Eyes-Free Graph Legibility: Using Skin-Dragging to Provide a Tactile Graph Visualization on the Arm

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ABSTRACT

Recent technological advances have enabled novel tactile displays which have mainly focused on providing shorter sensations for notifications and/or simple messages. These have been primarily been used to enhance the user experience. In contrast, conveying information via data charts, such as a line graph, remains largely unexplored. To address this gap, we developed a tactile display prototype. Our prototype uses skin-dragging, a method to produce longer tactile perceptions from dragging a tip on the skin, as the primary means to convey the data. We postulate that if such an approach is successful, it could convey the data in eyes-free scenarios, an element common for on-the-go computing. In an experiment (n=12), we compare the recognition performance of graphs with two different skin-dragging properties, *Full-Drag* and *Dot*. The results show that participants performed both techniques equally well, but our *Full-Drag* technique was greatly preferred. We conclude with design guidelines for tactile displays that focus on graph representations.

CCS CONCEPTS

•Human-centered computing → Haptic devices

KEYWORDS

On-body interaction; Tactile display; Eyes-free interaction; Skin-drag interaction

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1 Introduction

Tactile displays have been the subject of much research in recent years [3, 14–16, 29, 32, 36]. Chouvardas et al. [7] denoted these displays as a '*human–computer interface that can reproduce as closely as possible the tactile parameters of an object, such as shape, surface texture, roughness and temperature*'. These tactile displays provide the possibility for many different output modalities on the skin. Many applications could directly benefit from conveying information across the skin using such tactile displays for VR applications or on-the-go computing. Indeed, if designed appropriately, they can provide hands-free and eyes-free interactions.

Among the different applicable types of tactile displays, skin-dragging has emerged more recently for its ability to maintain a length of perception beyond a brief sensation [15–17]. Skin-dragging consists of a small tip, or tactor, that drags across a user's skin. This can stimulate a user's skin both spatially and temporally [16]. The skin-dragging technique presents several advantages over other common display types, such as vibrotactile or skin stretching. First, skin-dragging is more efficient with conveying information than vibrotactile [15]. Second, these prototypes are built to be in con-tact with a larger area of the skin rather than using single-point contacts [17]. Therefore, they could be suited to display complex in-formation. Finally, skin-dragging is the combination of vibrotactile displays and skin stretching [15] and thus, skin-dragging should lead to longer haptic sensations that could potentially add more variety to the information that needs to be conveyed. However, previous work has mainly focused on providing notifications and alerts to users [3, 28, 36] through tactile displays. Among those few studies which explored the potential of dragging to represent information, Ion et al. [15] proposed a set of different shapes that can be recognized by users using their skin-dragging devices. We further expand skin-dragging to assess whether it can facilitate more complex graph information displays using tactile information.

Nowadays, wearable devices are increasingly being used to rep-resent personal data, such as fitness or well-being information. Such representations are rich in content and novel methods are often needed to ensure the information can be conveyed appropriately. The representation of line-graphs can be challenging on the screens of these wearable devices [23]. As a complement to visual representations, we introduce skin-dragging as an approach to convey the data. In a first step, we explore the possibility of conveying information and data, rather than simple notifications. We then aim to explore a tactile display that may be useful, as well as providing eyes-free and hands-free interaction. We aim to quickly help user's perceive max/min points on a graph. This could allow for real-time feedback of information without disrupting users' core tasks, such as potentially walking, jogging or otherwise. In this first contribution, we explore the potential of representing line-graphs in an eyes-free manner. More specifically, we look to address the following research questions: 1) How effective is skin dragging for conveying complex information?; 2) Are line-graph representations across the skin possible in an eyes-free environment?; 3) How should the data be represented across the user's skin?

To explore these questions, we built a new tactile display prototype that relies on skin-dragging to convey graph information. Our prototype consists of a tactor connected to mechanical arms, emulating a pantograph, with a programmable motor. It was designed so the tactor is not constantly in contact with the user's skin, but only when needed. In controlling the motion of the tactor, we can convey graphic information to the user across their skin. For this study, we first identify and describe the design and characteristics of our tactile device. Then, we study two data representation methods, namely, *Full-Drag* and *Dot*. To display the data points of our line-graphs, the *Full-Drag* technique is constantly in contact with the user's skin while *Dot* is only when data points are on the graph. We then compare the performance of these tactile techniques, in which participants were asked to recall data representations given to them through our prototype. Thus, our contributions are: 1) a skin-dragging tactile display for conveying line-graphs; 2) an eyes-free validation of tactile line-graphs.

2 Related Work

Tactile displays are not as widespread as visual displays, for obvious reasons. However, tactile displays offer complementary and some-times unique benefits over visual displays such as for the visually impaired [37]. Furthermore, tactile displays can be used on different parts of the body, such as forearms [15, 29], fingers [16, 17, 36], and even the neck and head [3]. Among these options, we chose to explore the use of a tactile display on the forearm, as this can be discreet while providing ample surface area to convey data.

2.1 On-Arm Output

Some of the most common forms of tactile displays include ones that use vibrotactile feedback [6, 20], stretching of the skin [3], dragging across the skin [10, 16], thermals [34, 35], and colors and lights [29]. Each of these methods can be identified as one of three main modalities: thermal, electrical, and mechanical [3]. We describe these as well as their strengths and weaknesses.

2.1.1 Thermal. Thermal feedback provides hot and cold sensations to convey information. Wettach et al. [34] explore thermal feedback and found that participants could differentiate up to five different temperatures within a 10 degree range. Wilson et al. [35] studied thermal feedback in mobile conditions compared to static conditions. They discovered that the palm was the most sensitive, where colder temperatures could be differentiated more effectively, a result also found by Peiriset al. [27]. Lastly, Roumen et al. [31] explored using heat in the context of transmitting information. They found that thermal notifications required the longest to be recognized, and had the highest error rate. These studies indicate that while thermals can be recognizable, response time is too long for conveying graph information and thus may be less practical in conveying immediate information. This ambient type of feedback can therefore not be used to convey line-graph information in the context of tactile displays.

2.1.2 Electrical. Electrical stimulation as an output modality benefits from being extremely small, thin, and flexible [13]. Often, this modality is built into a small patch or tattoo that can be worn anywhere on the body [18, 33, 36]. The electro-tactile display can be placed on the fingertip [36]. This part of the body allows for the highest acuity for tactile perception on the human body, without blocking normal sensation [36]. The small interaction space provided by these displays makes them very suitable to provide simple notifications, but challenging to be utilized when conveying graph information.

2.1.3 Mechanical. Mechanical tactile displays move their constituent parts to convey information to a user. We explored vibrotactile displays, which use a single vibrator to convey information. These vibrators can vary certain parameters for different interpretations, such as frequency, amplitude, waveform, and duration [12]. Vibrotactile displays benefit from being small and lightweight [2], allowing them to be placed within other hardware components and on various other body parts.

Previous work has shown that vibrotactile displays can be used in rehabilitation [30], smart device alerts [20], for progress monitoring [6], gaming [2], and navigation or situational awareness [11].Vibrations have been shown to be beneficial in these contexts to capture users' attention or to provide simple feedback or instruction. What lacks from these works is the ability to use vibrotactile displays for data representation. Vibrotactile displays, as seen in the previously mentioned works, mainly provide momentary feedback [20]. Although this short lived feedback can be very accurate, it is not suitable for conveying graph information over time.

Skin stretching is another form of a mechanical tactile display which can come in many form, and may be less intrusive [3]. Such work done by Alhuda Hamdan et al.[3] utilized springs in lightweight, and small, stickers that could be placed on the body. They created a wide range of tactile sensations such as pinching, directional stretching, pressing, pulling, dragging, and expanding. Rotational skin stretching was also explored by Bark et al.[4]. While these methods proved to be perceivable, they again only allow for a representation of basic information. With the human perception of skin stretching between 0.13-0.3mm [25] there is also not enough physical space to convey more complex data.

Skin-dragging method, another form of a mechanical tactile display, combines the essential stimuli from both vibrotactile and skin stretching [15]. Many rings or circular devices employ the skin-dragging approach. These have been studied [10,15–17]. These devices allow for a small physical tactor to rotate either within a fixed area, around the circumference of the arm, or up and down the length of the arm. First, Dobbelstein et al.[10] studied a device that moved up and down the arm. They noted that participants could detect the device’s position to within 1.2cm as well as the length of the movement to within 1.44cm of the actual position and movement length [10]. Second, Ion et al. showed that shapes could be more effectively recognized using a skin-drag technique over vibrotactile techniques. Je et al.[17] explored the use of skin-dragging around the finger, which benefited from a more acute disambiguation of points. Targeting was shown to be successful by Je et al., but data representation was not explored. With these studies in mind, along with Norrsell and Olausson who showed that movement direction was also perceivable [24], we look to build and study a prototype that allows for accurate data representation along the forearm.

All of the above described mechanical methods are able to provide a fine spatial resolution due to the mechanoreceptors present in the skin [9]. We chose skin-dragging for its ability to provide continual, non-discrete, precise, and fast acting feedback in a larger physical range.

2.2 Eye-Free Data Representation

While eyes-free interaction on the arm has been explored [21], the representation of eyes-free data remains relatively unexplored. Linet al. [21] studied participants’ ability to differentiate locations of tactile stimuli on their arm in an eyes-free environment. One of the most valuable aspect of tactile displays is their ability to convey information without visual or auditory cues.

Most data representations are visual [22], auditory [1, 5, 8] or use tactile perceptions [26]. Visual data representation comes in familiar forms such as bar, line, pie, and scatter plots. Auditory data representations utilize sonification, which is the use of non-verbal auditory communication to convey information [5, 19]. The use of different tones allows users to determine whether the graph is rising or not. However, these tone based systems have drawbacks. They do not allow for the location of the individual data points to be known, and instead primarily convey the trends in the graphs. As well, being auditory they can be overcome by other ambient noise causing disruptions in perception. Thus, tactile feedback is mainly used to convey information for people with visual impairments as for example with the use of a force-feedback mouse [38]. In this work, we explore the means for data representation that is both eyes-free and audio-free, relying only on tactile cues. This provides a method for data representation that can be used in many contexts where visual and auditory attention is not possible and/or suitable.

3 Prototype

3.1 Concept

The design of our prototype is based on prior work concerning tactile displays. Skin-dragging, as a type of tactile device, offers the largest set of advantages to convey eyes-free information over other tactile displays. These include better accuracy than a vibroctactile device [15], a wider range of interaction space, and fast continual feedback. We followed Ion et al. and Dobbelstein et al. [10,15] and decided to use our device on the forearm because the length of the forearm allows us to utilize a larger area for conveying graph information.

The design of our tactile display was inspired by the structure and capabilities of a panto-graph, see Figure 1. Although we do not wish to reproduce shapes, the way the arms articulate can be applied to line-graphs display as well. Lastly, our tactor is not directly in contact on the user’s skin. It articulates up-and-down when ever required to convey information. This seemingly clear dichotomous aspect of our data representation (i.e., Touch vs. Untouch) will enable the users to identify when the data is being displayed or not. We specifically note that the provided prototype was only designed to evaluate the feasibility of skin-dragging for conveying information. We do not expect it to use for every day use. In our final Discussion section, we propose other, more elaborate designs which we intend to produce for true mobility conditions.

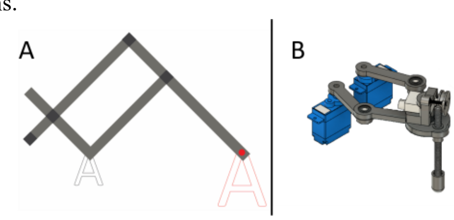

Figure 1. A: View of panto-graph; B: Top view

3.2 Implementation

3.2.1 Hardware system. The developed prototype is an electro-mechanical device capable of translating in the x and y dimensions, within a 70mm x 30mm range respectively. The vertical actuation of the tactor in the z axis has a range of 9mm, see Figure 2. At the start, the tactor has to be calibrated to the correct height to suit the user’s arm. Thus, when the tactor reaches its lowest position the user can comfortably perceive it along their arm. To assure that participants actually felt the tactor, a pressure sensor (CapacitiveForce Sensor 8mm 1N (0.2lbs)) was used to record a set pressure level felt by the tactor on the arm. Once calibrated, the tactor has the ability to move up and down, as well as drag across the user's skin while maintaining consistent pressure. To alter the x and y positions, two 2.1 kg·cm digital servomotors (Towerpro MG90D) with 90 of range were used. A 4-bar mechanical linkage system, with 34mm and 40mm arm lengths and two degrees of freedom, was utilized to convert rotational movement of the motor shafts to Cartesian movement. The arms were printed using PolyLactic Acid (PLA).

3.2.2 Tactor mechanism. The mechanical and structural components were also printed using PLA with bearings installed at all joints for smooth movement. The tactor is spring-loaded with a compression spring (9657K45) with a density 51.8 g/cm which allows for directed pressure applied to the participants' skin. For tactor actuation, an additional 0.17 kg·cm digital servo (HK-5330) was used to raise and lower the tactor. The servo has an attached spool which varies the compressive force applied to the spring with an attached polyethylene line, allowing for 9 mm of vertical travel. The speed of the tactor is 150mm/s.

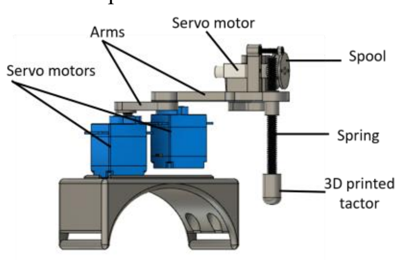

Figure 2. Schematic diagram of our prototype

3.2.3 Software implementation. Positional data is relayed from a laptop via a micro USB serial port to a Sparkfun Pro Micro, 5 V/16MHz development board. Patterns are specified as a series of Cartesian coordinates to the software. The software then generates the correct angles for the servos that will allow the linkages to translate to the requested position. Given that the motor position and linkage lengths are fixed, this could be accomplished rather simply using basic trigonometry. The onboard MEGA32U4 microcontroller interprets the provided commands and generates the respective Pulse Width Modulation (PWM) control signals for the servo motors to modulate their respective angles. Arduino's pre-existing Software Serial and Servo libraries were utilized.

4 Tactile Line-Graph Representation

4.1 From Visual Line-Graphs

Paneels and al. [26] define line-graphs as a "representation form for presenting continuous data and are used in several domains such as mathematics, statistics, finance, etc". Generally, visual line-graphs are represented across two-axes, x and y. Data points are often shown by being thicker than the edges linking them all. However, representing line-graphs on a reduced space can be challenging [23]. Neshati et al. proposed to compress the graph solely on the x-axis [23]. While compressing a line-graph seems beneficial as it reduces the required area, it may not be suitable for our implementation as this means the distance between two data points needs to be reduced. Paneels and al. [26] refers to effective representations of graphs as possessing the ability to convey the underlying knowledge. To achieve this, we next explore an effective mapping from visual to tactile graphs for our prototype.

4.2 To Tactile Line-Graphs

Transforming a visual line-graph to a tactile one requires some adjustments. As we often rely on visual or auditory cues to discern graph information, one challenge to overcome for tactile graphs is to identify a minimum distance between two data points. We based our design off of the study by Dobbelstein et al. [10]. As our device moves up and down on the forearm, we rely on the fact that participants could perceive the length of the movement to within 1.44cm [10]. Thus, the distance between two data points can not be less than 1.44cm, and the number of data points that can be displayed is limited across the width of the forearm. To accommodate for this limitation, we propose to use only the length of the forearm by removing one axis to display our graphs.

We chose to remove the x-axis, thus all the data points will be represented on a single line. By only representing the position of points on the y-axis and moving the tactor to the corresponding position, we benefit in many ways. First, while the actual contact points denote the y-axis value, the actual movement of the tactor can denote a change in the x value. This is done without having to display a graph in two dimensions. Second, an increased number of data points can be represented as space never runs out with this method. Theoretically, this allows for a possibly infinite time-series graph to be represented, without having to reset to a starting position. We identified different mappings between output modalities to convey data points: either focus on the line of the graphs (*Full-Drag*) or on the data points itself (*Dot).*

4.2.1 Full-Drag. In the *Full-Drag* technique the tactor is constantly in contact with the skin when displaying a line-graph, see Figure3-A. Thus, the tactor moves to the first position, descends to touch the skin, moves to the second position, and so on and so forth. When the tactor reaches the last position, the tactor moves back up above the skin. When reaching a specific data point, the tactor stops for 500ms. This pause is crucial so that the user can differentiate a point and the movement towards a point. With this *Full-Drag* technique, users should be able to perceive a line graph moving to different data points.

4.2.2 Dot. Contrary to the *Full-Drag* technique, the tactor is not constantly in contact with the skin, see Figure 3-B. In the *Dot* technique, the tactor moves to the first position, descends to touch the skin, pauses for 500ms for users to perceive the point, goes back up, and moves to the next position repeating till the graph representation is complete. With this technique, users perceive only the graph points on their skin. The tactor does not move on the skin of the user, and thus the time change in the x axis is perceptually processed between the points.

5 Study

The goal of this study is to explore the performance of the two tactile techniques using our skin-dragging prototype. The prototype was tested by observing the participants' ability to recognize the graph displayed to them in a tactile manner through our prototype. Specifically, we aimed at assessing whether movement on only one axis would produce the perception of a graph.

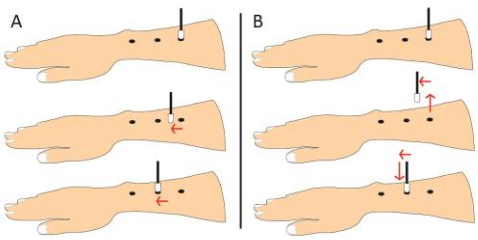

Figure 3. A: Full-Drag technique; B: Dot technique. Points are only used as references for this figure

5.1 Task and Instructions

The task consisted of having our tactile prototype represent a line-graph on the participant's forearm in an eyes and audio-free manner. Participants were then provided a forced-choice question, in which they had to select the corresponding line-graph. Participants were given three possible graphs, and chose the one they thought to have perceived.

5.2 Design of Line-Graphs

We created two sets of graphs for this experiment. To control the complexity across graphs, all the graphs in each set had the same number of peaks, either 3 or 4, see Figure 4. We define a peak as a point where a change in direction within the graph takes place. Our graphs were then generated randomly. All of our line-graphs contained 7 data points that fell in a range of 0-2 on the y axis. Each set was composed of 10 individual graphs. Half of which had 3 peaks while the other half had 4 peaks. To minimize errors in response coding, we chose forced choice responses instead of freehand drawing. As we gave our participants a forced-choice question, we needed to control the difficulty level of the recognition across all the trials. Thus, one of the choices provided was correct, while two wrong options were also offered. Of those two options, one was always off by 2 data points and the other choice was always off by 4 data points. We also assured that the number of peaks was the same for all graphs.

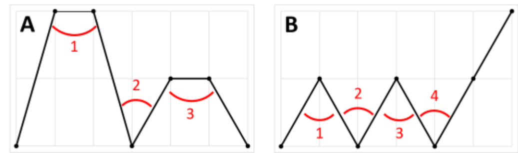

Figure 4. A: an example of a line-graph with 3 peaks; B: an example of a line-graph with 4 peaks

5.3 Participants

Twelve participants (2 females) volunteered, aged between 20 and 34 years old (SD= 4.36) from a local university. All of our participants were right handed. The participants decided which arm they were the most comfortable to perform the tasks: 9 used our prototype on their left hand and 3 on their right hand.

5.4 Design and Procedure

We used a within-participant design with the tactile technique (*Full-Drag* or *Dot*) as the main factor. Each block consisted of ten trials in which the same tactile technique was used. We counterbalanced the blocks' order across participants using a Latin Square design. This ensured no practice effects were seen across the tactile techniques or graphs used. Participants were informed that they could take a break between blocks, if they would like. Before using each technique, participants completed a training session. The two techniques (*Full-Drag* or *Dot*) were explained and participants completed two trials before recording their answers. During this training session, we asked our participants to choose one arm to perceive line-graphs for the entirety of the experiment. During the training session, the instructor ensured that participants could feel the tactor on their skin and adjusted it when it was needed.

5.5 Apparatus

We minimized error by using our skin-dragging tactile display prototype in a controlled manner. The participant's arm was placed in a still position on a table. We built a platform out of Lego blocks to maintain the arm's position throughout the study, see Figure 5. The stabilization of the arm also assured the same pressure from the tactor was felt throughout the entire study. The tactor's pressure upon the skin was measured to validate its consistency. Based on pilot tests, we operationally defined adequate pressure to be between 0.2N and 0.3N. This measure corresponds to the tactor putting enough pressure on the forearm to be felt without exerting too much force to cause pain. We used a computer to display and record the forced-choice questions asked after each trial. We occluded participants' view of the prototype, and used a pair of headphones with noise cancellation to ensure the participants could not see or hear the position and movement of the tactor during the task.

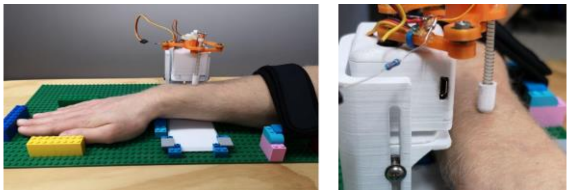

Figure 5. Experimental setup for the study

5.6 Data collection

We logged successful recognition for the two tactile techniques. At the end of the study, we asked our participants to classify the techniques by preferential order and we collected their subjective comments. In total, we collected 2 tactile techniques×2 graph sets x 10 repetitions×12 participants = 480 trials.

6 Results

6.1 Line-Graph Recognition Accuracy

We used a Kolmogorov-Smirnov test to determine the normality of the distributions of the recognition of graphs: The data was slightly negatively skewed (-.08). Because the distributions were not normal, and could not be normalized, we used a non-parametric Wilcoxon test for two or multiple comparisons.

6.1.1 Tactile Technique Effect. No significant main effect of technique type was found for the recognition rate of line-graphs for the tactile techniques, (*Full-Drag* or *Dot*) (p=0.52). On average, participants had recognized line-graphs in 60.83% using *Full-Drag* and 65% using *Dot*, see Figure 6.

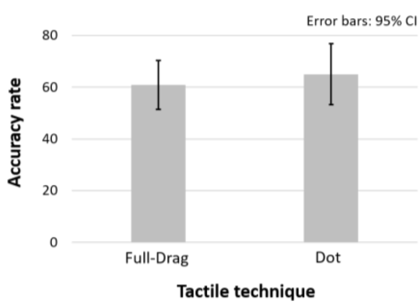

Figure 6. Percentage of accuracy for each tactile technique

6.1.2 Graph Complexity Effect. We examined whether the different complexities of our graphs (either 3 or 4 peaks) impacted the user's performance level. We did not find any differences between the complexity of the *Full-Drag* technique (p=0.66) and the *Dot* technique (p=0.77). Using *Full-Drag*, on average participants performed a score of 60% (CI[9.38; 9.38]) with the graphs containing 3 peaks and 61.66% (CI[12.06; 12.06]) with the graphs containing 4 peaks. Using *Dot*, on average participants performed a score of 64.16% (CI[17.23; 17.23]) with the graphs containing 3 peaks and 65.84% (CI[9.56; 9.56]) with the graphs containing 4 peaks.

6.1.3 Summaries. Concerning the tactile techniques, we did not see any performance differences. This result is rather surprising as we predicted that *Dot* would perform better than *Full-Drag*. The *Dot* only contact with the skin corresponds to single data points, which we believed to be less distracting for participants. Concerning the complexity of the graphs, we anticipated that graphs with 4 peaks were easier to perceive. Graphs with 3 peaks had consecutive data points which made it more challenging to distinguish. It was surprising that both techniques performed equally well in this scenario.

6.2 User preference

6.2.1 Ranking Tactile techniques. Participants ranked our two techniques by preferential order. Nine of them declared that they preferred *Full-Drag* while 3 preferred *Dot.*

6.2.2 Subjective Preference. We asked our participants to explain what they liked and disliked about the two tactile techniques. Concerning *Full-Drag*, approximately 67 percent of participants felt comfortable when tracking the tactor movements (P2, P3, P5, P7, P8, P9, P10, P11). They especially liked that they could constantly perceive the tactor dragging on their skin as it was "easier to understand and feel a mental path for the graph" (P3). Finally, 3 participants (25 percent) reported "feel better [with the tactor] while dragging on my skin" (P7, P11, P12). Nevertheless, approximately 42 percent of our participants felt it was relatively difficult to understand when a graph stayed at the same point across time when using *Full-Drag* (P1, P3, P7, P8, P10). For participant 10, it was challenging to "estimate the time" passed between two consecutive data points. The tactor's speed was also mentioned as going fast for participant 11. One participant (P12) made a comment about the hair on the skin causing the feeling to be less accurate.

The most resounding benefit about *Dot* was the clear distinction between two consecutive data points that stayed at the same value (P2, P3, P4, P7, P9, P10; 50 percent). Participant 5 noted that the feeling of the pointing of the tactor was pleasant and less irritating. On the other hand, building a mental image of the line-graph was perceived as more difficult (P3, P4, P5, P7, P9; approximately 42 percent). Participant 10 felt it was "hard to retain in memory" the data positions. Also, participants felt is was difficult to sometimes know which data point was being represented for spatial reference when the tactor rose above the skin (P1, P4, P5, P12; 30 percent).

6.2.3 Summaries. Even though the performance did not vary across the two techniques tested, *Full-Drag* was the preferred skin-dragging technique by our participants. This technique helped them build mental images of the line-graphs, even if they had difficulties perceiving two consecutive positions. The difficulty in perception was countered as the strongest design aspect of *Dot*, which allowed for the distinction of points at the same value. Overall though, they felt less confident using *Dot* than *Full-Drag* even though the comparison between both techniques showed no significant difference.

7 Discussion

7.1 Accuracy of Line-Graphs

The accuracy in users' recognition of line-graphs was higher than expected. *Full-Drag* was preferred by our participants. We proposed a novel method to represent line-graphs without any visual or audio guidance, by compressing and using a single axis. Participants felt more comfortable using our tactile techniques over time during the study. Learning effects can influence the line-graph recognition accuracy. Most prior works on line-graph visualizations rely on specific tasks such as searching for the min/max or look at graph trends [23]. Such tasks require no need to remember the position of all data points, unlike the task we used for our study.

7.2 Location On The Body

Our device was used on the length of the participant's forearm. This location allows a wider interaction space than using the width of the forearm. However, this specific location has some constraints. First, because of forearm hair, the feeling of the tactor may differ from one participant to another and thus might impact the sensitivity of the tactor felt on the arm. Second, each participant needs to adjust the height of the prototype until they feel the most comfortable with at least the minimum amount of pressure from the tactor. It can be challenging to find a height that fits for every participant due to many different arm shapes and sizes. The difference is prominent enough to raise the question of testing the prototype on other locations of the body, such as the underside of the forearm as there is less hair.

7.3 Mobility Conditions

Eyes-free and audio-free visualizations are especially suitable in mobility condition while users are focused on other tasks: skin-dragging on the arm needs to be tested in these conditions. Thus, we are interested in the cognitive demand of the user to perceive a change in the position from the tactor while mobile and on-the-go.

7.4 Possible Applications and Designs

Tactile displays, being eyes-free and audio-free have the potential to be used in many in-situ situations. Such activities include using VR applications. While the user is immersed into a virtual world, a tactile display on their arm could provide the necessary feedback. This could include stats, game health, directions, and other aspects. Another application of tactile displays could be during fitness activities. Such information provided could be heart rate or intensity level. Lastly, we propose that tactile displays could be better used for visually impaired people to convey a wide array of information as tactile feedback has been widely studied. These possible applications all benefit from being able to understand complex information without having to stop and use a smart device. Our study proposed an option in conveying complex information that was previously unavailable. Currently our prototype cannot be use in mobile conditions. Rather, for this study we focused on conveying information. Nevertheless, we envision a new prototype that can be used on-the-go. We propose that a bracelet or the band of a watch can be used to render information using a discreet tactor and ergonomic design. The tactor will move around the bracelet, and depending on its position, users can differentiate data points representing many forms of information (see Figure 8). This could possibly be done without disturbing applications mentioned previously, and be done in an eyes-free and hands-free manner.

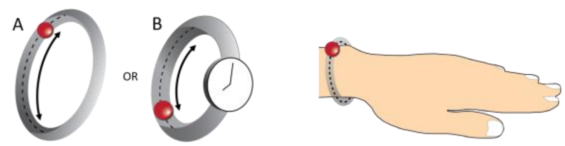

Figure 7. A and B represent either a bracelet or a smartwatch respectively. The tactor (red circle) can move all around bracelets to convey the tactile sensation

8 Limitations of the Prototype

8.1 Tactor Shape

We printed the tip of the tactor for our device based on our pilot tests. However, not all of the participants enjoyed the feeling of the tactor dragging on their skin, as some found it slightly irritating. Having the smoothest tactor possible is essential for user acceptance of the tactile display. Furthermore, due to the forearm curve, our prototype needed a strong force-feedback from the servo motor that controlled the tactor. This might have influenced the participants' experience about the shape of our tactor. It is worthwhile to note that with these technical limitations, our tactor was as thin as possible so as to not compromise tactile sensation.

8.2 Noise Produced by the Prototype

Using motors to control the tactor generated noise. To control any potential distraction effect, or recognition bias, when using our prototype we cancelled this noise by using earplugs and headphones. For the tactile displays to be true to their nature they must be free from noise. This is a limitation of our device that needs to be corrected in future work.

9 Conclusion and Future Work

In this work, we proposed a new skin-dragging tactile display to represent line-graph information while compressing the information on the x-axis. Thus, we proposed an eyes-free, audio-free, and hands-free representation of relatively complex information. Using a skin-dragging method as a type of tactile display has many advantages to convey complex information. Our prototype can allow real-time feedback in a gentle and non-disturbing way. Based on our results, participants were able to understand line-graphs in an eyes-free and audio-free manner. The results of our study were encouraging in participants' ability to recall graphs drawn on their arm. This study is an early first step towards eyes-free data representation of relatively complex information across the body. Future works would potentially look at whether participants can detect trends in infinite graphs that are drawn across the body. Theoretically, using a single axis allows us to display time series data potentially without any concrete time restrictions. Furthermore, the integration of a skin-dragging tactile display into fabric is an interesting challenge to better suit users' everyday life.

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