Composite Line Designs and Accuracy Measurements for Tactile Line Tracing on Touch Surfaces

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Eyes-free operation of mobile devices is critical in situations where the visual channel is either unavailable or attention is needed elsewhere. In such situations, vibrotactile tracing along paths or lines can help users to navigate and identify symbols and shapes without visual information. In this paper, we investigated the applicability of different metrics that can measure the effectiveness of vibrotactile line tracing methods on touch screens. In two user studies, we compare trace Length Error, Area Error, and Fréchet Distance as alternatives to commonly used trace Time. Our results show that a lower Fréchet distance is correlated better with the comprehension of a line trace. Furthermore, we show that distinct feedback methods perform differently with varying geometric features in lines and propose a segmented line design for tactile line tracing studies. We believe the results will inform future designs of eyes-free operation techniques and studies.

CCS Concepts: • **Human-centered computing** → **HCI design and evaluation methods**; *Haptic devices.*

Additional Key Words and Phrases: Tactile Line Tracing; Haptics; Metrics; Touch Screens

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1 INTRODUCTION

Eyes-free operation of user interfaces is critical in a variety of applications when visual attention is needed elsewhere or unavailable altogether [9, 20, 23–25]. For instance, non-visual or multimodal interfaces are often recommended in attention-intensive applications such as automotive user interfaces [9], navigation [17, 25] and even aeroplane cockpits [24]. Specifically, Zhao et. al. identifies *competition for visual attention*, *absence of a visual display*, *user disability*, *inconvenience* or *reduction of battery life* as five distinct factors where visual feedback is undesirable [34]. Arguably, the most important application of eyes-free techniques lies within the development of accessible interfaces to support people with visual impairments [11, 13, 23].

Multimodal interfaces, especially auditory [4], tangible [2, 6] and haptic [1, 13, 17, 21] are often used to supplement or replace the visual channel in eyes-free operations. A majority of interfaces

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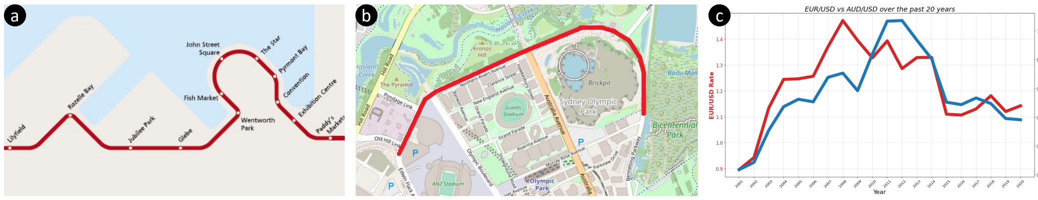

Fig. 1. Example application scenarios with lines consisting of acute, right and obtuse angles and curved segments. a) A light rail transit map[1]; b) A path in a digital map[2]; c) A plot of two forex exchange rates.

we use today are made of spatially arranged graphical widgets. Research shows that tactile feedback is the more popular and the preferred non-visual medium to represent such spatial information [13].

When tactile interfaces are used to explore graphics, *line tracing* emerges as a fundamental strategy to discover visual information; for instance, tracing along paths or the edges of shapes as the means to understand the shape [13, 20, 28]. Furthermore, there are many applications like digital maps or data plots where information is not encoded in shapes, but lines themselves. Figure 1 shows three example scenarios where information is in the form of complex lines consisting of acute, right and obtuse angles and curved segments. Despite this importance, *tactile line tracing* is under-explored with a few recent exceptions showing there are unique challenges and important factors involved in tactile line tracing compared to that of shapes (e.g. angular and linear separation, minimum line widths, etc.) [23, 33]. Even then, studies often do not account for different features. For instance, curved segments, a feature seen in many line-based maps/plots (Figure 1), were notably missing in recent studies[23, 33].

More importantly, commonly used accuracy metrics such as correctly identifying a shape, do not translate well to lines since lines can be a complex assembly of many segmented features (e.g. horizontal, vertical, curved, different angles, etc). Studies have instead used approaches such as asking participants to re-draw the traced line for later analysis [20] or comparing lines through two tracing tasks [33] as successful metrics. However, these methods need time-consuming manual analysis or participants doing extra tasks, which may lead to extended study times and user fatigue.

In this paper, through two user studies, we investigate three alternative computable accuracy metrics for evaluating eyes-free vibrotactile line tracing performance on touch screens. These proposed measures include Line *Length Error* (LE), *Area Error* (AE), and *Fréchet Distance* (FD). Furthermore, we developed a new *segment-based line design* to facilitate the tactile line tracing tasks in our studies and a custom-developed *vibrotactile feedback system*. We tested the performance measures and line designs against four different feedback methods in a user study with 12 participants. This was followed up in an online study with 90 participants where we collected subjective feedback on the line tracing performance collected in our first user study. This feedback was used for the validation of the accuracy metrics. Our main findings from the studies are:

- *Fréchet distance* is a good alternative accuracy measure for line tracing tasks and shows a higher correlation to the perceptibility of a traced line compared to the commonly used measure, *tracing time*.
- Different vibrotactile feedback methods result in significantly different line tracing performances on various line geometries suggesting a *segmented line design* with different geometries is better suited for vibrotactile line tracing tasks.

[1]https://transportnsw.info/sydney-lightrail-network-map ©Transport for NSW (Accessed on 2021-07-05)
[2]https://www.openstreetmap.org ©OpenStreetMap contributors (Accessed on 2021-07-05)

2 RELATED WORK

2.1 Shape Identification and Line Tracing

Non-visual shape identification studies often use basic geometric shapes such as squares, triangles, pentagons, and circles [13, 28]. Participants are asked to trace these shapes utilising the feedback provided without the use of sight. In Tennison and Gorlewicz's work on eyes-free shape identification, lines/edges of each shape were provided with similar vibrotactile feedback, whilst corners/vertices were provided with a secondary but stronger sensation [28]. To determine accuracy, participants were asked to verbally identify the shape they thought they were tracing. Tennison and Gorlewicz identified that individuals who traced the shapes with "slow and deliberate movement" were more accurate compared to participants who utilised "quick and sweeping movement" [28]. In Goncu and Marriott's work in GraVVITAS, they conducted similar shape identification tasks, however, feedback was also provided when users were touching inside the shape and did not report specific accuracy rates [13].

In contrast, line tracing tasks use smaller lines connected to form one continuous and larger line, e.g. zig zag [20, 29, 33], or be just one continuous line, e.g. sine wave [27]. Klatzky et. al. provided vibrotactile feedback of 250 Hz when the user was on the line, and a secondary pulsing vibrotactile sensation when the user was instead touching either an endpoint or vertex on the line [20]. Additionally, Taibbi et. al. presents another interesting method for line tracing on touch surfaces in their application AudioFunctions [27]; a program for displaying mathematical functions on tablets utilising auditory feedback. Variable contextual feedback is provided based upon how far the user is from the line being traced. Taibbi et. al. define this as "bi-dimensional interactive exploration" in which a high-pitched sound is provided when a user is touching the line, but when the user moves off the line whilst tracing, the pitch diminishes [27]. This "bi-dimensional" method, which may also increase the accuracy of line tracing, provides increasingly loud warnings to users as they begin to deviate away from the line. In VibHand, Zhao et. al. introduced a feedback method that directed users towards a certain direction during line tracing. To reduce the tracing error, Zhao et. al. used four vibrators on the back of participants' hands to direct them to trace a given line accurately [33]. The four feedback mechanisms used in our study was inspired by this literature.

2.2 Vibrotactile Feedback for Line Tracing

The characteristics of vibrotactile pulse feedback are identified as the frequency, amplitude and duration of a vibration [3]. Modifying these feedback attributes changes the vibrotactile sensations a user perceives and can be utilised to convey information. For instance, increasing the amplitude of the vibrotactile feedback increases the intensity, whilst decreasing the duration creates sensations similar to a quick tap or jab to users [3]. However, for users to robustly discriminate between distinct vibrotactile stimuli in practical applications, the amplitude or frequency of each different sensation must vary by at least 20% or 30% [5].

In line tracing tasks, just as important as how individuals perceive vibrotactile feedback is how graphical elements such as lines should be best rendered on touch screens for vibrotactile feedback. Palani et. al. present design guidelines for rendering accurate and meaningful on-screen graphical elements [23]. One of the key guidelines for line tracing and discrimination tasks is that lines should be rendered using a minimum of 4 mm thickness. Other guidelines such as line spacing, angular separation, and individual line orientation were also defined [23]. These design rules are presented in regard to lines could also help inform the design of shapes in shape identification tasks. We adhered to these guidelines in our line designs.

2.3 Accuracy Measures

In tactile shape and line tracing tasks, being able to measure participants' understanding of the shape or line is essential. In shape tracing, asking participants to identify the traced shape is a good metric of accuracy[28]; however, with lines, this is not possible. While tracing time (or speed) is a commonly used measure to compare between participants, it may not directly reflect the tracing accuracy because sections of the line can be skipped in tracing, leading to shorter times. Researchers have used creative alternatives to overcome this issue. For example, Klatzky et. al. asked participants to re-draw the traced line immediately after tracing and analysed it for accuracy later using a manual annotation mechanism [20]. While re-draw analysis is a very good measure, analysing redraws is a cumbersome task without a generalised or computable method. Another approach, Delayed-Matching-to-Sample (DMTS) was introduced by Zhao et. al. where participants were asked to trace two lines instead of one and compare if they are the same or not as an accuracy metric [33]. However, previous research shows that tactile line-tracing is a time consuming and tedious task, where, depending on the line, each trial could take approximately 40 seconds on average [23] to over 130 seconds [20]. Consequently, tracing two different lines can take double the completion time of a study, which increases the strain and physical load on study participants, and lead to increased fatigue. Therefore, a computable accuracy metric without over-loading the participants can be significantly beneficial in line-tracing tasks.

Previous research has shown that there are some computable methods to calculate error metrics. For instance, calculating the deviation between the original line and the traced line by pixel-wise distance has been used as an error metric [31, 32]. This is susceptible to tracing speed and erroneous choosing of samples from a trace can lead to error and biases. Yoo et. al. suggests another way to calculate accuracy in traces [30] called "line-length error". This method measures the total deviation of a participant's traced line to the original line in its length, with larger errors indicating less accurate line traces. We used this as one of the computable accuracy measures in our study.

Interestingly, in other research areas such as materials engineering research, there has been analysis into how to better quantify the difference between two curves or lines [18]. These alternative methods have not been explored in other line tracing studies nor in the HCI context. Jekel et. al. showed metrics in addition to "line-length error" such as *the area between two curves* and *Fréchet distance* can be used to gauge line similarity/accuracy [18]. Our accuracy metrics for line tracing tasks are inspired by the findings made by Jekel et. al.

3 SEGMENT BASED LINE DESIGN

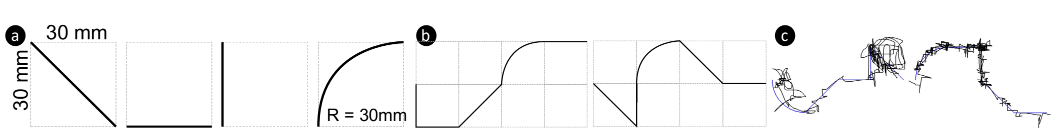

Fig. 2. Pilot study line designs. a) Line segment types. Each line segment fits within a 30 mm by 30 mm square. Diagonal, horizontal, vertical, arc (Left to Right); b) Example of composite Lines used in a pilot study. These lines are four segments wide and two segments high, (120mm by 60mm); c) Example line traces from the pilot.

In tactile aided shape exploration studies, it is common to select a set of basic geometrical 2D shapes such as squares, circles, triangles as the visual components [20, 28, 29]. Having this shared design space allows the results to be compared against previous and more importantly, in future studies. However, when it comes to lines, it is not easy to define a set of simple designs, and different

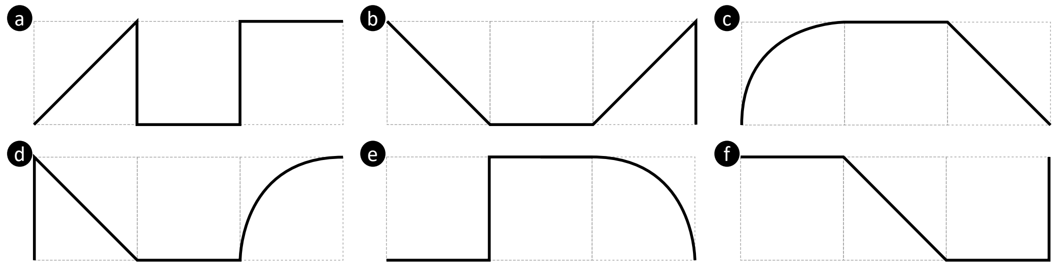

Fig. 3. Composite Lines designed for the user study, (90mm by 30mm). These lines have been formed by joining multiple line segments together. a) Trial Line; b-f) Lines 1-5

studies often use completely different and incomparable line designs [13, 23, 33]. Furthermore, most of these line sets do not contain different geometric features observable in many visual applications. For instance, lines with curves can be seen in many situations such as public transit maps and mathematical diagrams (Figure 1), but are missing in previous studies [23, 33]. Therefore, it is important to produce a systemic approach to design lines for *tactile line tracing* tasks to represent the complexity of lines while ensuring consistency for comparison.

In this study, we follow a segmented approach for line designs where four different line features are connected with three different joint angles to generate different composite lines. Figure 2-a shows the four segments, *diagonal*, *horizontal*, *vertical* and *curved*. Each segment is drawn to fit a fixed-sized block of a $30mm \times 30mm$ square. We selected $30mm$ block size to encapsulate the average human index finger width ($16mm - 20mm$ [8]) while keeping the overall line lengths to a minimum to avoid longer study times. These line segments allow us to generate lines that approximate the ones used in previous studies [10, 14, 29].

Composite lines can be generated by joining and stacking blocks together. Blocks can also be rotated in 90° increments before joining or stacking. It is good to have lines containing at least one *acute*, *right* or *obtuse* angles. Initially, we tested connecting blocks together four wide and two high (4×2 in Figure 2-b), resulting in very complex lines. In a pilot study with two users and 6 lines of this size, we realised that the lines were too long and complex leading to numerous errors as shown in Figure 2-c and participants spending approximately 2 minutes tracing each line. Therefore, we decided to connect a maximum of three (3) blocks in one direction (i.e. either connect them horizontally or vertically) but not both, which led to better tracing times. Furthermore, composite lines of size three blocks also fit well within commonly available smartphone screens sizes.

Using this systematic approach, we designed six lines for our user studies as seen in Figure 3. One line (Figure 3-a) was selected as the trial line whilst the other five lines were selected as the tracing lines to be used in the user study. These six lines were designed in such a way that there would be at least three opportunities for participants to trace an acute angle, right angle, obtuse angle, and curved line segment in at least three different lines. We believe this approach creates a comparable set of lines, even with other combinations of the same segments.

4 ACCURACY MEASUREMENTS FOR TACTILE LINE TRACING

Commonly used accuracy measurements in other tactile tracing studies such as accurate recognition of shapes cannot be translated to tactile line tracing. Completion time (T) is the most commonly used dependent variable and accuracy measure in similar studies and is often used to indicate the performance of given eyes-free techniques [13, 23]. However, completion time may not be indicative of an accurate understanding of the line through tracing. As an alternative, recent studies

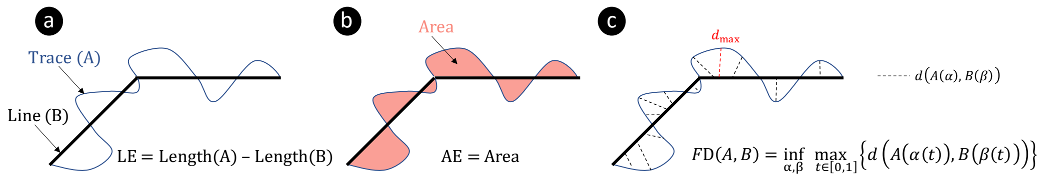

Fig. 4. Measurements made from trace coordinates. a) Mean line-length error (LE); b) Area between two curves (AE); c) Fréchet distance (FD)

have asked the participant to immediately redraw the line after the trace and manually annotated them to check the similarity [20]. However, this is a time-consuming process and does not scale to larger studies. Zhao et. al. proposed Delayed-Matching-to-Sample (DMTS), where participants were asked to trace two lines instead of one and compare if they are the same or not as an accuracy metric [33]. While this is a very promising accuracy metric, it can lead to user fatigue and longer study times in large studies.

An intuitive assumption to gauge accuracy is: the better one can trace *as quickly as possible* and *as close as possible* to the line, the better the individual's perception of the traced line will be. Therefore, in addition to completion time (T), we propose three other commonly used line similarity metrics as accuracy measures for tracing tasks. They are 1) Mean line-length error (LE), which is the length difference between the reference line and the trace, 2) Area between the reference line and the trace or area error (AE), and 3) Fréchet distance (FD), the shortest length that is sufficient for two connected points to traverse their separate paths (i.e. trace and line) from start to finish, irregardless of their tracking speed [18]. Mathematically, the formula for the Fréchet distance between two curves A and B as seen in Figure 4-c, is defined as the infimum over all reparameterizations α and β of the maximum distance between A(α(t)) and B(β(t)). A(α) and B(β) are the ways in how the trace (A) and line (B) could be drawn. A(α(t)) and B(β(t)) are the time domain mappings from them. In this context, the α and β can be treated as the speeds of line tracings. More generally, the Fréchet distance calculates the lower limit, which is infimum, of the maximum distance in every possible speed pair when two points traverse forward along two curves. The calculation process for the Fréchet distance is independent of the users tracing speed and only focuses on the curves themselves and can be calculated in $O(mn \cdot \log(mn))$ time.

5 STUDY SETUP AND FEEDBACK METHODS

This section describes the devices and feedback methods used in our study including stimulation design and implementation details including hardware and software.

5.1 Tactile Feedback Methods

To ensure the versatility and comparability of our study, we decided to test our line designs against a set of tactile feedback methods representing both well-established and relatively novel techniques. To minimise the undesired effect of tactile feedback on the device affecting the tracing task, we utilised a *distal tactile feedback* method or feedback that is *not co-located* on the tracing finger. Research shows that distal tactile feedback is equally effective to co-located tactile feedback [15, 22].

In our design, we selected two feedback approaches, namely, *directional* and *non-directional* feedback, representing how the tactile system guides the user in line tracing tasks. *Non-directional* methods provide feedback indicating the proximity of the finger to the line without any explicit direction information for correction if the finger steers away from the traced line. In contrast, if the user steers away from the line, *directional* feedback will try to steer the user in a certain direction to

a
$$f(x) = \begin{cases} 0 & |x| > 2 \\ 320 & |x| \leq 2 \end{cases}$$

b
$$f(x) = \begin{cases} 0 & |x| > 15 \\ 320 & |x| \leq 2 \\ \frac{60}{13^2}(|x| - 15)^2 + 180 & 2 < |x| \leq 15 \end{cases}$$

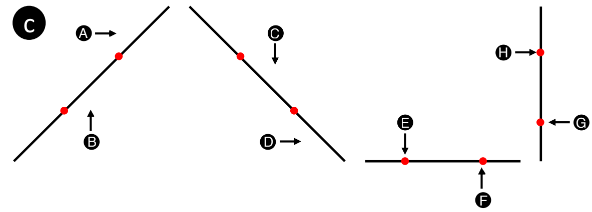

Fig. 5. Feedback algorithm details. *Non-Directional Algorithms* where x represents mm away from the centre of the line: a) Line Only; b) Frequency Feedback. *Directional Algorithms*: c) Various possible line orientations and the resulting directional feedback dependant on user location to the line. *Black circle*: potential finger location; *Red circle*: closest point to the line from the black circle; *Arrow*: feedback direction.

minimize the error. At first glance, it may seem intuitive to design a directional feedback algorithm to traverse back to the line once-off via the shortest distance. However, our initial pilot studies showed that participants became confused when they were given directional feedback towards the opposite direction of the progression of tracing. In our directional feedback system, we direct users only in four directions, Up, Down, Left, and Right, but always towards the progressive direction of the task. Figure 5-c highlights the eight conditions (A-H) in which an individual can be off any line segment and the direction in which the directional feedback methods will steer the user back to the line. The smaller red circles in the figure indicates the closest point to the line respectively for each of the eight conditions.

We selected two feedback methods for each class of feedback approaches. While our methods primarily focus on vibrotactile feedback these approaches can be generalised to other modes [19, 21]. Distances from the lines were selected to fit the average finger width and to be compliant with Palani et. al. findings of minimum 4*mm* line width for tactile tracing [23].

5.1.1 Non-Directional - Line Only (LO). This algorithm was used as our control condition and is similar to the one used by Zhao et al. [33]. The method provides constant vibrotactile feedback (at 320Hz) when the tracing finger is within 2 mm from the centre of the line. When the user is further than 2 mm, no tactile feedback is provided as shown in Figure 5-a.

5.1.2 Non-Directional - Frequency Feedback (FF). In this method, we provided constant vibrotactile feedback (at 320Hz) when the tracing finger is within 2 mm from the centre of the line, however, as the finger moves further than 2 mm, the tactile feedback becomes increasingly "aggressive" by changing the frequency, warning the user that they are deviating away from the line. The tactile frequency changes parabolically (to minimise the effects of Weber's law) from $240 - 180Hz$ as the user moves away from the line (Equation in Figure 5-b). Once the user is further than 15 mm from the centre of the line no feedback is given to avoid overlapping with other segments of the line.

5.1.3 Directional - Direction Feedback (DF). Similar to the other methods, Direction Feedback provides constant vibrotactile feedback (at 320Hz) when the user is within 2mm from the centre of the line. However, as the user moves their finger further than 2 mm away from the line, a stronger (240Hz) sensation is provided to a specific finger based on the tactile actuator holding position as seen in Figure 7-e-f. This stronger feedback indicates which direction (up, down, left, and right) the user should move to return to the line. Once the user is further than 15 mm from the centre of the line no feedback is given.

5.1.4 Directional - Virtual Force (VF). Using the Virtual Force feedback human illusory sensation [19, 26], we produced tactile pulling feedback that contains a sensation that can indicate a direction.

Our setup in Figure 6-a-b produces Virtual Force feedback in the four directions: up, down, left, and right. When users feel the pulling sensation, they should move towards that direction to return to the line. Again, similar to the other methods, constant tactile feedback (at $320Hz$) is provided when the user is within 2 mm from the centre of the line.

5.2 Implementation

In our setup, we used eight linear resonant actuators (LRAs - *ALPS HAPTIC Reactors*), each measuring $10 \times 22.6 \times 9.1mm$. The actuators were used in two different configurations as shown in Figure 6, each consisting of four actuators that were able to be independently controlled by an Adafruit nRF2840 microcontroller.

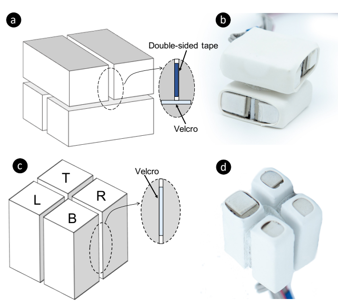

Fig. 6. Actuator Configurations; a) Configuration 1; b) Heat shrink wrapped configuration 1; c) Configuration 2; d) Heat shrink wrapped configuration 2.

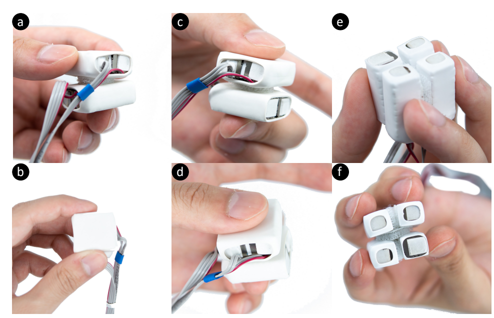

Fig. 7. Actuator Holding Methods; a-b) Holding method 1 for configuration 1; c-d) Holding method 2 for configuration 1; e-f) Holding method for configuration 2.

5.2.1 *Actuator Attachment Methods.*

One of our vibrotactile feedback methods required the use of the Virtual Force feedback human illusory sensation [19, 26]. We created this by applying an asymmetric signal to an LRA (2ms ON and 7ms OFF) which results in a pulling force sensation (see [26]) in a certain direction. Reversing the polarity reverses the direction of the virtual force. However, when tested, the strength of the virtual force feedback was stronger in one direction than the other. Therefore, we decided to attach two actuators with one flipped 180° using 1 mm thick double-sided foam tape as seen in Figure 6-a. This allowed us to create an even pulling sensation whilst also increasing the intensity of the sensation overall. To make the setup two dimensional (i.e. force in x and y-axis), we mounted two pairs of actuators joined as described above perpendicularly together (Figure 6-a-b). This was done by affixing each pair of actuators, one on top of the other against the largest face. We initially tried and subsequently found that using rigid materials as joining mechanisms distorted and spread out the sensation in multiple directions causing individuals to feel just simple vibrations. The use of softer materials (in our case Velcro) performed better at maintaining the virtual force directionality. This phenomenon was also found by Culbertson et. al. [7].

We used actuator configuration one (Figure 6-a-b), for feedback methods *Line Only*, *Frequency Feedback*, and *Virtual Force*. This configuration has two holding methods; holding method one (Figure 7-a-b) for both Line Only and Frequency Feedback and holding method two (Figure 7-c-d) for the Virtual Force feedback method. Furthermore, we wrapped each pair of actuators with heat shrink material to allow each pair to retain its shape and to protect the wiring.

The design for configuration two (Figure 6-c-d) on the other hand stemmed from the inability to comfortably place a different finger on each of the actuators for *Direction Feedback*. To fix this issue, we decided to join four actuators together vertically in a diamond shape using Velcro. The holding method can be seen in Figure 7-e-f where each finger excluding the little finger individually touches a separate actuator.

5.2.2 Touch Screen and Control Software. We used a Samsung Galaxy Tab S6 running Android OS Version 10 as the touch screen ($244.5 \times 159.5mm$). The tablet's display resolution is 1600×2560 pixels; with approximately $287PPI$ in density. The tablet was utilised in the landscape orientation and fixed to the table throughout the study.

A custom Android application (Figure 8-b) was developed to render lines for the tracing task, communicate with the microcontroller through a serial port to control the tactile feedback and collect user touch-point and timing information for further analysis.

6 EVALUATION

The goals of our evaluation were to understand (i) the effectiveness of the accuracy measures for tactile line tracing using vibrotactile feedback, and (ii) the effects of different line features on tactile line tracing performance. To achieve these goals, we conducted two separate but interrelated user studies. Study 1 was a controlled experiment in which the participants were presented with lines with different feedback methods. Study 2 was an online survey in which the redraws from Study 1 were evaluated by human participants to create the ground truths for the similarities between the original and redrawn lines.

6.1 Study 1: Tactile Line Tracing

The first study was a controlled tactile line tracing experiment with a 4×5 factorial design having the four (4) feedback methods as blocks, (Line Only (LO), Frequency Feedback (FF), Direction Feedback (DF), and Virtual Force (VF)) and the five (5) composite lines as shown in Figure 3 (without the trial line). We used a *Latin Square* to order the blocks and lines which were presented in random order to limit order issues. Participants were asked to wear a blindfold during each block of the study to ensure that they could not see any of the lines that they were tracing. Furthermore, during the study participants never saw any of the lines. Vibrotactile stimulation was provided through the prototype system that was described in Section 5.2. Participants used their dominant hand to trace the line on the screen while holding the actuators with their non-dominant hand as shown in Figure 7. White noise was played using noise-cancelling headphones during tracing tasks to prevent participants from utilising the sound produced by the actuators to help guide them to trace the lines.

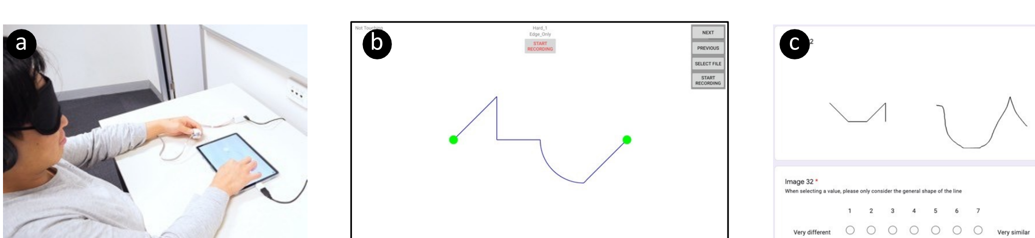

Fig. 8. Study details. a) First user study setup for the line tracing tasks; b) Screenshot of the Android application used in tracing tasks; c) A sample survey question from the redraw analysis study.

6.1.1 Participants. We recruited 13 participants (9 male, 4 female) ranging from 19 to 29 years old. One participant was removed from further analysis since they failed to complete one block. All the participants were right-handed. Ethical approval was granted by the University Human Research Ethics Committee. All participants gave informed consent and the University COVID-19 safety guidelines were followed during the user evaluations.

6.1.2 Procedure. Participants sat at a table with the tablet affixed on the surface in front of them as seen in Figure 8-a. The tablet had a 10mm diameter marker (made of Velcro) attached to the screen to indicate the start of each as all lines started from the same position. The participant's dominant index finger was guided to the marker attached to the tablet by the experimenter.

In each experiment block, participants were first blindfolded and presented with a trial line for training. Participants were allowed to explore the trial line until they felt familiar with the feedback method and the hardware holding pose. After the training period, participants were asked to trace the five lines once. An auditory tone was played on the headphones once the participant reached the end of the line, at this point the participant lifted their finger off the tablet. Immediately after the completion of each line trace, participants were asked to redraw the line on the tablet surface from memory with the blindfold still on; if requested they were allowed to recomplete their line redraw. The goal of the redraw task was to understand how much the user's recent tracing motion impacted how well they could recall from memory the line just immediately traced. Touchpoint data from the tablet (as pixel coordinates and time) were recorded for both the line trace and the redraw.

After each block, participants removed their blindfold and were asked to answer the NASA Task Load Index (NASA TLX) questionnaire and additional questions using the same Likert scale. After completing the questionnaire, a short break was provided to the participant before continuing onto the next block.

At the completion of the study, participants gave their preferences for the best and the worst feedback method together with their reasoning in a short free-response post-study questionnaire. The whole experiment took approximately one hour to complete. Altogether, 12 participants × 4 blocks × 5 lines resulted in 240 line traces and redraws.

6.2 Study 2: Redraw Similarity Evaluation

The goal of the second study is to evaluate the similarity between redraws and the original lines participants traced in Study 1. This similarity is indicative of how well the participants grasped the line geometries. However, comparing two line geometries computationally is a challenging task. While previous research has shown approaches such as using the Gardony Map Drawing Analyzer [20], they are not designed to validate subtle and nuanced similarities/differences. Therefore, we chose to conduct an online survey to collect subjective feedback from human participants.

6.2.1 Survey Design. Participants were presented with a series of source lines and the corresponding redraws side by side as shown in Figure 8-c. They were asked to rate the similarity of each line pair on a seven-point Likert scale from "Very Different" (1) to "Very Similar" (7).

6.2.2 Line Selection for Survey. Through a pilot survey, we realised a participant could rate close to 60 lines in 20 minutes, and beyond that the task became monotonous. Therefore we decided to select a subset of the 240 line redraws and dispatch them in three separate surveys. First, we selected 100 lines randomly. Then, to balance the number of lines from each block and accuracy measures, we selected 12 lines (6 highest and 6 lowest values) from each measure (4) × each block (4) resulting in an additional 192 lines. After removing the common pairs (original and redrawn) in the two sets, 153 unique pairs were selected. We recruited 30 participants per survey resulting in 30 ratings per pair or 4590 line ratings in total.

7 RESULTS

In this section, we present the results from our two user studies and (i) explore whether there is a computable measure that better correlates with the accurate perceivability of the overall geometric features of the line and (ii) whether different geometric features of a line are important to be studied in tactile line tracing tasks.

7.1 Comparison of Accuracy Measures

We calculated all four measures Time (T), Length Error (LE), Area Error (AE) and Fréchet Distance (FD) and removed the outliers of the data set where completion time was 2 standard deviations away from the mean. There was a total of 9 outliers from 240 lines traced (~ 4% of the data). All the data processing and analysis were conducted using R[3]. Since the Shapiro-Wilk Normality test revealed Likert responses were not normally distributed, statistical analysis was conducted using the non-parametric Pairwise Wilcoxon rank-sum test.

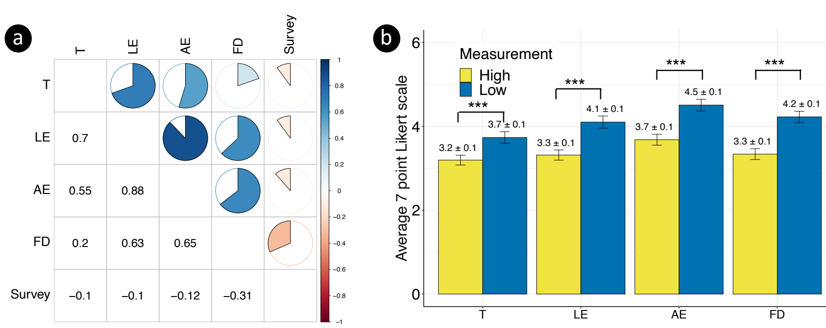

Fig. 9. Results from the redraw analysis survey. a) Spearman's Rank-Order Correlation between each accuracy measure and the Likert scale rating for randomly selected 100 line pairs; b) Average Likert scale rating against the measurement type grouped into low (smaller values) and high (larger values) groups with respect to the measurement for 122 lines from high and low groups per measure (With 95% CI).

7.1.1 Findings. We calculated the correlation between each measure and the survey ratings to find the best matching accuracy measure that is indicative of redraw quality, (i.e. a users' understanding of the line geometry). Spearman's Rank-Order Correlation was used to account for the ranked data in the Likert scale. Figure 9-a shows the correlation matrix for the 100 lines used in the survey (randomly selected). Results show that there is a high correlation between measures T-LE ($\rho = 0.7$, $p < 0.001$), and T-AE ($\rho = 0.55$, $p < 0.001$). The correlation between time and Fréchet distance however is much lower T-FD ($\rho = 0.2$, $p < 0.001$). This is indicative that the *Fréchet distance (FD) could produce independent information to the commonly used Time (T) metric*. More importantly, *Fréchet distance (FD) showed moderate correlation with the user ratings of the redraws FD-Survey* ($\rho = -0.31$, $p < 0.01$) in contrast to T-Survey ($\rho = -0.10$, $p = 0.32$), LE-Survey ($\rho = -0.10$, $p = 0.32$) and AE-Survey ($\rho = -0.11$, $p = 0.25$). *Spearman's Rank-Order Correlation coefficient ρ for FD-Survey is twice as high compared to the other metrics.* This finding is indicative that FD is moderately

[3] https://www.r-project.org/ Version 4.0.3

correlated with the user ratings of redraws, (negative sign indicates the lower the FD the higher the quality of redraw).

To further examine the discriminative properties of each measure, we compared the Likert ratings of best and worst traces with respect to each measure. Figure 9-b shows the results, with each bar showing the average Likert scale rating for redraws identified as having *low* (smaller values) and *high* (larger values) scores respective for each measure (T, LE, AE, and FD). Each bar in Figure 9-b represents the averages of 720 ratings consisting of 6 redraws (either having the 6 highest or 6 lowest scores per measure) $\times$ 4 blocks $\times$ 30 participants.

The data reveals that all the measurements showed significant changes of redraw quality ratings between *High* and *Low* groups. Wilcoxon rank-sum test with continuity correction revealed significant differences between *High* and *Low* for all measures ($p < 0.001$). However, out of the four measures, *Fréchet distance (FD) showed the highest difference between average averages.*

7.2 Comparison of Line Geometric Features

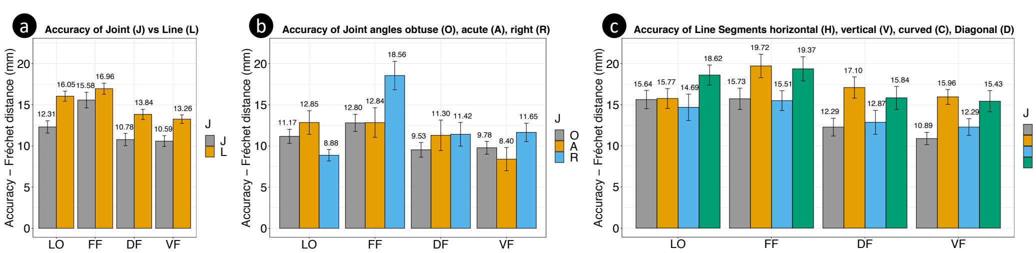

Fig. 10. Fréchet distance measures for different line segments with different feedback types. (With 95% CI)

In order to analyse the importance of including different line segments, we also analysed the Fréchet distance of varying user line trace segments. Each segment comprised of a third of the line segment distance from either the joint location for joints or from the centre of the line segment for lines. Figure 10-a shows that, surprisingly, participants made more errors at line segments than at joints. Further analysis shown in Figure 10-b shows, different joint types are harder to trace with different feedback types. For instance, Line Only (LO) resulted in having the best performance for right-angle joints whilst virtual force worked best for acute angle joints. Similarly, Figure 10-c shows different line types also perform differently, notably horizontal and curved lines are much easier to navigate than vertical and diagonal lines. This indicates that different types of line segments are necessary to be included in line tracing studies to acquire versatile results.

7.3 Qualitative Survey Analysis

We asked study participants to complete a post-study questionnaire after each user study. These surveys outline users' overall opinions towards our experiment. When participants were asked to "Select which algorithm was best?" from a list, nine out of twelve participants chose a directional feedback algorithm as their preferred method. Subsequently when participants were then asked, "Why did [they] select the above algorithm as the best one?", participants responded that these line tracing methods were more "informative", "non-confusing", and had "distinguishable vibrations". Two users however mentioned that we "reverse the direction" or "change [the] orientation of up-down" to make the setup easier to use.

8 DISCUSSION

8.1 Directional vs Non-Directional Feedback Methods

Different from the work of other researchers e.g. [13, 23, 33], our results compare both non-directional feedback (Line Only, Frequency Feedback) and directional feedback (Direction Feedback, Virtual Force). We show that both non-directional and directional feedback lead to comparable completion times in user line tracing. However, when looking at other performance measures for each of the feedback methods, directional feedback methods can be seen to have significantly higher accuracy. With this information, it may seem advantageous to only use directional feedback methods in future applications as it is more accurate. However, designers should still choose between these two methods depending on the application and use case.

One of the main disadvantages of directional feedback methods is that the algorithm removes users' ability to freely explore and analyse the line/information presented to them. Directional feedback methods try to direct users to follow an explicitly defined path in a specific direction e.g. following a map. In some applications, providing this feedback may not be practical. One such example is in lines that can be traced in two directions, i.e. a forwards motion and a backwards motion, which is commonly seen in sliders (a UI component). In this situation, providing non-directional feedback to users may be best as users may need to change the direction of sliding based on personal preference.

8.2 Line Tracing Performance Comparison

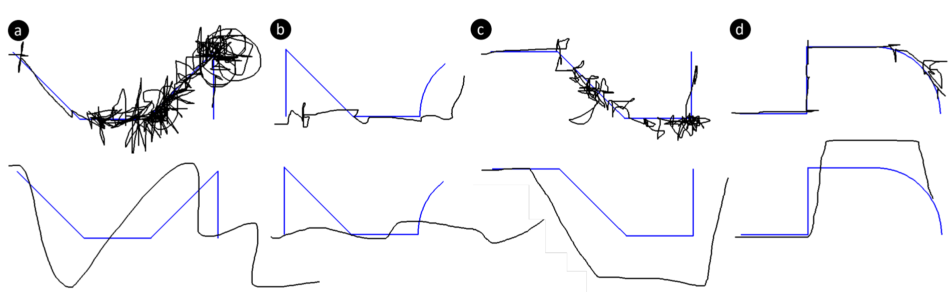

Fig. 11. Example user line traces to line redraws. The top row contains line traces whilst the bottom row contains the resulting redraws. a-b) - Poor line traces; c-d) - Good line traces.

In other studies of a similar nature, completion time is one of the most frequently used dependent variables and sometimes the only measurement made to determine user understanding. This study shows there can be other computable accuracy measures, namely, Length Error (LE), Area Error (AE), and Fréchet Distance (FD) which can be used as dependent variables.

Our results indicate that whilst time is a good measurement for eyes-free line tracing (as it also leads to significant differences in line redraw performance), the accuracy metric Fréchet distance is a more robust indicator of user's perception of a line and correlates better with the subjective quality of the user's redraws of the traced line (Figure 9-a). This can be understood intuitively where the further away a user's trace moves from the line during line tracing, the poorer the recognition of that line's shape. It is also important to note in Figure 9-a the other two accuracy metrics LE (used in [30, 33]) and AE are highly correlated with completion time (T), whilst FD is not, indicating that FD can provide new information about the tracing task independent of T. Additionally, in our results we see that a shorter line trace (time or length) does not necessarily mean that the user has traced the line correctly. Figure 11-b shows a trace where the LE is low because the user has completely missed tracing the acute angle and subsequently recorded a poor redraw. With this information, we highly recommend Fréchet distance (FD) to be used alongside tracing time (T) as an important accuracy metric in future studies. This will allow researchers to further understand how users may perceive a presented tactile feedback method in similar tracing tasks by using many more measurements.

8.3 Line Design

Of the previous research into eyes-free line tracing, there have been different line sets used within each study [20, 23, 27]. The use of diverse lines between studies makes it difficult to compare methods and techniques. In this work, we developed line design guidelines to ensure consistency in developing line sets. We showed how by combining line segments, a range of different composite lines could be formed. Segmented line design can be used to create an approximation that can maximise their recognition when they are used to display a path on a touch screen with a vibrotactile interface. The composite lines utilised in our user studies were well balanced in design. We could not find any significant performance differences between the lines we used, and our subjects were not able to guess the lines presented to them; (we did not see any significant learning effect).

However, when designing lines in future user studies, lines should not include abrupt or large angle changes e.g. acute angles. In our studies, we found that users tended to overshoot lines in line tracing tasks in this situation, this caused users to become lost and unable to find or determine the line's continuation. Having fewer abrupt angles in lines makes it easier and less likely that users will become lost whilst tracing the line. We found that users trace curved and horizontal lines more accurately than vertical and diagonal lines. Therefore, if a sharp change in direction needs to be conducted, the use of multiple curved segments may be more helpful as individuals would be slowly eased into making the directional change.

Furthermore, we surprisingly found that users had more difficulty in line tracing within each segment rather than at the joint between two segments. This reinforces the need for composite lines in the future to be designed with segments that are easier for users to trace to reduce line tracing errors made by users and thus increase understanding of what is being traced.

All in all, we present and recommend the use of our line design guidelines in future research studies. This will help to ensure consistency within the research conducted in the community.

9 LIMITATIONS AND FUTURE WORK

The first limitation is that the directional feedback method utilised contains the limitation of lines not being able to contain any right to left traversal. This constraint reduces the usability of the presented directional feedback methods as many lines encountered every day contain this direction of movement. Examples include right to left languages such as Arabic and Hebrew and vector line drawings. Further work in the future should be conducted to design a methodology that allows for lines to be traversed in all directions. This is especially important as participants mainly preferred the use of directional feedback in our studies, particularly the method Direction Feedback (DF) according to the post-study questionnaire.

Another limitation that was experienced was the lack of participants available to participate in in-person user studies due to the COVID-19 pandemic. Having only 13 participants, (one of which did not complete the study) resulted in only a small data set of user line traces and redraws for the tested tactile feedback methods. Moreover, as seen in the results, the majority of our independent variables collected from users in user study one were not normally distributed. This suggests that we needed to have included more participants in our user studies. In order to mitigate this issue, future research in this area should include more participants to ensure that a better snapshot of potential users can be gathered and to ease the impact of participant-related issues.

Furthermore, the research conducted did not include participants who were part of the blind or visually impaired community (BVIC). Much of the research within this area [16, 23, 33] includes participants both with and without sight to ensure that the methods being presented actually assist and benefit all people. It was due to the COVID-19 pandemic that prevented us from expanding our user study to include members from the blind or vision impaired community. We acknowledge that sighted and blindfolded individuals have different perceptual capabilities than individuals in the BVIC [12]. Should future researchers continue working on the presented line tracing methods they should ensure that feedback from individuals in this important user group is included.

10 CONCLUSION

In this paper, we investigated the applicability of different accuracy metrics that can be applied to tactile line tracing tasks on touch screens. We conducted two user studies for this investigation. We used a segmented line design with different geometric features that is suitable for vibrotactile line tracing and evaluated different accuracy metrics. We show that out of the four accuracy metrics, Fréchet distance is a better indicator for maximising the recognition of the lines. Having a large Fréchet distance in a line trace more often produces poorer line redraws by users. This provides an additional new measure for future studies and systems to judge the accuracy of tactile line tracing. Furthermore, this paper presents a set of line design guidelines consisting of multiple line segments. These segments can be joined together in different orientations to produce a wide range of composite line sets. We show that different feedback methods perform differently with varying geometric features, suggesting a segmented line design can help to improve comparisons in vibrotactile line tracing tasks. Overall, the contributions of this paper should inform future studies in tactile information tracing.

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