects helps precise drawing in general [23]. Since the virtualized pen head cannot provide the required tactile feedback, we employed a surrogate pen tip hidden under the pen barrel that mediates the physical reaction force (Figure 2a). During the design of PhantomPen, the position of the hidden pen tip with respect to the pen barrel was an important factor. When the contact point is pushed further back the occlusion may be reduced, but the user may feel uncomfortable if the contact point is too far away from the virtual tip.

Pen Grip

We also paid special attention in designing the pen grip style. An ellipsoidal cross-section longer in the vertical direction can lead the users to hold the pen with a grip similar to the one used with the Wacom Airbrush Pen. With such a form there is an affordance for users to grab the stylus with the thumb holding the wider side of the pen and the index finger holding the narrower side, a grip that prevents inadvertent rotation.

The final design of PhantomPen is shown in Figure 4.

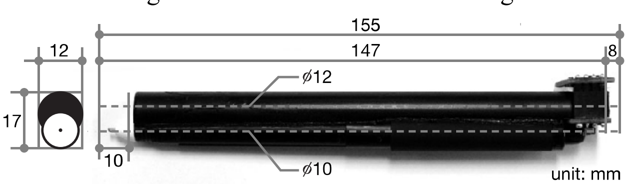

Figure 4: The design of PhantomPen.

Sensing

The geometric model explained above is such that the image of the virtualized pen head of PhantomPen changes according to the direction of the line of sight. To render the virtual pen head, therefore, physical contact point $\boldsymbol{p}$, pen tilting direction $\boldsymbol{t}$, and eye position $\boldsymbol{e}$ are required.

Pen Posture

With the 5 values $(P_x, P_y, P_z, \theta, \varphi)$ provided by Wacom Intuos 4 Art Pen, the physical contact point $\boldsymbol{p}$ is calculated from (P_x, P_y). The tilt values (θ, φ) of the Art Pen, however, contained severe noise to the extent that they could not be used. Such noise was also reported by other researchers [1, 29]. To solve this problem Bi et al. [2] and Lee et al. [13] used Vicon (IR camera) to acquire accurate tilt values. We instead used a 9DOF sensor (E2Box EBIMU-9DOF) to make PhantomPen a stand-alone device. The 9DOF sensor provided 3 geomagnetic, 3 gyro, and 3 acceleration data. We used these data to calculate the tilt angle. The sensor weighed 4.2 g, and set the centroid back by 12 mm (8 %) when attached to the 155 mm, 19 g pen.

In addition, the distance from the pen tip to the screen was measured to render the virtual pen head before and after the pen contacted the screen. Height information (P_z) was not provided by the default Wacom tablet driver, so JTablet driver (http://jtablet.cellosoft.com/) was used. The maximum value measurable was 20 mm from the display.

Eye Position

The virtual pen head of PhantomPen should be rendered with respect to the position of the user's eye and the position and orientation of the pen barrel. In our proof-of-concept prototype, however, we assumed that the line of sight was fixed perpendicular to the tablet surface, based on our observation from the drawing classes and the drawing posture recommended in drawing education [3]. While variable eye position would have been ideal, we excluded eye tracking sensors, which can cause additional delay, to increase the fidelity of the prototype.

Virtual Pen Head Visualization

PhantomPen was developed using Java and JOGL (http://java.net/projects/jogl/). We used a Wacom Cintiq 21UX of which the maximum resolution is 1600×1200. However, there was a lag resulting in a mismatch between the pen barrel and the virtual pen tip for pen movements at high speed. So we set the resolution to 800×600, to boost the rendering speed and perform our formal experiments in a reasonable condition.

Pen Head Model

The virtual pen head is a rendered image of a 3D pen head model (Figure 5). In the model, a semi-transparent cone (pen cap) and a cylinder (pen barrel) are rendered to look connected to the physical pen barrel. The pen tip and lead indicate the color and thickness. The semi-transparency was for indication of pen information and for visibility of the canvas beneath the virtual pen head. As a result, the color of the pen lead seems desaturated, but the pen tip, modeled as a truncated cone, shows the original color.

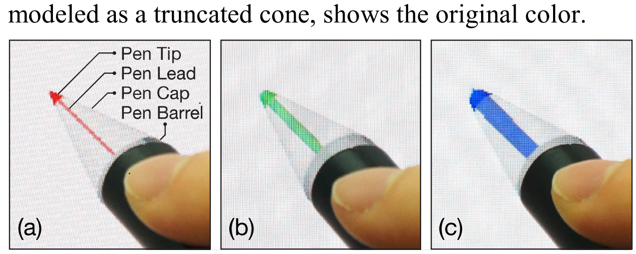

Figure 5: Virtual pen head consists of pen tip, pen lead, pen cap, and pen barrel (a); color and thickness change (a-c).

Transparency Control

PhantomPen is a type of offset cursor that has its cursor position away from the actual contact point, thus disadvantageous in quick pointing because of additional costs for cursor finding, but advantageous in accurate pointing [16]. However, PhantomPen differs from the conventional offset cursors in the following ways. First, with PhantomPen the user can intuitively expect where the cursor will appear based on the direction of the physical pen barrel, reducing the cursor finding cost. Second, the transparency of PhantomPen's pen head changes as a function of the distance from the pen tip to the screen (Figure 6). When the physical tip touches the screen, the pen head is rendered with the predefined maximum opacity, at which point the user can either select (click) or start to draw. This helps to avoid the possible awkwardness of a suddenly appearing or disappearing virtual pen head.

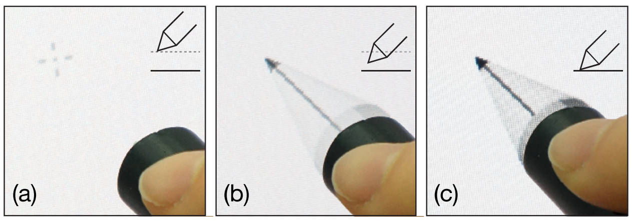

Figure 6: Transparency changes according to proximity of the pen to the display: far away from (> 20 mm) (a), hovering over (b), and in contact with (c) the display.

EVALUATION

We conducted experiments simulating natural drawing to evaluate the PhantomPen concept. The experiments were designed based on design drawing activities [19] and observations from drawing classes. Experiment 1 was to evaluate whether PhantomPen would perform at the same functional level as a normal stylus in basic line drawing. Experiment 2 and 3 were to evaluate whether PhantomPen would increase drawing performance by solving the problems of direct pen input. The participants, procedure, and apparatus were identical in all three experiments.

Participants

12 design major students (2 female, 10 male), with age ranging from 20 to 28, participated in the experiments. Participants were all right-handed and not color-blind. They were all trained in design drawing for at least 4 months.

Procedure

All participants took part in the three experiments sequentially. They were randomly divided into two groups of 6 to counterbalance the order of presentation; one group used the normal stylus first, whereas the other group used PhantomPen first. Before using each pen, participants were given 5 minutes of a warm-up session to familiarize themselves with the pen. They were free to have a break in between the experiments. The combined experiments lasted about 30 to 40 minutes.

Apparatus and Environment

The experiments were conducted using an Intel i5 2.8GHz PC running Windows 7 with OpenGL for graphics. We used a Wacom Cintiq 21UX and oriented the tablet towards the participant at an angle of 10° off the desk. The participants were seated in a height adjustable chair so that they could view the center of the display at an angle of 90°. We asked them to take a straight posture when they bent too much. We attached the flexible USB cable to the participants' forearm with a clip so that they could freely move the arm without being hindered by the cable.

Experiment 1: Basic Line Drawing

In this experiment we intended to test whether the upsides of PhantomPen could make up for its downsides in comparison with the normal stylus in the most frequently performed task in design drawing.

Designers frequently face the situation where they have to draw a line through two specific points. It is typical for designers to initiate the line away from one point so that the stroke can land smoothly on the point at a non-zero velocity. Designers also end the line a short while after passing through the other point to take off smoothly. In addition, designers draw lines away from the body. The first experiment was designed with this continuous drawing technique in mind.

PhantomPen might arouse awkward feelings for designers and therefore lose performance, with its particular shape and distance from the physical contact point to the virtual pen tip. However, it could also gain performance with the three harassing problems of direct pen input alleviated.

Hypotheses

- H1-1. PhantomPen will perform the same as the normal stylus in terms of movement time.
- H1-2. The error rates of the two styli will be the same.

Task

Participants were asked to draw a line between two points displayed on the screen. The starting point was green and the end point orange, so they could recognize the start and end of the line (Figure 7). The angle between the horizontal axis of the screen and the projected line was randomly set between 0° to 45°. The values were set to reproduce natural drawing situations [19]. The color of points changed to gray when the pen passed through them. Whenever the participants missed one or more targets it was considered a failed attempt and no correction, including returning or drawing a second stroke, was allowed.

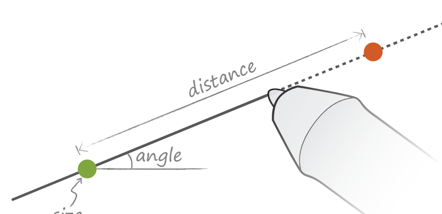

Figure 7: Basic line drawing task.

Design

A repeated measures within-participant design was used. The independent variables were pen type (normal stylus, PhantomPen), target distance (40, 80, 120 mm), target angle (0, 15, 30, 45° CCW), and target size (2, 3, 4 mm radius). In total, the experiment consisted of:

2 pen types × 3 target distances × 4 target angles × 3 target sizes × 2 blocks = 144 line trials per participant.

Results

Movement time measured in millisecond (ms) was the main dependent variable, and was defined as the time taken to connect the two targets. A paired-samples t-test showed PhantomPen to be faster than the normal stylus ($t = 3.333$, $df = 863$, $p < .05$) (Figure 8), with the overall movement time of 470 ms for the normal stylus and 447 ms for PhantomPen. Thus we favorably reject H1-1.

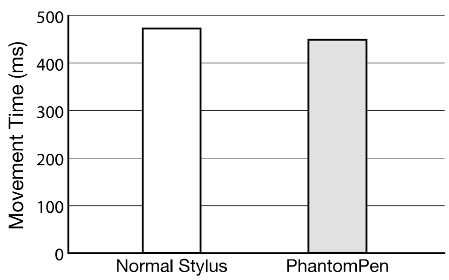

Figure 8: Movement time (basic line drawing).

Repeated measures analysis of variance showed significant main effects for target distance ($F_{2,574} = 625.506$, $p < .05$) (Figure 9), target angle ($F_{3,645} = 4.921$, $p < .05$) (Figure 10), and target size ($F_{2,574} = 16.550$, $p < .05$) on movement time. There was also an interaction effect on movement time for pen type × target distance ($F_{2,574} = 10.246$, $p < .05$). Paired-samples t-test showed no significant main effect on movement time for both pens with the shortest distance, 40 mm ($t = 1.239$, $df = 287$, $p = .22$), but that PhantomPen becomes comparatively faster as target distance increases.

Chi-square analysis showed that there was no difference in terms of error rate between the normal stylus (18.4 %) and PhantomPen (19.3 %) ($\chi^2 = .242$, $df = 1$, $p = .67$). Thus, we confirm H1-2.

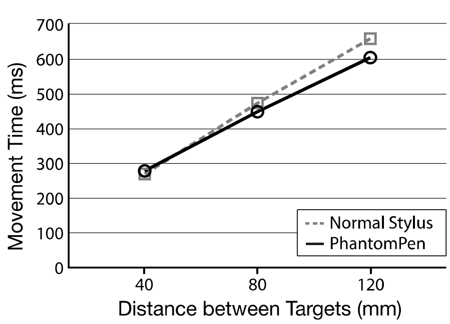

Figure 9: Movement time by target distance (basic line drawing).

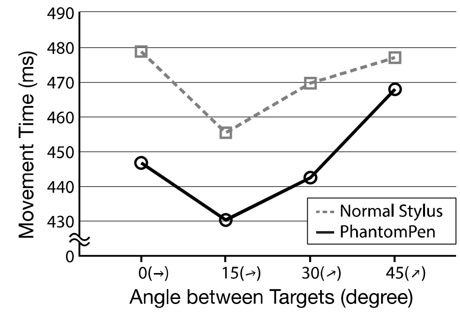

Figure 10: Movement time by target angle (basic line drawing).

Discussion

The distance between the physical contact point and the virtual pen tip could cause usability issues for PhantomPen. In addition, previous experiences with the normal stylus could have had an adverse effect on PhantomPen's performance. Yet PhantomPen was faster, pointing to the possibility of the occlusion and parallax issues being resolved.

PhantomPen might have been faster for larger distances because the end target was clearly visible at all times and enabled users to retain the speed, whereas the drawing speed dropped with the normal stylus because the pen head occluded the target as it approached. The case is analogous to the situation where we underline a phrase in a book. When we cannot see where the phrase ends, we decrease the underlining speed in order not to overshoot, as explained by the impulse variability model [20].

Designers tend to orient the tablet at a certain angle when they draw [4], and there seems to be a comfortable angle to draw lines. If we look at changes in movement time in relations to target angles (Figure 10), both pens show the best performance at the angle of 15°. Such a performance may be due to the anatomical mechanism of the human arm.

Experiment 2: Focus Region Drawing

Pen occlusion can be especially problematic when drawing small and detailed shapes. In the second experiment, we compared PhantomPen and the normal stylus in the focus region drawing context in order to quantitatively validate the effectiveness of PhantomPen in removing pen occlusion.

We referred to the geometric model of hand occlusion proposed by Vogel et al. [29] to determine the size of the pen occlusion region. In the model, the pen tip protruded from the hand by 16 mm on the screen as seen by the user, thus we assumed the pen occlusion area to span about 16 mm on the screen. In addition we designed our target angle range from -90° to +90° where the east is 0°. The range was set wider than that of the first experiment because it is more convenient to draw short lines to various directions [19].

Task

Participants were asked to draw short line segments between points sequentially without taking the pen off the display. Upon crossing the target point, a new target point colored in green was revealed on the right side (Figure 11). This was repeated fifteen times until an orange point appeared as the last target point.

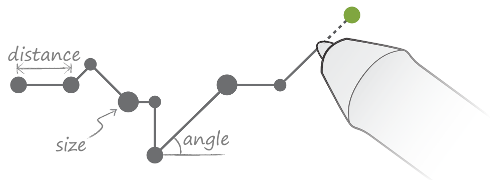

Figure 11: Focus region drawing task.

Hypotheses

- H2-1. PhantomPen will be faster for stroke length of less than 16 mm with the performance benefit diminishing for larger distances.
- H2-2. PhantomPen will be faster than the normal stylus at target angles of 0° and -45° in which occlusion is expected to occur often.

Design

A repeated measures within-participant design was used. The independent variables were pen type (normal stylus, PhantomPen), target distance (8, 16, 24 mm), target angle (-90, -45, 0, 45, 90° CCW), and target size (2, 3, 4 mm radius). All independent variables were presented in random order. In total, the experiment consisted of:

2 pen types × 3 target distances × 5 target angles × 3 target sizes × 2 blocks = 180 line trials per participant.

Results

Movement time was the main dependent variable, and was defined as the time taken in touching two successive targets. Paired-samples t-test showed significant main effect on movement time for pen type ($t = 6.962$, $df = 1080$, $p < .05$) (Figure 12). PhantomPen was 17 % faster (138 ms) on average, with 829 ms for the normal stylus and 691 ms for PhantomPen. A noticeable movement time difference was found in the extreme focus region of 8 mm away, the region in which PhantomPen was expected to excel by eliminating occlusion. PhantomPen was 26 % faster (176 ms) ($t = 7.948$, $df = 360$, $p < .05$) in this region, with 669 ms for the normal stylus and 493 ms for PhantomPen (Figure 13).

Repeated measures analysis of variance showed significant main effects for target distance ($F_{2,574} = 625.506$, $p < .05$) (Figure 13), target angle ($F_{4,860} = 35.246$, $p < .05$), and target size ($F_{2,718} = 40.638$, $p < .05$) on movement time. There was no significant interaction effect for pen type × target distance ($p = .27$). We thus favorably reject H2-1, because PhantomPen was faster for all target distances.

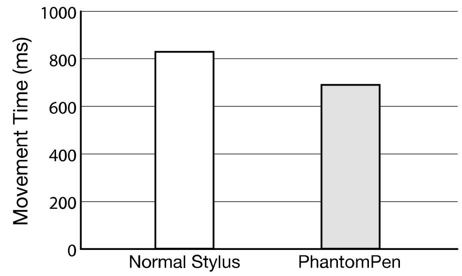

Figure 12: Movement time (focus region drawing).

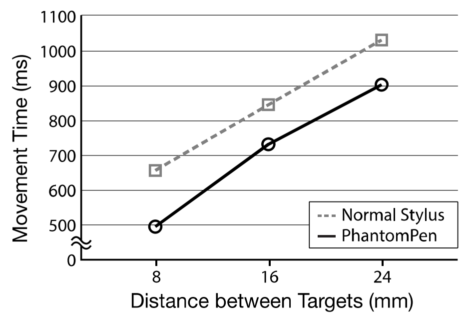

Figure 13: Movement time by target distance (focus region drawing).

There was an interaction effect for pen type × target angle ($F_{4,860} = 51.524$, $p < .05$) (Figure 14). Contrary to our speculation that the performance of 0° and -45° would be impaired due to occlusion, PhantomPen was faster than the normal stylus only at 0° with the normal stylus performing significantly better at -45°. We therefore reject H2-2.

The normal stylus showed the lowest performance at 45° (564 ms difference with PhantomPen), whereas PhantomPen performed the highest at 45°. In the range between 0° and 45° (shaded in Figure 14), which represents a typical range of basic line drawing used in Experiment 1, the average movement time for PhantomPen was 39 % (400 ms) shorter, with the normal stylus at 1013 ms and PhantomPen at 614 ms.

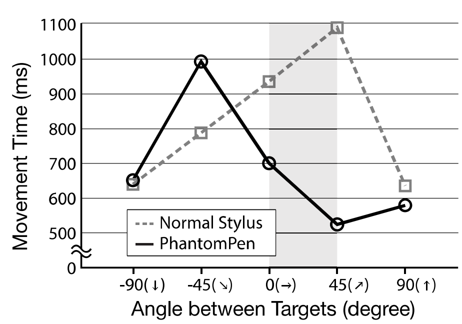

Figure 14: Movement time by target angle (focus region drawing).

Discussion

The overall result of Experiment 2 (Figure 12) shows that pen occlusion is indeed a problem when drawing details in the focus region, and that PhantomPen can increase the drawing performance by solving it. We observed that the participants behaved differently in a number of ways when they used PhantomPen and the normal stylus, and interpreted different performance characteristics for different target distances and angles accordingly.

In terms of target distance (Figure 13), we speculated that hand occlusion would be the dominant effect at the target distance of 24 mm and therefore the movement times for the two styli to be identical. However, PhantomPen was faster at this distance, as well as at 8 mm and 16 mm. We interpreted the result in the following ways. First, when using PhantomPen, out of all the targets, only the target 24 mm away in the -45° was entirely occluded, whereas many targets at different angles and distances were occluded for the normal stylus depending on the hand posture. Because of this, when the participants could not see a target while using PhantomPen, they could immediately guess that it was in the -45° direction, whereas with the normal stylus they had to search for it, increasing movement time. Second, when PhantomPen leant towards the screen (increasing the zenith angle) the non-occluded area underneath the stylus increased, increasing visibility. In evidence, we frequently observed participants leaning PhantomPen, possibly in attempts to avoid occlusion of a wider region.

In addition, the performance characteristics in relation to the target angle (Figure 14) seem to be affected by how the participants hold the styli. When using the normal stylus, the participants swung the stylus back and forth in order to search for the target. In addition, when they found the target, they frequently drew the stroke with their stylus leaning towards it. These behaviors seemed to have a detrimental effect for the target angle of 45°; when they found the target and started to draw, the pen leant toward the target and blocked the view, increasing the movement time (Figure 14). This phenomenon of occlusion in the first quadrant region rather than the fourth quadrant region, has been reported in other studies [27, 29].

On the other hand, we observed that the participants held PhantomPen relatively still at about -45°, possibly because of the stylus form and grip. In addition, there were less searching movements, as PhantomPen had provided a better view of the focus area. Moreover, the participants performed relatively slow translational motion with their elbow and shoulder (Figure 15b) to draw their strokes, rather than relatively fast rotational motion with their wrist and fingers (Figure 15a) as they did with the normal stylus. Translation can be especially slow in the -45° direction, accounting for the peak at -45° for PhantomPen. However, in drawing education [3], using shoulder and elbow rather than wrist and fingers are recommended for better line quality. In this regard, the grip style of PhantomPen and the motion it affords are appropriate.

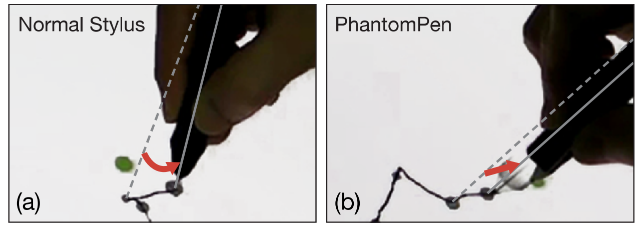

Figure 15: Different pen movement behaviors when drawing a short line to -45° angle: rotational motion for the normal stylus (a), and translational motion for PhantomPen (b).

Experiment 3: Face Drawing

The third experiment was designed to find out the error reducing characteristic of PhantomPen. Users frequently change pen attributes in drawing, but since the normal stylus does not display much information about pen attributes in the focus region, users are prone to err. Visualization might reduce mistakes when users draw without knowing that they have selected the wrong pen attribute. In this experiment the participants were given a task to draw, without being told that mistakes they make were being counted.

Hypothesis

- H3-1. Mistakes of drawing without knowing that the incorrect pen attribute has been selected will be fewer for PhantomPen.

Task

The task was to draw the right sides of faces so that they would be symmetrical to the provided left sides of faces. Participants were asked to draw 10 faces consisting of 6 lines using the normal stylus and PhantomPen. On the task screen, palette panels with 6 colors (pink, orange, green, blue, purple, black), 3 stroke weights (3, 5, 8 pixels), and two opacity (20, 100 %) options were provided (Figure 16). In addition, 'undo' and 'proceed' buttons were provided, so that the participants could freely correct their mistakes and choose to proceed to the next face.

Figure 16: Face drawing task.

Design

The experiment consisted of:

2 pen types × 10 faces × 6 strokes
= 120 stroke attributes per participant.

Results

We considered only the case of drawing a stroke with the incorrect pen attribute as a countable failure. We did not count it as a failure when the participants undid and then drew again with the same pen attribute to adjust the stroke shape.

Chi-square analysis showed a significant difference on error rate between the two pens ($\chi^2 = 9.755$, df = 1, $p < .05$) (Figure 17). Of the total of 720 strokes for each pen there were 87 failures for the normal stylus, and 52 failures for PhantomPen. The participants made 40 % less mistakes with PhantomPen, thus confirming H3-1.

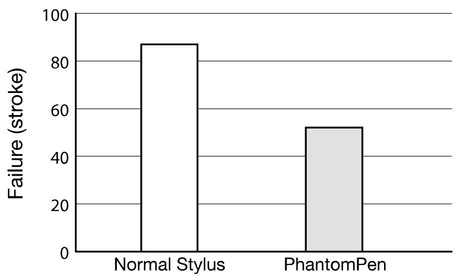

Figure 17: Number of failures (face drawing).

Discussion

We expected PhantomPen to reduce the number of mistakes in selecting the right pen attributes, because it visualizes pen information holistically and intuitively. During the experiment, the participants indeed retracted and reselected the correct pen attribute often by recognizing the incorrect selection through the virtual pen head, before drawing a stroke. PhantomPen thus seemed to lighten the user's workload of checking the selected pen attributes by providing useful visualization at the focus region.

In addition, we had conducted an additional experiment with the same face drawing task as the third experiment to test the information deliverability of two additional virtual pen head designs. We analyzed which elements of the virtual pen head were effective in delivering pen information.

Virtual pen head design 1 (Figure 18a) renders a pen lead, three ellipses, and a cross-hair cursor in 2D. Design 2 (Figure 18b) renders an opaque 3D cap. Design 3 (Figure 18c) renders a pen tip, pen lead, semi-transparent pen cap, and pen barrel in 3D, and is the optimized design used for our formal experiments.

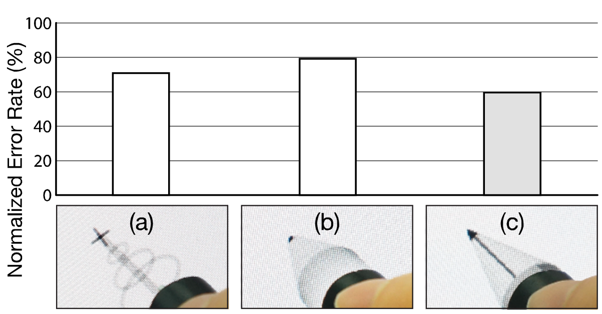

Figure 18: Normalized error rate for three virtual pen head designs: design 1 (a), design 2 (b), and design 3 (c).

We found that design of the virtual pen head matters in reducing errors. With the error rate of the normal stylus normalized as 100 %, the error rate of design 1 was 70 %, design 2 79 %, and design 3 60 %. Design 2 delivered pen information only through the pen tip, and sometimes the participants did not even notice the change of the pen tip. The error rates of design 1 and 3 were relatively low, meaning that delivering pen information such as stroke weight and color through a visible pen lead reduced errors. The error rate of design 3 was lower than that of design 1, indicating that rendering a realistic 3D virtual pen head with appropriate silhouette lines is more effective than a simple pen lead and a cross-hair cursor.

USER FEEDBACK

Before and after the experiments, informal interviews were conducted about the experiments and PhantomPen in general.

First, the participants highly appreciated the possibility of a virtual pen displaying pen attributes, and also commented that they would anticipate for a virtual pen simulating a wider variety of drawing tools. Also, one participant suggested, and we agree, that the virtual pen head can be made to look more realistic by casting a shadow on the canvas [10].

Second, even though our prototype did not consider users' eye motion, when we asked about the mismatch between the pen barrel and the virtual pen head, they did not report any complaint. Thus, we interpreted that our approximation held: the eyes and the head do not move much when drawing with a digital tablet and stylus.

Third, before the experiments some participants doubted the usability of PhantomPen saying that the virtual pen tip not being displayed at the point of physical contact might distract from fluent drawing. However after the experiments, they were satisfied overall, with no participant reporting the tactile difference as a problem.

CONCLUSION AND FUTURE WORK

In this paper, we began by identifying pen occlusion, visual parallax, and hidden pen information as problems of direct pen input. We held the physical form of the pen head liable for these problems, and introduced PhantomPen, a solution involving a drastic change of the form of the stylus.

PhantomPen removes the physical pen head and replaces it with a virtual pen head to secure visibility in the focus region. The virtual pen head is rendered connected to the pen barrel on the display plane to remove visual parallax. In addition, the virtual pen head provides pen information to the user in a more holistic and intuitive way.

We analyzed professionals' drawing behaviors and observed digital drawing classes to design and conduct three experiments that simulate natural drawing contexts (basic line drawing, focus region drawing, and face drawing). The results of the first experiment showed that PhantomPen is as usable as a conventional stylus in non-focus regions. The second and third experiments showed that PhantomPen enhances speed and accuracy by resolving pen occlusion in focus regions, overcoming the limits of the current digital drawing.

In the near future, we intend to explore visualization of the virtual pen head accounting for the user's eye position, design various types of virtual drawing tools (such as a marker or brush), and conduct long-term user studies regarding pen ergonomics.

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