

Visual, Tangible, and Touch-Screen: Comparison of Platforms for Displaying Simple Graphics

ABSTRACT

Four different platforms were compared in a task of exploring an angular stimulus and reporting its value. The angle was explored visually, tangibly as raised fine-grit sandpaper, or on a touch-screen with a frictional or vibratory signal. All platforms produced highly accurate angle judgments. Differences were found, however, in exploration time, with vision fastest as expected, followed by tangible, vibration, and friction. Relative to the tangible display, touch-screens evidenced greater noise in the perceived angular value, with a particular disadvantage for friction. The latter must be interpreted in the context of a first-generation display and a rapidly advancing technology. On the whole, the results point both to promise and barriers in the use of refreshable graphical displays for blind users.

KEY WORDS: Haptic I/O, Human information processing, Information Search and Retrieval, Performance evaluation

1. INTRODUCTION

The goal of conveying graphical media to blind individuals is centuries-old (Perkins Museum, 2013). A common solution has been to convert 2D displays like graphs and pictures to tangible versions, an effort that has been recently aided by new methods of duplication and printing such as thermoform and graphic embossers ([McCallum, 2005](#); Jehoel et al. 2005). The importance of this effort is considerable, as access to graphical content is thought to be critical for blind students' development of quantitative skills ([Walker & Mauney, 2010](#)).

While they have considerable utility, traditional tangible graphic displays add expense and bulk to the final media product, whatever the production method. Durability is also a common concern, and the displays lack dynamic capability. Refreshable media based on the computer are an attractive alternative, as a single device can be used to store and display essentially limitless amounts of graphical data in dynamic or static form, as well as having general use. The dynamic nature of these graphic displays is truly what sets them apart from traditional static techniques. The conventional computer screen, however, does not suffice for those lacking vision, introducing the need for a display technology of graphical information that blind people will find accessible. A common approach is to ask the user to explore an on-screen graphic by keyboard or mouse, either freely or with audio or force guidance, then provide confirmatory feedback when an informative feature is encountered ([Ferres et al., 2010](#); [Walker & Mauney, 2010](#); [Yu & Brewster, 2002a, b](#)). Thus, for example, a shape might be defined by a vibratory signal that occurs whenever the user's exploratory tool enters a spatial location assigned to its edge.

With the advent of touch-sensitive screens, intermediaries such as a stylus or mouse can be jettisoned in favor of exploration with the bare finger. Using this approach with auditory labels and vibratory cues, Poppinga and colleagues (2011) conveyed a map on a smartphone screen, and Giudice and associates (2012) found similar graph learning and shape recognition performance compared to traditional embossed tactile stimuli. Others have used a touch-screen display with external vibrators to portray simple graphics ([Goncu & Marriott, 2011](#); [Petit et al., 2008](#)). Another approach is the TeslaTouch, an electrostatic device which guides the user by differential friction ([Xu et al., 2011](#)). Evaluations of these approaches have not been extensive but suggest that information encoding is relatively slow, even for simple graphics. Klatzky and associates (2014), for example, evaluated a touch-screen display with auditory and vibratory

feedback (initially developed by [Giudice et al., 2012](#)) for conveying two-line graphics and zig-zag patterns; the average exploratory interval was on the order of 4 min. [Xu et al. \(2011\)](#) asked subjects to identify shapes as circles, squares, and triangles and reported an average of < 2 min on each image with accuracy of 56%.

The purpose of the current research was to conduct a systematic comparison of methods of displaying perhaps the most fundamental stimulus for graphical purposes, an angled line. This simple task can be rendered on virtually any graphical platform. Our principal interest, of course, was in the efficacy of refreshable displays. In this relatively small-scale study, we evaluated two novel and evolving technologies that are currently under development.

The studies here compared performance in the task of exploring and identifying the magnitude of an angle across vision, a real tangible surface (fine-grit sandpaper), a friction-based tablet display called the TPad Fire, and a conventional tablet computer with resident vibration. The vision condition provided a baseline for the performance of an angle-judgment task by sighted participants. We chose the angle-judgment task not only because of its generality and potential for rendering on all platforms, but because it has been extensively described in the psychophysical literature with both vision and touch (e.g., [Appelle, 1972](#); [Baud-Bovy & Gentaz, 2012](#); [Holden & Hampson, 2014](#)) and provides a metric measure of accuracy and precision of perceptual outcome (inverse noise), as well as exploration time.

Vision is expected to lead to highly accurate and rapid perception, possibly with biases toward category boundaries ([Holden & Hampson, 2014](#)). Among touch displays, tangible stimuli are predicted to be superior, because the array information they provide across the fingertip can be used to guide the user along a graphical element without “getting lost” ([Rosenbaum, Dawson, & Challis, 2006](#)). In contrast, touch-screen platforms generally activate the entire display when a

stimulus element is contacted, so that the whole finger is stimulated. This can particularly be problematic at a point where the stimulus reaches a convex or concave point, because directional cues are not available. Finally, differences between friction and vibration may occur because of variations in signal strength.

The above hypotheses pertain to the performance of sighted people. One can expect that blind people will perform differently than sighted people in tasks that depend on the processing of haptic stimuli. However, it is difficult to anticipate the performance of blind people in this task, given the demands it imposes at sensory and cognitive levels. Blind people may have an advantage at the sensory level, as they have been found to have better spatial acuity than sighted, and Braille readers in particular retain acuity over the life-span (Legge, et al., 2008). On the other hand, blind individuals are less experienced in interpreting graphical information and representing spatial layout through mental imagery (Lederman et al., 1990). Given the uncertainty of how these and other factors associated with vision loss would affect performance, we acknowledge the need to further evaluate the ability to convey graphical information to blind users by using a touch-screen with a frictional or vibratory signal.

2. EXPERIMENT 1

This experiment evaluated the friction, visual, and tangible displays using a within-subject design to allow direct comparison across all platforms.

2.1. Method

Participants. Six males and three females (age 20-40 yr) volunteered to participate in the experiment. All procedures followed an approved institutional protocol.

Apparatus. The Friction and Visual conditions were presented on a tablet computer, a first-generation (2011) TPad Fire (Mullenbach, Shultz, & Piper, 2013), which integrates variable

friction technology from a TPad ([Marchuk, Colgate, & Peshkin, 2010](#); [Winfield, Glassmire, Colgate, & Peshkin, 2007](#)) into a Kindle Fire™. The tablet has a 7.0 in touch-screen, which was used conventionally for visual presentation. The user's finger position was sampled at approximately 60 Hz and used to calculate the friction output according to a programmed pattern on the screen. The friction coefficient is designed to be electronically varied over an approximate range of $0.1 < \mu < 0.9$, although operative levels may decrease with use. The application for the TPad Fire was written in the Android (Java) programming language and operated as a standard Android application.

Stimuli. Five angle stimuli were generated over a range from near horizontal right to near horizontal left, comprising 25°, 70°, 90°, 125°, and 155°. Each leg was .5 in wide and 2.5 in long. This edge width was selected as it is smaller than the average width of the index finger ([Ahlstrom & Poston, 2010](#)) while providing sufficient feedback. In the Friction and Visual conditions the angle images were generated using Inkscape (0.48), a scalable vector graphic (SVG) editor, with a textured pattern labeled "Sand" and presented on the TPad Fire. The angles in the Tangible condition were constructed from 400-grit extra fine sand paper made by 3M and were imbedded into a cardboard sheet the same size as the TPad Fire surface. The vertex was placed .5 in from the bottom and 3 in from the left border of the display.

Procedure and design. The experiment used a within-subject, counterbalanced design. The participants completed a series of 30 trials of angle estimations, 10 trials in each condition (Friction, Tangible, Vision) with 2 repetitions for each angle, in random order. Each non-visual trial began with the experimenter placing the participant's index finger on the vertex, followed by self-paced exploration of the angle without time limit. Participants explored the display using a single finger at a time. When ready, the participant reported the angle size relative to a visual

array, in which 8 numbered rays were distributed from 0° to 180° at equal (22.5°) intervals. The response was given by the number of the ray closest to the perceived angle plus an additional fraction if desired (e.g., 1-1/2 to indicate 33°). In the TPad and sandpaper conditions, the participants were blindfolded and wore sound-attenuating earphones throughout the exploration period. They lifted the blindfold at the point of responding. In the visual condition, the stimuli were placed in front of the blindfolded participants, and only then they were asked to remove the eye cover.

The order of the Friction and Tangible conditions was counterbalanced, but Vision was always presented last to avoid bias from knowledge of the response population. Four training trials preceded each condition, with the option of more training if the participant wished. Participants' hands' were videotaped in a subset of trials from a camera position above and to the side of the tablet.

2.2. Results

The measured variables were exploration time in seconds and the angular response, which was converted to measures of signed error and variability.

---Insert Figure 1---

Perceived angle. Fig. 1 shows the reported angle versus the actual angle, averaged over the two repetitions for individual subjects, by condition. Also included are the results from a vibratory display used in Experiment 2. It is apparent that the responses are tracking the angles on average, but with considerably different levels of variability across display modes, as discussed further below.

---Insert Figure 2---

Statistical analysis first examined the signed error, which indicates any systematic deviation from the correct response, shown in Figure 2. A common pattern in angle-judgment tasks is that error transitions from over-estimation bias for small angles to under-estimation at larger ones (e.g., [Baud-Bovy & Gentaz, 2012](#); [Holden & Hampson, 2014](#)), with relatively little error at cardinal values. A trend of this type is seen here only for the friction condition, and an ANOVA on angle and display found that no effects were significant. The average signed errors were quite small for all displays: -5.0° (s.e.m. 3.6°) and -5.5° (s.e.m. 3.0°) for Friction and Tangible, and -0.4° for Vision (s.e.m. 0.5). The Vibratory display of Experiment 2 had mean signed error of 0.3° (s.e.m. 1.4°).

---Insert Figure 3---

In contrast to systematic bias, noise in the participant's internal representation of the perceived angle can be measured by the absolute difference between the two responses made for each angle, shown in Figure 3. Noise in this sense is essentially inversely related to repeatability. (This measure of noise, which is proportional to the standard deviation of the two measures, is preferable to absolute error, which is contaminated by any systematic bias in the responses.) The ANOVA on the absolute difference with factors display and angle showed only an effect of display, $F(2, 16) = 24.24$, $p < .001$, with all three means differing significantly (by t-test on angle-averaged data, $p < .01$ for comparisons with Friction, $p = .03$ for Tangible vs. Vision). This reflects the relatively greater precision of vision vs. relatively greater noise in the friction-based display.

Whereas the absolute difference between two response repetitions is a within-subject measure of noise, another measure is the variability of responses across subjects, as can be seen in Figure 1. The sample s.d. across participants' average responses was 9.1° for Tangible, 10.7° for Friction,

and 1.5° for Visual. F-tests found all variances to be significantly different except for Tangible vs. Friction.

---Insert Figure 4---

Exploration Time. Fig. 4 shows the average exploration time by angle and display. An ANOVA found only a significant effect of display, $F(2, 16) = 24.89, p < .001$. Like the noise measure in Fig. 3, the temporal data reflect an advantage for the Visual condition and disadvantage for Friction. All three means differed significantly (by t-test on angle-averaged data, $ps < .01$).

---Insert Figure 5---

To illustrate exploration activity, Fig. 5 shows approximately 60 sec of exploration by one participant with the Friction display, obtained from frame-by-frame tracking of the video record (Tracker, 2014). While most of the period is spent in contact with the stimulus, there are also excursions to other areas that seem to reflect a deliberate strategy, as well as apparent loss of contact near the stimulus boundaries.

2.3. Discussion

Experiment 1's results demonstrated the differences and similarities between friction-based touch-pad display, tangible stimulus and vision. As expected for sighted participants, vision is a "gold standard" here, with very rapid encoding times as well as high accuracy. The friction display, however, leads to relatively long encoding times and greater variability, suggesting an internal representation of spatial layout that is intrinsically more noisy. This effect might stem from differences in intrinsic sensory processing (reviewed in [Klatzky et. al., 2014](#)), rendering lag, or the nature of exploration.

A sample exploration pattern tends to confirm this notion, in that even exploration that is near the signaled pattern is complex and spatially dispersed. Further research that systematically evaluates the time course and geometry of exploration patterns of friction-based displays could be very useful.

For purposes of further evaluation of flat-screen capability, Experiment 2 used a tablet display with vibration as the signal for contact with the stimulus. The use of vibration has the advantage of being based on commercially available technology.

3. EXPERIMENT 2

In this experiment we compared the data obtained in the Friction condition of Experiment 1 with data from the same task using a vibratory signal from the resident motor in a tablet. Comparisons should be treated with some caution, as the data sets were collected separately and hence constitute a between-subject, between-location design, but any observed differences may reflect the greater intensity of the vibratory signal in comparison to the friction in the TPad.

3.1. Method

Participants. Four males and four females (age 20-33 yr) at the University of Maine participated in a Vibratory condition. All procedures followed an approved institutional protocol.

Apparatus. The condition was conducted on a Samsung Galaxy Tab 7.0 Plus tablet with a 7-inch touch screen. The vibrotactile lines were rendered with a constant vibration, based on Immersion's Universal Haptic Layer effect "Engine_100," which uses an infinite repeating loop at 250 Hz with 100% power. The inter-section between the two lines was indicated by a pulsing vibration, based on the UHL effect "Weapon_1," a wide-band 0.01 s pulse with a 50% duty cycle and a 0.02 sec period.

Stimuli, Procedure and design. Except for the mode of interaction (i.e., vibratory), the stimuli,

procedure and design of this experiment were identical to those of the Friction condition of Experiment 1.

3.2. Results

The data analysis focuses on a comparison between data from the Friction condition of Experiment 1 and the Vibratory data. Again it considers perceived angle accuracy and variability, as well as exploration time.

Perceived Angle. The reported angles are shown by subject in Figure 1. To evaluate bias in the responses, measures of signed error (see Figure 2) were compared for the two display modes. ANOVAs conducted with angle as a within-subject variable and display as between-subject showed no significant effects, confirming that the two displays confer equally accurate encoding of angle. As noted above, signed errors were small.

Recall that internal noise can be measured by the absolute difference between the responses made for the two repetitions of each angle. The ANOVA on this measure (see Figure 3) showed no angle effect but did reveal a significant effect of display, $F(1,15) = 72.82$, $p < .001$, $\eta^2 = .51$, indicating greater noise with the Friction display. The difference in noise is also evident in the relative between-participant spread for the devices in Figure 1. The sample s.d. across participants' average responses for Vibratory was 4.1° , which differed significantly from Friction (and all other conditions, s.d.s reported above) by F-test.

Exploration Time. An ANOVA on exploration time, shown in Figure 4, with factors of angle and display showed no effect of display, $p > .25$. Only the effect of angle reached significance, $F(4, 60) = 3.00$, $p = .025$, reflecting non-monotonic variability across the angles.

4. GENERAL DISCUSSION

As was noted initially, this research was intended to compare refreshable and tangible graphical displays in a basic graphical task, determining the magnitude of an angle. The data are encouraging in that they show quite accurate encoding of angle using all platforms described here. The displays do differ, however, in two respects: the exploration period needed to extract the metric angle information, and in measures of the noise or imprecision in the resulting perceptual outcome. No touch display approaches vision, but tangible displays appear to have an advantage over smooth glass surfaces. This is not surprising, because the edges of such displays provide array information across the finger, whereas the touch-screen displays studied here stimulate the entire finger when it contacts the stimulus.

Comparing the two touch-screen displays, it is noteworthy that a vibration signal did not lead to faster encoding than the present friction-based display. It does appear to increase the certainty in the internal representation of the angle, as measured by the within-subject difference between two responses to the same angle and the between-subject variability.

Caveats are needed in making such comparisons: Like any technology, friction displays are a moving target. The TPad Fire tested here was a first-generation model. Subsequent developments including optimizing the strength of the friction reduction effect, decreasing lag between the TPad micro-controllers and the Android host, and improvement of position resolution (Colgate, 2014). These changes will no doubt increase perceptual certainty and may facilitate encoding as well. It is also important to consider that the present participants were untrained; experience with the technology should streamline exploration and may aid interpretation via top-down processing.

Thus, while the findings of this study are a useful first step toward evaluating tactile displays, they have clear limitations. One is the ability to extrapolate the findings of this study to the blind population. Research demonstrating cortical plasticity under even brief periods of visual deprivation (Kaufmann et al., 2002; [Facchini & Aglioti, 2003](#)) clearly indicates that tests on blindfolded, sighted users of a device are not sufficient to characterize the performance of blind users. As noted above, blind and sighted differ with respect to both sensory limited and cognitively limited aspects of information processing. Moreover, performance in tactile spatial tasks by blind persons is likely to be affected by factors such as age of onset of blindness and experience with other tactile tasks such as Braille reading. Therefore, there is a clear need to conduct additional studies that evaluate the performance of blind users of technologies like the present displays.

Also as noted previously, an important feature of the study is that the sighted participants were unpracticed with the tangible, friction and vibration conditions. Learning, especially with respect to the efficiency of exploration, could have a significant impact on performance. The current study highlights the need for better classification of exploratory patterns that would help us to understand how, through experience, participants refine their exploration and how different 2D representations might promote different approaches to search.

Refreshable displays offer numerous advantages over one-of-a-kind tangible renderings (see OModhrain et al., 2015, for a recent review). Beyond being capable of updating, they are embedded in multi-purpose devices, potentially dynamic and multimodal, and easy to author. These benefits are what make continued development of these displays so promising for many applications and educational, vocational, and social contexts. The results of the current study lay

the foundations for larger scale, more comprehensive research on the next generation of refreshable tactile displays.

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