Designing Unobtrusive Modulated Electrotactile Feedback on Fingertip Edge to Assist Blind and Low Vision (BLV) People in Comprehending Charts

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ABSTRACT

Charts are crucial in conveying information across various fields but are inaccessible to blind and low vision (BLV) people without assistive technology. Chart comprehension tools leveraging haptic feedback have been used widely but are often bulky, expensive, and static, rendering them inefficient for conveying chart data. To increase device portability, enable multitasking, and provide efficient assistance in chart comprehension, we introduce a novel system that delivers unobtrusive modulated electrotactile feedback directly to the fingertip edge. Our three-part study with twelve participants confirmed the effectiveness of this system, demonstrating that electrotactile feedback, when applied for 0.5 seconds with a 0.12-second interval, provides the most accurate position and direction recognition. Furthermore, our electrotactile device has proven valuable in assisting BLV participants in comprehending four commonly used charts: line charts, scatterplots, bar charts, and pie charts. We also delve into the implications of our findings on recognition enhancement, presentation modes, and function synergy.

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CCS CONCEPTS

• **Human-centered computing → Accessibility systems and tools**; **Visualization systems and tools**; • **Hardware → Haptic devices**.

KEYWORDS

Accessibility; Electrotactile; Haptic Data Visualization; Accessible Data Visualization.

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1 INTRODUCTION

Graphical information, including graphs, charts, and maps (commonly called infographics), holds significant importance across various fields, such as education, the workplace, navigation, and daily activities [88, 97]. However, the visual nature of graphical information poses a significant barrier to blind and low vision (BLV) people [74]. This population comprises around 2.2 billion according

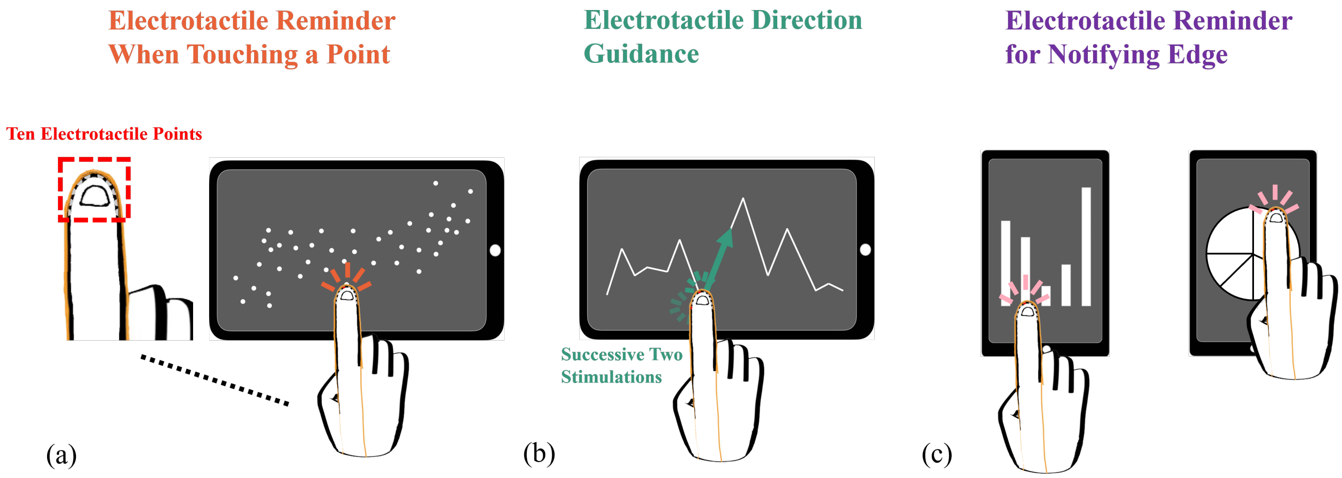

Figure 1: Overview of the Unobtrusive Modulated Electrotactile Tool to Assist BLV People with Comprehending Charts. (a) A red rectangle on the left marks the ten electrotactile points on the fingertip edge. The figure on the right shows the user perceiving an electrotactile vibration on one of the two top stimulation points when touching a data point; (b) Two successive electrotactile stimulations guide the user's finger to move towards the next data point on the line chart; (c) The user perceives an electrotactile reminder on one of the two top electrotactile points when touching the edge of a bar in bar charts (left), or the edge of a section in pie charts (right).

to the World Health Organization [73]. The lack of access to visualizations exacerbates the information gap, particularly concerning commonly used charts like line charts, scatterplots, bar charts, and pie charts [1, 56].

Efforts to address this issue have led to the development of various haptic assistive tools, including refreshable Braille displays and pin array haptic displays [35, 38, 58, 72], tactile graphics [7, 24, 31, 66, 91], and other haptic devices [1, 21, 29, 33, 90, 102]. However, these tools often come with limitations, such as being specialized for specific types of charts [2, 21, 29–31, 68, 80, 91, 96, 104], utilizing bulky or costly mechanical devices to render graphical information [1, 4, 33, 53, 68, 80, 91, 104, 106], or providing static charts without up-to-date information [7, 24, 31, 66]. These limitations give rise to the need for a light, conformal, non-expensive, and wearable device to assist BLV people in comprehending various commonly used charts they encounter in daily life.

To address these shortcomings, we present a new approach using electrotactile stimulation, which induces tactile sensations within the skin at the location of the electrode by passing a local electric current through the skin. The electrotactile interface is smaller, lighter, and more flexible, even suitable for elders and children [98]. While electrotactile feedback has found applications in various domains, including skill training [95], material textures rendering [101], VR and AR [62, 87, 92, 100], prostheses [52], guidance and notification [75] and assistive technology [62], prior research primarily concentrated on applying electrotactile feedback on either the fingertip pad or the backside of the finger [62, 98, 102]. These designs hindered BLV users' interactions with their surroundings (e.g., smartphone, door lock, and computer) while wearing the device, potentially causing inconvenience in real-life situations. To minimize disruption to multitasking and leverage the area with more densely distributed mechanoreceptors [45], we opted to apply electrotactile stimulation on the fingertip edge. In light of these research gaps and inspirations, we first designed an unobtrusive electrotactile system that applies electrotactile feedback on the fingertip edge based on a two-channel modulated signal to assist BLV users in comprehending commonly used charts. Then, we used it as a tool to investigate the following three research questions (RQs):

RQ1: How does our wearable electrotactile device perform in position recognition on the fingertip edge?

RQ2: How does our wearable electrotactile device perform in direction recognition on the fingertip edge?

RQ3: How could our wearable electrotactile device be designed to assist BLV people in comprehending common charts (e.g., scatterplots, line charts, bar charts, and pie charts)?

We conducted three studies with twelve BLV participants to evaluate its efficacy in assisting BLV individuals in comprehending commonly used charts. In Study 1, we determined that the optimal stimulation time of 0.5 s resulted in the highest position recognition accuracy of 0.789 out of 1. Most positions demonstrated consistently high accuracy, with positions 4, 5, 6, and 8 achieving an average accuracy of 1.0, and positions 2, 3, 7, and 9 achieving about 0.7 to 0.8. Moreover, we achieved high accuracy with much lower voltage (23 V) and smaller electrodes (3.14 mm^2) than the previous work. In Study 2, we found that an optimal interval of 25% of the stimulation time (0.12s) can achieve the highest direction recognition accuracy with an average angle of 7.975 degrees. In Study 3, participants exhibited minimal trajectory deviation under the *trajectory guidance* function of our device, which was as low as 0.21 cm (SD = 0.44 cm). Most of the participants completed all six chart comprehension tasks. Participants could replicate line charts, bar charts, and pie charts with our system's assistance, highlighting its effectiveness in providing an intuitive overview of the charts and efficiency in reducing time and effort to complete low-level visualization tasks. In summary, our device efficiently assists BLV users in comprehending commonly used charts. Our contributions include:

(1) The design and evaluation of an unobtrusive electrotactile system employing a modulated signal on the fingertip edge that provides ten-point stimulation;
(2) The investigation of the electrotactile device's performance in position and direction recognition and the selection of optimal parameters;
(3) The refinement of the electrotactile device to assist BLV users in comprehending charts with three presentation modes: chart guidance, chart exploration, and chart summarization.

2 RELATED WORK

2.1 The Accessibility Gap of Data Visualizations

The lack of access to graphical material is considered one of the biggest challenges that limit BLV people's independence and productivity [32]. Yet, they still encounter various obstacles when during this process. Recent studies explored BLV people's experiences with accessing visualizations and highlighted specific challenges [20, 36, 39, 47, 54, 55, 60, 65, 69, 83, 86, 107]. Fan et al. found that BLV people have concerns about accessing local COVID-19 data and charts promptly. Bar charts, line charts, and maps were rated as mostly not accessible, while bubble charts and pie charts were not accessible [20]. Sharif found that BLV screen reader users spent significantly more time and were less accurate in extracting information than sighted people when interacting with digital data visualization [86]. Holloway et al. found that BLV people have significantly lower comprehension of the COVID-19 pandemic's infection location distribution due to a lack of exposure to graphically presented information from news and other media [36].

To address the challenges that BLV people experience in accessing data visualizations, researchers designed various methods to improve their accessibility [47, 54]. For example, Jung et al. explored the current conditions of alternative texts in visualization. They found that BLV people actively try to construct an image of visualizations and wish to carry out visualization tasks as sighted viewers would [47]. Kim et al. identified three dimensions of strategies for verbally explaining chart types and developed an automatic system to generate text explanations from a given chart specification [54]. However, these methods rely on natural language descriptions, which may lead to missed visual details and a lack of spatial understanding, such as the size and shape of certain charts. It is of great importance and necessary to provide BLV people with direct access to the visual information of commonly used charts, such as bar charts, line charts, pie charts, and scatterplots. With more support for access to these charts, BLV people can obtain more insights from the data, improving their understanding of the world and allowing them to make more informed decisions [21].

2.2 Haptic Assistive Tools for Data Access

Haptic assistive tools presented data by rendering haptic feedback to the users, and can be classified into three main types: 1) refreshable Braille displays and pin array haptic displays [35, 38, 58, 61, 72, 82, 96], 2) tactile graphics [7, 24, 31, 66, 91], and 3) other haptic devices [1, 2, 4, 10, 21, 23, 29, 30, 33, 53, 67, 76, 80, 90, 102, 104–106]. For instance, Abu-Doush et al. developed a haptic device to assist BLV users in comprehending various charts and presented the related design principles [1]. Fan et al. developed two refreshable, 1-DOF audio-haptic interfaces (Slide-tone and Tilt-tone) to assist BLV users in understanding line charts [21]. Though several haptic assistive tools have been developed, some only explored one type of chart [2, 21, 29–31, 68, 80, 91, 96, 104], some utilized bulky or costly mechanical devices to render graphical information [1, 4, 33, 53, 68, 80, 91, 104, 106], while others offered static charts that did not provide up-to-date information [7, 24, 31, 66]. In particular, Chase et al. presented PantoGuide, which assisted BLV users in comprehending charts using skin-stretch feedback to the dorsum of a user's hand. However, it required a touchscreen for positioning and the physical printout of the charts for users to explore, which is touchscreen dependent and lacks flexibility [13]. In sum, the lack of compatibility with different charts, the large size and dependence on the touchscreen, and the unavailability of up-to-date information negatively impact the ability of previous devices to support BLV people with comprehending charts that they encounter in daily life. To address these limitations, there is an opportunity to develop a more lightweight, flexible, and touchscreen-independent haptic device that can render various commonly used charts (e.g., bar charts, line charts, pie charts, and scatterplots).

In addition, previous studies delved into the synergy between audio feedback and haptic feedback, revealing that the combination enhances task performance and reduces workload [19, 66, 81, 94, 103]. For instance, Yu et al. investigated the effectiveness of a kinesthetic force-feedback device and sonification in exploring bar charts, highlighting the utility of audio for obtaining a gist of the data and haptic feedback for navigation and comparing the relative size of bars [103]. In this study, we were inspired by the integration of the abovementioned two modalities and utilized audio to assist electrotactile feedback.

2.3 Electrotactile Interfaces

Electrotactile interfaces induce tactile sensations within the skin at the location of the electrode by passing a local electric current through the skin [48]. They are smaller, lighter, and more flexible than traditional haptic assistive tools (e.g., robotic arm, refreshable Braille display) [98]. With relatively low latency, a wearable electrotactile device enables BLV people to use it anywhere and anytime. In addition, using an electrotactile device prevented BLV people from moving the heavy and bulky mechanical device, which avoided potential inconvenience due to lack of vision. Currently, researchers have explored its use in skill training [95], material textures rendering [5, 26, 101], VR and AR [62, 87, 92, 100], prostheses [52], guidance and notification [75, 102] and assistive technology [15, 62]. Lin et al. developed a high-resolution electrotactile rendering system with several applications, including font braille rendering and VR. [62]. While these works investigated the potential applications of electrotactile devices for BLV users, many of them did not involve BLV individuals in their design or assessment processes [51, 62, 87]. Thus, there is an opportunity for us to actively engage BLV users during the design and evaluation of our device to ensure that it can effectively address their unique requirements for chart comprehension.

Furthermore, the cited works predominantly employed electrotactile stimulation on either the fingertip pad or the backside of the finger [62, 98, 102]. These designs impeded unobtrusive interactions with the surroundings, such as using fingerprints to unlock a cell phone or door lock or employing a keyboard and mouse to work on a computer, which are common real-life scenarios. In this context, it is crucial to minimize the disruption to multitasking, particularly without taking off the device during the process. This consideration inspired us to explore another skin area to apply electrotactile stimulation, such as the fingertip edge. More importantly, the fingertip edge has proven to be more sensitive to electrotactile stimulation due to the more densely distributed mechanoreceptors in this area compared to the fingertip pad or other areas[45]. Therefore, our research investigates how to design an electrotactile device that could effectively support BLV people with chart comprehension by applying electrotactile stimulations to the fingertip edge.

3 PROTOTYPE

To answer our research questions, we needed to build a prototype that could generate electrotactile feedback on the fingertip edge. We first present the working principle of inducing electrotactile perception. We then present the electrotactile system overview and the design of the wearable device. Last, we show how we ensured the safety of the proposed prototype.

3.1 Working Principle of the Electrotactile Perception

Electrotactile perception refers to the haptic sensation under the skin induced by electrical stimulation from an electrode [48]. Compared to mechanical tactile stimulation, electrotactile stimulation can induce a wider range of perceptions, including vibration, tingling, numbness, and burning, among others [25, 93]. The perception type, intensity, or quality can be easily modulated by adjusting the electrical signal parameters, providing a high degree of flexibility and control over the sensory feedback [5, 64]. Our study used a signal generator and power amplifier to generate electrical signals. Specifically, we employed a square wave with a frequency of 1 kHz, an amplitude of 1 Vrms, and a phase of 0 degrees, amplitude-modulated (AM) by a sine wave with a frequency of 40 Hz for channel 1. The same signal was applied to channel 2, except for the square wave phase, which was set to 180 degrees. Figure 3 (c) shows the signal for each channel and the combined signal. This type of signal produces a perception of high-frequency vibration.

Once the electrical signal was set, current transmission became another critical factor influencing electrotactile perception. The signals were transmitted to the skin through the round electrode of FPC. To produce a localized vibration under a specific electrode, it needed to be connected to channel 1 to serve as a positive electrode, while the other nine electrodes needed to be associated with channel 2 with the opposite phase to serve as negative electrodes. This allowed the current to flow to position under the target electrode to stimulate the mechanoreceptor to generate the electrical signal and transmit it along the nerve to the brain, where the signal was interpreted as a localized high-frequency vibration [27, 46]. Figure 3 (d) illustrates this process.

3.2 Electrotactile System Overview

Figure 2 (a) shows three main components of the electrotactile system: 1) signal generation, 2) stimulation selection, and 3) perception control. The signal generation component contains a dual-channel signal generator to output two signals of opposite phases (indicated by the red and blue arrows in the figure) to the amplifier, two oscilloscopes to monitor the current and voltage in real-time, and a dual-channel amplifier to magnify the input signal to provide sufficient stimulation voltage. The stimulation selection component mainly consists of ten relays and an Arduino board. Each relay receives two opposite-phase signals as input, and the switch of each relay is controlled by an Arduino board, which enables precise control over the electrotactile stimulation. The perception control component involves a customized, flexible printed circuit (FPC) with each electrode connected to the output of each relay. A computer is connected to the amplifier, Arduino board, and camera to facilitate data collection and monitoring. The camera captures finger movements during the studies, while a tablet records the patterns drawn in subsequent experiments.

3.3 Design and Fabrication of the Wearable Haptic Device

Figure 3 (b) shows the critical wearable device to induce haptic perception on the fingertip, which is composed of an FPC, FPC connector, connector container, and a watch strap. The FPC is soft, thin, and pliable, making it practical for soft electronics. The FPC is 460 mm long and 5.5 mm wide, with 4 mm long and 0.3 mm wide strip electrodes on both sides to match the connector interface. These strip electrodes are connected to ten round electrodes in the middle of the FPC through the copper path with a width of 0.2 mm. Figure 3 (a) shows that these round electrodes have a diameter of 2 mm and a center-to-center distance of 4 mm. The narrowest part in the middle of the FPC is only 3 mm. All conductive elements of the FPC are made of copper with a thickness of 1 ounce to ensure it can withstand the current.

After the FPC was fabricated, we welded hemispherical tin electrodes onto the top of the copper electrodes and used the tape on the knuckle to facilitate close contact with the skin, as shown in Figure 3 (d). Additionally, colored indicators were adhered to the corresponding positions of each electrode on the other side of the FPC, serving as markers for computer vision recognition. The upper part of Figure 3 (d) shows the resulting FPC and corresponding electrodes and markers are numbered 1 to 10 in a clockwise direction. The FPC was then attached to the FPC connector to receive an electrical signal. The FPC connector was placed in a 3D-printed connector container, which could be easily worn with a watch strap. Most importantly, the notch in the middle of the FPC was designed to ensure that only the fingertip edge was covered while the fingertip pad remained uncovered. This kind of unobtrusive design was proposed to allow interaction with the surroundings (e.g., smartphone, door lock, and computer) after wearing the electrotactile device. Moreover, the wearable device, control board, and switching relays are at a very low cost, less than USD 50 in total.

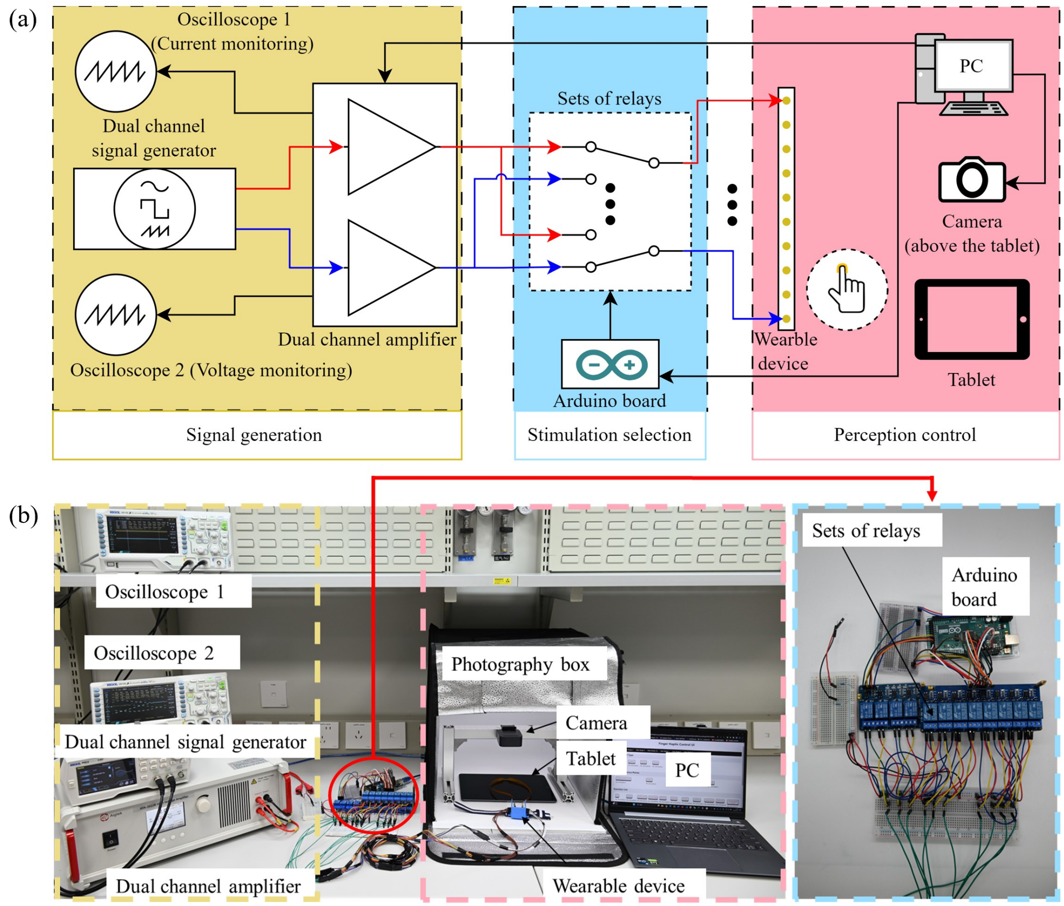

Figure 2: Overview of the electrotactile system. (a) The composition diagram consists of three components: signal generation, stimulation selection, and perception control. (b) The real image of the whole system.

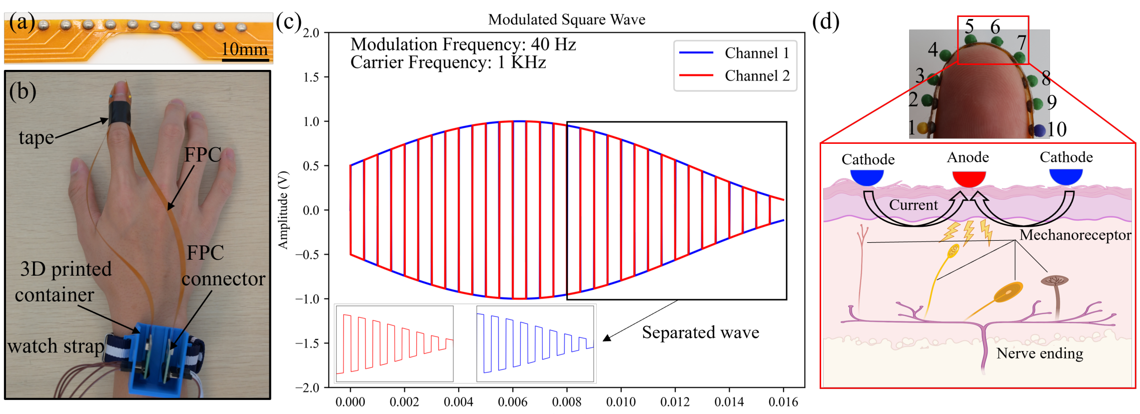

Figure 3: The design of the wearable device and the working principle of electrotactile perception. (a) The close image of the main part of the flexible printed circuit (FPC). (b) The real image of the hand after wearing the haptic device. (c) The waveform diagram of the two-channel two-phase modulated signal for inducing haptic perception. (d) The front view of the fingertip after wearing the FPC (upper part) and the schematic diagram of the working principle of electrotactile perception (lower part).

3.4 Safety Assurance

To ensure safety during the studies, various measures were adopted. First, the voltage and current were continuously monitored in real-time by two oscilloscopes. The maximum voltage applied to the skin was maintained below 50V, which is the safe limit for humans under 1KHz, by the International Electrotechnical Commission (IEC) standard. And the maximum current flow was kept below several mA. The current for electrotactile stimulation only traveled to the local and superficial skin area under the electrode, and the deeper motor nerves and muscles were not stimulated [16]. Additionally, The signal generator and power amplifier were also equipped with physical output cutoff buttons, which could also be controlled from the PC. Moreover, the coding was set to prevent the program from running when the voltage exceeded 36V. Before the studies, all participants underwent extensive safety training to ensure they understood the potential risks and how to avoid them. Furthermore, the electrodes used in the experiments were sterilized before each use to prevent infection. It is also worth noting that any adverse effects or discomfort reported by the participants were immediately addressed, and appropriate measures were taken to ensure their safety and well-being.

4 STUDY 1: POSITION RECOGNITION STUDY (RQ1)

To answer RQ1, we conducted Study 1 to investigate the effectiveness of the proposed electrotactile perception in position recognition. Since electrotactile experiments rely heavily on stimulation time, which can significantly impact the subject's perception intensity, accuracy, and comfort level [14], we also evaluated the effect of stimulation time on position recognition accuracy. This research was approved by the university's ethics review board.

4.1 Participants

We recruited 12 BLV individuals (9 males, 3 females) from the local community. All participants had received at least a middle school education, where they learned basic knowledge of charts and statistics. Their demographic information is shown in Table 1.

4.2 Independent Variables

The two independent variables in this study were stimulation position and stimulation time.

Stimulation position referred to the position on the skin under electrodes when the FPC was in close contact with the fingertip edge. Ten stimulation positions were represented by the number of the marker, as shown in Figure 3 (d).

Stimulation time referred to the duration of each stimulation. The stimulation time had an upper bound because prolonged stimulation would induce discomfort and pose potential safety risks. We selected five different stimulation times, including 0.1s, 0.5s, 1s, 1.5s, and 2s based on the previous study [14].

4.3 Dependent Variables

The dependent variable was the position recognition accuracy. For each position, the accuracy was calculated by dividing the number of correct perceptions by the stimuli number with an error tolerance of 1 position in both directions, within the range from 0 to 1.

4.4 Procedure

Participants were introduced to the experiment setup, especially the wearable device. To ensure optimal conductivity, participants were required to clean and dry their right index finger. An even layer of conductive gel was then applied to the index fingertip edge to reduce contact impedance. We attached the device to the participants' fingers and ensured that the position of the FPC was centered and symmetrical. Participants were then guided to touch the FPC and markers with the other hand to get familiar with the arrangement of the ten electrodes. Then we performed a calibration process, which was essential because the skin-electrode contact impedance can be affected by the skin properties like the humidity, temperature, and thickness of the skin layer [22, 70]. Even though we applied conductive gel, variations in contact impedance persisted across different positions. Voltage calibration was performed to ensure consistent and perceivable intensity across all ten positions. We began at 5V on each electrode, starting from position 1, and gradually increased until the reported sensation was at level 3 on a Likert scale (1: no perception, 5: very strong perception). Customized voltages were set for each electrode and adjusted until consistent for short (0.1s) and long (2s) periods. These final voltage settings were used in subsequent experiments. During this experiment, we stimulated the electrodes at different times: 0.1s, 0.5s, 1s, 1.5s, and 2s. We had three random stimulation sequences of the ten electrodes for each stimulation time. After each stimulation, participants were asked to report the perception position. In total, 150 simulations were conducted for each participant, taking approximately one and a half hours to complete.

4.5 Results

Voltage on Electrodes. Figure 4 (a) [1] shows the calibration results for ten stimulation positions. Positions 2, 3, 4, 5, and 6 have higher calibration voltages ranging 19-23V, while positions 1, 7, 8, 9, and 10 have lower calibration voltages ranging 10-15V. Figure 4 (b) shows the required voltage for this work compared with previous works. Generating effective tactile perception with small electrodes and lower voltage is a significant challenge. Previous studies [3, 50, 78, 79, 85, 98] have used either larger electrodes with lower voltage or smaller electrodes with higher voltage to achieve satisfactory perception, but these approaches may have safety limitations and practical constraints. Our study achieved effective perception with a required voltage of 23V, less than the 50V safety limits set by the International Electrotechnical Commission (IEC), and a smaller electrode area of around $3.14mm^2$.

Stimulation time. The position recognition under five stimulation times (0.1s, 0.5s, 1s, 1.5s, 2s) were 0.769, 0.789, 0.786, 0.764, and 0.783, demonstrating the effectiveness of our system for position recognition. Accuracy and minimizing discomfort or potential danger from prolonged stimulation were important factors when selecting a stimulation time. Therefore, a stimulation time of 0.5 seconds was chosen for subsequent experiments.

[1] The color scheme of the following charts was based on an established color-blind friendly palette [77]

Table 1: BLV participants' demographic information.

No	Gender	Age	Impairment level	Congenital impaired	Ability to read characters	Color perception
1	F	35	Totally blind	No	No	No
2	M	28	Totally blind	Yes	No	No
3	M	47	Totally blind	No	No	No
4	M	27	Totally blind	Yes	No	No
5	M	34	Low vision	Yes	Yes	Yes
6	M	30	Totally blind	Yes	No	No
7	F	33	Totally blind	Yes	No	No
8	M	34	Totally blind	Yes	No	No
9	M	36	Totally blind	Yes	No	No
10	M	36	Low vision	No	Yes	Yes
11	F	50	Totally blind	Yes	No	No
12	M	44	Low vision	No	Yes	Yes

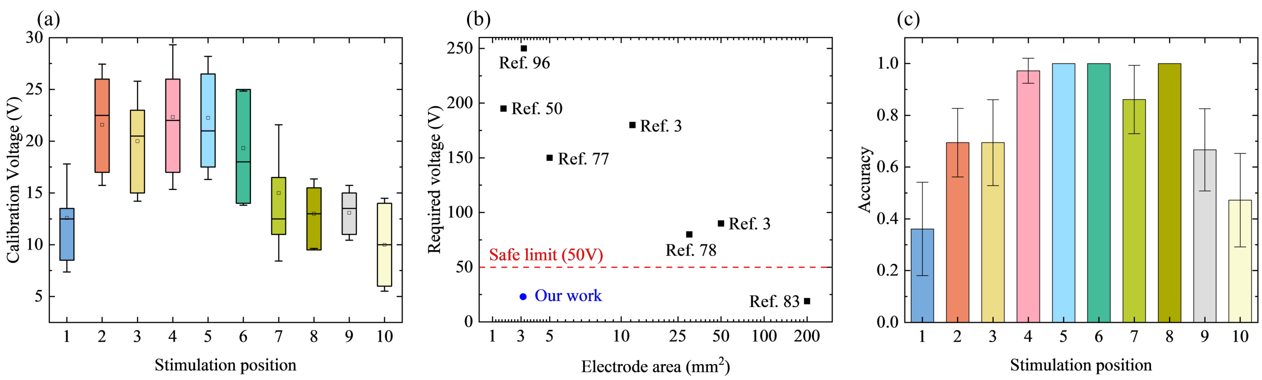

Figure 4: Calibration and position recognition results. (a) Box plot displaying the calibration voltage results. (b) The comparison of the required voltage for this work and previous research. (c) Position recognition accuracy for different stimulation positions at a fixed stimulation time of 0.5s.

Stimulation position. Figure 4 (c) shows the position recognition accuracy for 10 stimulation positions under the stimulation time of 0.5s. Most positions demonstrated consistently high accuracy, with positions 4, 5, 6, and 8 achieving an average accuracy of 1.0, and positions 2, 3, 7, and 9 achieving around 0.7 to 0.8. However, the accuracy at positions 1 and 10 was much lower, averaging about 0.4 to 0.5. Participants reported two phenomena related to positions 1 and 10: sensation shift and sensation defocus. Sensation shift refers to a shift in perception for 2-3 positions, where participants reported sensations at adjacent positions (3 or 4 for position 1, and 7 or 8 for position 10). Sensation defocus describes a sensation that lacks specificity to any particular position, instead encompassing a larger area (positions 1-5 for position 1, and positions 6-10 for position 10). Similar phenomena have been reported in previous research [50], attributed to mistaken interpretation in the brain. Although this affected positions 1 and 10, subsequent studies were not affected due to the redundancy of the ten stimulation positions. This allowed positions 1 and 10 to be substituted by other positions, as shown in the stimulation pair selection process in study 2, without compromising the study's objectives.

5 STUDY 2: DIRECTION RECOGNITION STUDY (RQ2)

To further answer RQ2 and prepare for RQ3, we conducted Study 2 to investigate the effectiveness of the proposed electrotactile perception for direction recognition and to evaluate the effect of the stimulation interval on the direction recognition accuracy.

5.1 Concepts Definition

Building on the results of Study 1, we conducted a direction recognition study to evaluate the performance of direction recognition under the effect of different stimulation intervals. This study involved four defined concepts: **Stimulation direction** refers to the direction of the line drawn from the first stimulation position to the subsequent stimulation position. **Stimulation pair** consists of two positions that are stimulated in succession. **Stimulation time** refers to the duration of stimulation for a single position. **Stimulation interval** refers to the time between the end of the first stimulation and the beginning of the second stimulation in a stimulation pair.

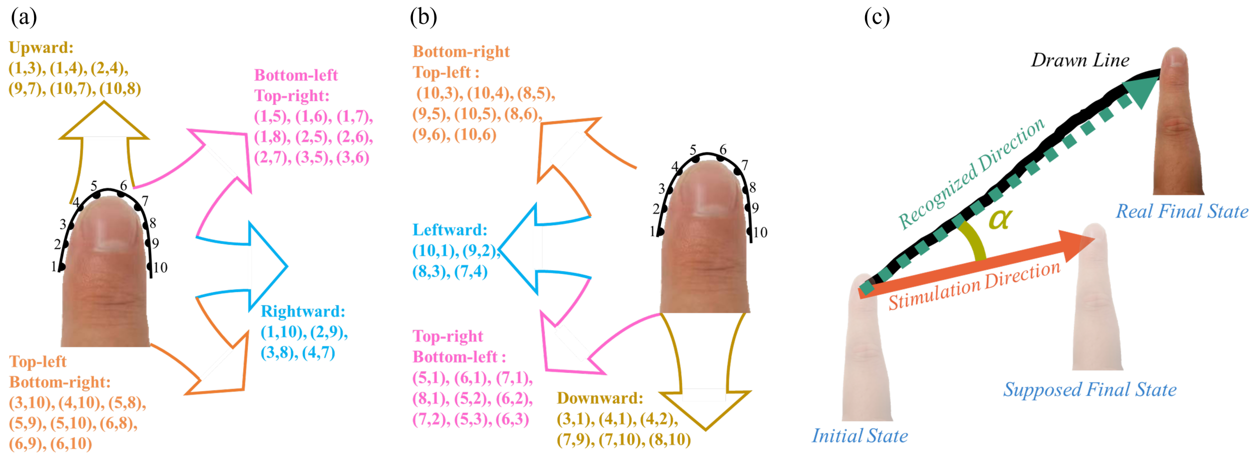

Figure 5: (a) & (b) The stimulation direction and list of stimulation pairs for each direction, where colored arrows indicate the direction ranges; (c) The illustration of the angle error calculation, where the recognized direction is the direction of a certain range of the drawn line from the starting point, and the applied stimulation direction is the line connecting the corresponding electrodes in this stimulation pair, the angle error is obtained by measuring the angle difference between these two directions.

5.2 Independent Variables

The stimulation pair and stimulation interval were the two independent variables. Based on the position recognition accuracy from Study 1 and the participants' comfort, we selected 0.5s as the stimulation time. As shown in Figure 5 (a), four stimulation pairs were selected based on the perception quality reported by the participants, one in each direction (colored arrow). The stimulation positions in each stimulation pair were reversed to achieve the opposite navigation, as shown in Figure 5 (b). It is worth noting that positions 1 and 10 were excluded by most participants due to their perception of sensation shift or defocus phenomena mentioned in study 1; a few participants who did not experience these phenomena could select positions 1 or 10.

Based on previous research [14], there should be an interval between two stimulations to avoid the masking effect between those two stimulations, and the ratio between the stimulation time and the interval should not exceed 1:1. Therefore, we selected these five stimulation intervals to test: 0%, 25%, 50%, 75%, and 100% of the stimulation time.

5.3 Dependent Variables

The dependent variable in this study was direction recognition accuracy, represented by the angle error. We calculated the angle error between the stimulation direction (represented by the line connecting two electrodes) and the recognized direction (represented by the line drawn by participants), as shown in Figure 5 (c). However, the lines drawn by participants were not perfectly straight and tended to deviate from the initial direction after a certain distance. To address this, we calculated the recognized direction by performing line fitting on the line drawn from the starting point to the last point before a major deviation occurred. Essentially, the smaller the angle error between the stimulation and recognized directions, the higher the accuracy.

5.4 Participants and Procedure

The same set of participants in Study 1 also participated in Study 2, which followed the same preparation process as Study 1, with only minor voltage adjustments made based on participant feedback. Then, we selected one stimulation pair for each direction, as shown in Figure 5 (a) based on the perception quality, and the stimulation of the selected pair should induce a clear perception along that direction. After stimulation pair selection, we helped the participant put their index finger on the marker (tape) at the center of the tablet screen so that the camera could capture their real-time finger movement on the screen. During the tasks, participants placed their index finger on the central marker and were asked to draw a line in the perceived direction after stimulation. A photo of the finger position and drawn path was taken at the end of each cycle, and three cycles were performed for each stimulation pair. A total of 60 tests were conducted for each participant, taking about one and a half hours.

5.5 Results

For all participants, we found that the drawn lines showed no apparent direction deviations within a range of 1cm. Therefore, we selected this range of drawn lines to calculate the recognized direction and plotted the angle error in four directions (the radius of the colored sectors) at five stimulation intervals in Figure 6. The angle errors in the bottom-left top-right, top-left bottom-right directions were slightly higher compared with horizontal and vertical directions. Most average angle errors were less than 10 degrees and the maximum angle error was 13.5 degrees. This level of accuracy was considered sufficient for Study 3, as the deviation of a shorter length under such an angle difference can be relatively small. For instance, we instructed and ensured the participants moved slowly in study 3, less than 5mm per stimulation. In the case of the maximum angle error of 13.5 degrees, the deviation is about 1.2mm, which is acceptable for exploring charts with a size of tens of centimeters. Figure

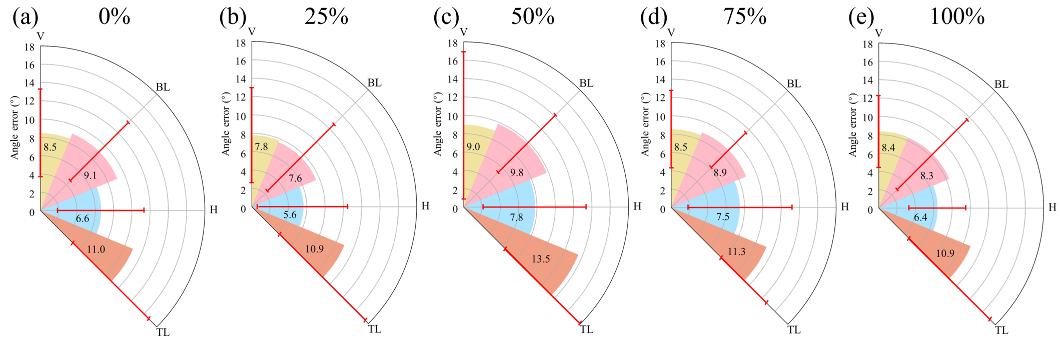

Figure 6: The direction recognition results under the stimulation intervals of 0% (a), 25% (b), 50% (c), 75% (d), and 100% (e) of the stimulation time. (H: horizontal direction, V: vertical direction, BL: bottom-left top-right direction, TL: top-left bottom-right direction) The radius of the colored sector represents the angle error. The smaller the radius, the lower the angle error, and the interval of 25% of stimulation time led to the lowest error in these directions.

6 (b) shows the angle error under the stimulation interval of 25% of stimulation time is the lowest, with an average of 7.975 degrees, compared with other intervals. We considered both accuracy and participants' fatigue due to prolonged stimulation and selected 25% of the stimulation time, which is 0.12s as the stimulation interval for Study 3.

6 STUDY 3: CHARTS COMPREHENSION STUDY (RQ3)

To answer RQ3, we conducted Study 3, where we explored how our device could assist participants in comprehending four commonly used charts: line charts, scatterplots, bar charts, and pie charts. In Studies 1 and 2, we demonstrated that two successive stimulations to the fingertip edge could achieve the highest position and direction recognition accuracy with an optimal stimulation time and stimulation interval of 0.5s and 0.12s, respectively. We used these values in Study 3.

6.1 Design considerations and functions

To develop an electrotactile assistive tool to aid BLV users in comprehending charts, we needed to track the participant's finger, calculate the required electrotactile stimulation pairs in real-time, and provide them with the necessary functions to comprehend charts. Therefore, we followed two design considerations: chart identification and marker recognition, and chart comprehension design.

6.1.1 Chart Identification and Marker Recognition. We used the MobileNet model to classify the data charts from real media, such as smartphones and newspapers [37]. We used the object detection model (YOLOv5) and EasyOCR to identify chart components and extract data[44, 57]. For marker recognition, we used the Canny edge detection algorithm to recognize the edges of markers[84]. We used each marker's position to approximate the electrode's position and recorded the relative positions of ten electrodes at the beginning of each participant session to match their fingers' shape and size. We tracked the electrodes' positions in real-time and calculated the position where the participant's finger touched the tablet, which we refer to as the "touching point." For electrotactile guidance, we compared the direction of each electrode pair with the direction between the touching point and the chart's next point (target direction), then we stimulated the electrode pair whose direction was the closest to the target direction. For the electrotactile reminder, when the finger's touching point was close to the key point (line chart, scatterplot) or edge (bar chart, pie chart), one of the top two electrodes (point 5 or 6) was stimulated to notify participants that they touched a data point, bar or section's edge.

6.1.2 Chart Comprehension Design. In line with prior work with three presentation modes for charts [1], we also developed three presentation modes: chart guidance, chart exploration, and chart summarization. We developed eleven functions to assist participants with overall chart comprehension, which were classified into these three presentation modes (Table 2). The presentation modes were designed based on Abu-Doush's classification criterion [1]: chart guidance mode utilized the electrotactile device to guide the user in exploring the chart in a predefined trajectory or directly to a key data point, chart exploration mode encouraged participants' active exploration of the chart, while chart summarization mode presented the key statistical information and values of data points, bars, and sections directly to the participants.

For the functions in chart guidance mode, the *trajectory guidance* guides participants' fingers along the predefined trajectory from the start point, bar, or section to the end with the audio report to present data information of each data point, bar, or section. In particular, pie chart guidance was conducted along the chord of each section rather than along each arc because following the guidance of a chord (straight line) compared to an arc required less short-term memory load. In addition, a ratio relationship exists between a pie section's chord length and arc length so that participants could understand the relative size of each section by comparing the length of each section's chord.

The *maximum guidance*, *minimum guidance*, *start point guidance*, *end point guidance* guided the participant to the four key points and read out their values through speech. The *comparison* allowed the participants to choose the two bars in a bar chart or two sections in a pie chart to compare the value of both bars or sections. Figure 7 shows the specific steps in both charts. When reaching the top

Table 2: Eleven Functions in Three Presentation Modes: Guidance, Exploration, Summarization.

ID	Modes	Functions	Function Descriptions
1	Chart Guidance	Trajectory Guidance	Guide the finger along the predefined trajectory
		Maximum Guidance	Guide the finger to the maximum, then report the value via audio
		Minimum Guidance	Guide the finger to the minimum, then report the value via audio
		Start Point Guidance	Guide the finger to the start point, then report the value via audio
		End Point Guidance	Guide the finger to the end point, then report the value via audio
		Comparison	Restructure the bar chart and pie chart for two bars or two sections comparison
2	Chart Exploration	Free Exploration	Freely explore the chart, notify when touching the edge
		Clustering	Notify the edge and points amount of each data cluster
3	Chart Summarization	Title Reading	Report the current chart's title via audio
		Average Calculation	Report the current chart's average via audio
		Current Value Report	Report the current value via audio

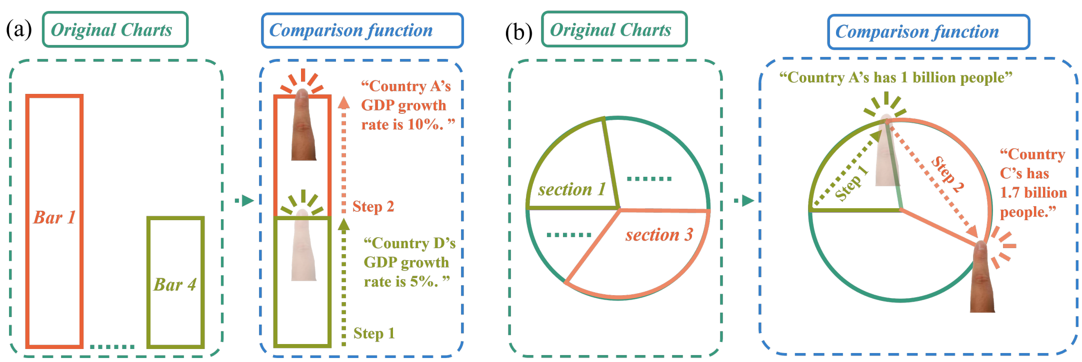

Figure 7: *Comparison* function: (a) For bar charts, the second bar was moved to overlap with the first bar. Then, the user's finger was guided by the electrotactile feedback from the bottom of the overlapped bars to the top of the shorter bar. After the audio reported the shorter bar's value, the user's finger was guided to the top of the longer bar, and another audio report of the longer bar's value was played. (b) For pie charts, the two sections were moved beside each other, and the user's finger was guided along the two section's chords sequentially. At the end of each chord, an audio report of that section was played.

edge of each bar or the end point of each section's chord, an audio report of the value of the traversed bar or section was played.

For the function in chart exploration mode, in *free exploration*, participants could freely explore the charts. A 0.1 s electrotactile reminder on one of the finger's top points (point 5 or point 6, according to participants' conditions) notifies any touch of the data point, bar, or section. An audio notification played when the finger was out of any bar or section in the bar chart and pie chart. *Clustering* function first clustered all the data points in the scatterplot, and participants would be notified by electrotactile reminder if they touched the edge of any cluster, and an audio notification played when the finger moved out of a cluster. There was no electrotactile reminder of data points but only clusters' edges.

For the functions in chart summarization mode, the *title reading* and *average calculation* reported the chart's title and average through speech. The *current value report* reported the current value when the participant's finger was on or within any data point, bar, or section.

6.2 Participants and Experiment Set-up

We recruited 12 BLV participants who participated in both Study 1 and Study 2. Participants returned one week following the completion of Study 2 to participate in this session. The experiment set-up of Study 3 is shown in Figure 2 (b). Participants sat on the chair with their right arm resting on the table and index finger wearing the FPC. They were allowed to either put their finger on the tablet or in the air with their most comfortable posture. All the participants chose to put their finger on the tablet during the training session because the touch between the finger and the screen provided them with a location reference. Python's CV2 library rendered all the charts, which only appeared on the operator's screen. The participants were allowed to draw freely on the tablet's screen.

6.3 Selection of Charts

We included four commonly used charts in our study: line charts, scatterplots, bar charts, and pie charts, based on Abu-Doush et al.'s findings of most commonly used charts in 836 Excel worksheets [17]. The four charts used in the study were based on real-world data. The line chart contained seasonal stock prices obtained from Yahoo Finance between 7.6.2017 and 7.6.2021 [99], the scatterplot contained data from UCLA's SOCR dataset of Human Heights (cm) and Weights (kg) [89], the bar chart showed world GDP growth (annual %) in 2016 from the World Bank's database [8], and the pie chart showed the world population (billion) in 2022 from the World Bank's database [9]. We made revisions to each chart according to our study design. The four charts are shown in Figure 8.

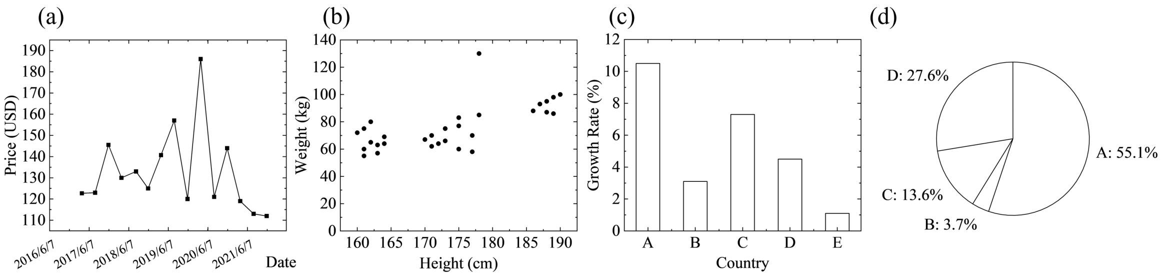

Figure 8: Four charts used in Study 3. (a) a line chart representing the stock chart for Company D with a Head and Shoulders (H&S) pattern, (b) a scatter plot depicting the Adolescent Height-weight in Region A, (c) a bar chart illustrating the GDP growth rate for countries in the year 2016, and (d) a pie chart showcasing the population distribution by country in a region for the year 2023.

6.4 Selection of Tasks

We designed six tasks to evaluate how electrotactile feedback could assist participants in comprehending four commonly used charts, shown in Table 3. We referred to Lee et al.'s work, which presented a series of visualization tasks for each commonly used chart. As mentioned by prior work [18, 43], BLV people could answer some of these tasks by traversing datasets, such as *Find Maximum*, *Find Minimum*, or *Calculate Average*. Our device included corresponding functions to provide such information automatically. However, other tasks, such as *Find Trend*, *Make Comparison*, *Characterize Distribution*, and *Find Clusters*, were hard to complete without visual information [18]. Therefore, we explored how our device could provide such visual information using electrotactile feedback and audio feedback.

The six tasks were selected based on Fan et al. [21] and Abu-Doush et al.'s tasks [17] that were used in evaluating their haptic device. We also referred to Boy et al.'s six fundamental data literacy questions [11], Lee et al.'s Visualization Literacy Assessment Test [59], and Amar's low-level visualization tasks [6]. The participants were asked to describe the chart in as much detail as possible and to draw it so that we could assess how well they understood the chart using our device. However, the drawing was non-compulsory, and the participants could choose to report the results orally.

6.5 Procedure

The participants first completed a training session to become familiar with each function. The moderator introduced each function and allowed participants to practice using them. In particular, we asked them to complete two training tasks (triangle for TN1 and rectangle for TN2) to teach them how guidance mode works. After the training session, they were asked to finish each task (T1-T6), with the order counterbalanced across participants. We recorded their trajectories under *trajectory guidance* in TN1 (follow triangle guidance), TN2 (follow rectangle guidance), and T1 (find line chart's trend). We only recorded these three trajectories because the line chart's trajectory was the most difficult, while the triangle and rectangle trajectories were the easiest, which showed the upper and lower limits. We recorded each task's oral report, replication drawings, and task completion count (TCC). After each task, participants completed the NASA-TLX questionnaire [34]. After participants finished all tasks, they partook in a semi-structured interview about their feedback on each function and their suggestions for improving the device. In total, the experiment lasted 2-3 hours.

6.6 Results

6.6.1 *Deviation of Trajectories.*

We calculated the root means squared (RMS) distance deviations of participants' finger movement under *trajectory guidance* from the predefined trajectory in TN1 (follow triangle guidance), TN2 (follow rectangle guidance), and T1 (find line chart's trend), which were 0.35 cm (SD = 0.39 cm), 0.51 cm (SD = 0.74 cm), and 0.21 cm (SD = 0.44 cm), while the entire screen was 23 cm by 18 cm. The trajectories are shown in Figure 9. We observed that the deviation of long movements in Figure 9 (a) and (b) are higher than the short movements in Figure 9 (c). One reason is that at each turning point of the shape (e.g., each corner of the triangle and rectangle, each peak of the line chart), an electrotactile reminder was applied to inform the participants that they had reached a key point. This reminder helped them focus on the guidance for reaching the next point. With more short movements, it was more likely that the participants could focus on the guidance direction. However, in long movements, the participants' concentration gradually weakened due to the lack of this reminder.

6.6.2 *Task Completion.*

The drawing was non-compulsory, so a correct oral report was also considered a correct answer. **Most participants (10/12) completed T1 (find line chart's trend)**. The task was marked as successful if they reported the overall trend containing four peaks. Indeed, Figure 10 (a) shows that participants could recognize the maximum peak and the other three peaks and drew them in the correct locations. The other lower peaks, however, were easily missed by the participants. **Most participants (10/12) completed T2 (pattern matching)**, and they successfully reported the pattern range by pointing out the start and end points of the pattern. They used the *maximum guidance* to locate the maximum peak and the *free exploration* to look for the pattern's other two peaks. **All participants (12/12) completed T3 (find scatterplot's trend)** and reported a gradually increasing trend of the scatterplot. **Almost all participants (11/12) completed T4 (identify clusters in the scatterplot)**. Some participants (P4, P6, P10) usually started with the free exploration function and when they encountered a data point, they moved their fingers in a spiral

Table 3: Charts Comprehension Tasks

ID	Chart Type	Detail Description of Tasks	Subtasks Involved
T1	Line Chart	Please describe the trend of the line chart and draw it if possible.	Find Trends
T2	Line Chart	Please find the maximum of the chart, and identify the start and end point of the Head and shoulders pattern (three continuous peaks with the highest peak in the middle).	Retrieve Value, Find Extremum, Make Comparisons, Determine Range
T3	Scatterplot	Please specify whether the scatterplot has a trend. If yes, please draw the trend.	Find Trends, Characterize Distribution
T4	Scatterplot	Please identify the number of clusters in the scatterplot. Please identify the location of each cluster and rank them in cluster size.	Find Clusters, Find Anomalies, Make Comparisons
T5	Bar Chart	Please identify the value and location of each bar in the bar chart and draw the bars in order.	Find Extremum, Make Comparisons
T6	Pie Chart	Please identify the value and location of each section in the pie chart and draw the sections in order.	Find Extremum, Make Comparisons

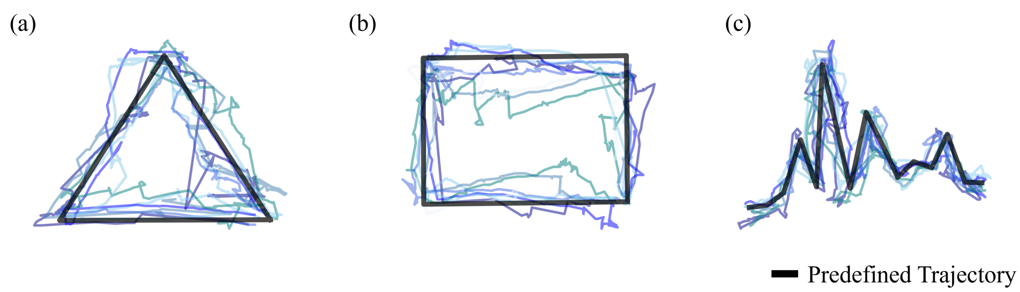

Figure 9: The trajectories of the two training tasks (TN1, TN2) and T1. The blue lines were the participants's finger-moving trajectories, while the black lines were the predefined trajectories: a) TN1 (follow triangle guidance); b) TN2 (follow rectangle guidance); c) T1 (find line chart's trend)

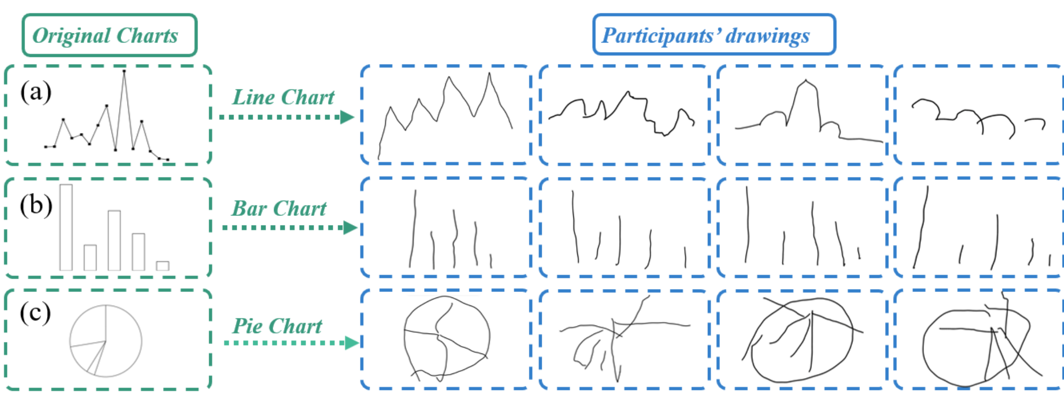

Figure 10: Replication of charts: (a) The original line chart (left), and four examples of participants' line chart replications (right); (b) The original bar chart (left), and four examples of participants' bar chart replications (right); (c) The original pie chart (left), and four examples of participants' pie chart replications (right).

motion around that point to find the nearby data points. One participant (P7) also mentioned directly using the *clustering* function as it showed a clear border of each cluster and notified him when his finger was out of any cluster. **All participants (12/12) completed T5 (replicate bar chart)**, and they reported the correct number of bars and their locations in the chart and correctly ranked them in value. Seven participants drew the charts, as shown in Figure 10 (b). The heights that some participants drew (P7, P8, and P9) were nearly identical to the original chart's bar heights. The distances between adjacent lines were also nearly identical to those between the adjacent bars in the original chart. Participants reported that after repeated exploration, they could clearly understand each bar's absolute shape, size, and location and thus could draw it as the original chart presented. **More than half of the participants**

(7/12) completed T6 (replicate pie chart). From the comparison in figure 10 (c), we observed that although they reported the correct number of sections, each section's size, and location, they could not replicate the chart accurately. One reason might be the relatively close distance between adjacent radii, especially when the participants' fingers moved close to the circle's center.

6.6.3 Qualitative Feedback. We report key findings from the interviews about two presentation modes: Chart guidance mode assisted participants in obtaining the chart's overview (*trajectory guidance*), reduced the time and effort required for low-level visualization tasks (*Maximum guidance*, *minimum guidance*, *start point guidance*, and *end point guidance*), and provided a precise comparison of data bars and sections (*Comparison*); Chart exploration mode further strengthened the comprehension of charts (*free exploration*) and provided an addition and validation to the *free exploration* of the scatterplot (*clustering*).

Regarding the chart guidance mode: ***Trajectory guidance* assisted participants in obtaining an overview of the charts.** We found that *trajectory guidance* helped the participants in four ways: 1) build a mental map of each chart, 2) obtain an intuitive understanding of the absolute size of each data bar or section, 3) understand the trend of the line chart, and 4) decrease the information gap between them and the sighted people.

Participants felt that they could construct a mental map of the chart because our device guided their fingers throughout traversal, which allowed them to understand the exact size of the whole chart and the length, width, and location of each data point, bar, or section. One participant mentioned:

> " The *trajectory guidance*, generated solely through haptic feedback, informed me of the exact shape of the pie chart. I thought the pie chart was like a fan rather than a circle. Compared to audio feedback, haptic feedback provided more precise direction guidance, and thus helped me understand the trend of line chart and the actual shapes of the bar and pie charts" -P1

Participants easily identified the trend for line charts with clear electrotactile guidance. Once they deviated from the expected trajectory, they could feel that the guidance changed its direction to navigate the fingertip back to the next point. This error correction strengthened their memory of direction changes between data points. One participant mentioned the usefulness of electrotactile guidance for large amounts of data:

> "Haptic guidance informed me of a trend's intuitive overview, different from tedious and time-consuming audio speech. This works well, especially for large amounts of data." -P8

Additionally, some participants mentioned that *trajectory guidance* decreased their information gap with sighted people by getting the chart overview. They mentioned that although screenreaders could convey the data values, they lacked information about a chart's shape, size, and distribution. For example, the immediate overview from the bar chart was also provided to them, thus making them more confident in reading charts.

***Maximum guidance, minimum guidance, start point guidance, end point guidance* reduced the time and effort required for low-level visualization tasks.** These four functions directly provided the participants with the desired location or statistic without the need to search for or calculate them. The *start point guidance* and *end point guidance* could take the participants to the start or end point, which was useful for informing the participants of the exploration area's range. P6 summarized these functions' usefulness: he could quickly obtain a chart's overview by using the four guidance functions to build a mental map of the chart's structure, and there was no need for him to conduct repeated traversals or bother his colleagues.

***Comparison* could precisely compare data bars and sections.** Figure 7 shows that during comparison, the bars and sections were relocated to be close to each other. Some participants mentioned that the overlap between two bars allowed a more precise comparison than *free exploration*, while others appreciated its use for comparing pie charts:

> "This function is especially suitable for comparing two pie chart sections as it moves them together. I could make a precise comparison by memorizing the distance of two guidance trajectories. " -P11

Regarding the chart exploration mode: ***Free exploration* further strengthened the comprehension of charts.** Participants repeatedly strengthened their memory of the chart and efficiently made comparisons. After traversing the entire chart under guidance, participants sometimes wanted to return to certain areas to ensure that their memory of the chart's details was correct. For instance, when continuously moving through several peaks in the line chart, they sometimes forgot the number of peaks and relative height between different peaks. As mentioned by P7, with *free exploration*, he could quickly double-check areas of interest.

Free exploration also ensured efficient comparison between the value of data points, bars, and sections. By moving fingers horizontally, the participants could understand whether the following bar or point was higher than the current bar or point. For the bar chart, the participants moved their fingers from the top edge of one bar. If no side edge of another bar was touched, the initial bar was the highest. For the line chart, when searching for the two lower peaks in T2, participants compared the value of the potential points by moving their fingers horizontally (See Figure7). One participant mentioned that:

> "I could quickly compare the value of one bar and another with *free exploration*'s haptic feedback. Specifically, I could measure the size with my finger's movement rather than memorizing abstract numbers read out by the screen readers." -P9

***Clustering* supported and validated the *free exploration* of the scatterplot.** Participants often used the free exploration function to comprehend scatterplots at first and then checked their understanding of the clusters using this function. Nevertheless, participants mentioned that this function could be used independently to learn the cluster distribution, which was suitable for participants who only focused on the clusters or would like to obtain an overview rapidly. Participants also learned the cluster boundaries since voice notifications were played when participants' fingers left a cluster. One participant mentioned the possible usage:

> "I could use it to understand people's location in a room. For instance, when walking in the shopping mall, I could easily avoid collision with the pedestrians if I know the clusters of them. " -P3

7 DISCUSSION

We conducted three studies to understand how could our electrotactile device assist BLV participants in comprehending commonly used charts. In Study 1, we investigated how stimulation time affected position recognition accuracy and found the optimal stimulation time (0.5s) for all the electrotactile points. We also achieved a high average position recognition accuracy (0.789) with much lower voltage (23V) and smaller electrodes (3.14mm^2) than previous work. In Study 2, we investigated how the stimulation interval affected the direction recognition accuracy and found the optimal stimulation interval (0.12 s), which achieved the highest direction recognition accuracy (average angle error of 7.975 degrees). We derived the two optimal parameters for study 3, where we explored how our prototype could assist participants in comprehending four commonly used charts, and we found that our device provided an intuitive overview of the charts effectively and reduced the time and effort to complete low-level visualization tasks. Next, we discuss the implications of the findings from three perspectives: enhancing the position and direction recognition with unobtrusive modulated electrotactile feedback, presentation modes of haptic charts comprehension assistive tools, and the synergy between *trajectory guidance* and *free exploration.*

7.1 Enhancing The Position and Direction Recognition With Unobtrusive Modulated Electrotactile Feedback

Compared with prior work that used electrode arrays on the fingertip pad [79, 87, 108], our proposed unobtrusive design only used a linear arrangement of 10 electrodes that could be wrapped around the fingertip edge, not only providing a more natural and intuitive stimulation and allowing for other unobtrusive interactions, such as using a mouse or a keyboard to work on a computer or unlocking cell phone or door lock with the fingerprint, but also utilizing the fingertip edge where the mechanoreceptors are more densely distributed compared to the fingertip pad or other areas [45]. Additionally, the stimulation signal used in this research involved applying a dual channel modulated signal, which has been shown to provide higher accuracy in position and direction recognition with less voltage in small electrode areas than other methods, such as using a high voltage signal to induce suitable perception [49, 98]. The current study achieved an average position accuracy of over 75%, higher than the previous work [42] and very close to another previous work (78%) with mechanical actuators [40]. As for the direction recognition accuracy (average angle error of 7.975 degrees), it's a little lower than the previous work [21, 63], but it is still satisfactory considering the mechanical stimulation they used instead of electrotactile stimulation. More importantly, our system is more compact and lightweight compared with these bulky mechanical setups.

Moreover, the trade-off between accuracy and resolution depends on various factors such as the number and spacing of the electrodes. Since the 10-electrode arrangement was a redundant design, which mitigated the effect of sensation shift or defocus on positions 1 and 10, the accuracy of our system could be further improved by reducing the electrodes at positions 1 and 10.

7.2 Presentation Modes of Haptic Charts Comprehension Assistive Tools

We elaborate on the chart guidance and chart exploration mode by comparing the task performance of our work with prior haptic assistive tools and by discussing the synergy between haptic and audio feedback.

The chart guidance mode provided two successive stimulations without limitations on the direction of movement. When moving away from the predefined trajectory, the guidance's direction also changes to steer users back to the target trajectory. In contrast, many prior works guided the participants in a predefined trajectory using robotic arms and limited participants' free movement [17, 76]. Although their mechanism could achieve a low deviation from the target trajectory, our mechanism encouraged the user to recognize the guidance direction proactively. The subtle adjustments in guidance direction allowed participants to swiftly return to the expected trajectory, which helped them build an intuitive overview of different charts. For instance, in T1 (find line chart's trend), we achieved a TCC of 10/12, which is similar to that reported by Abu-Doush et al.[1], where participants verbally described and drew the line chart after haptic guidance, achieving an accuracy of 84%. In addition, our device could directly guide the user's finger to the start point, end point, maximum, and minimum on the chart. Compared to an audio report of the value, physically guiding participants to key points provided a better understanding of the chart's size and structure. For instance, in T2 (pattern matching), we achieved a TCC of 10/12. This task, which encompassed subtasks like value retrieval, extremum identification, comparisons, and range determination, did not have a direct equivalent in prior research assisting chart comprehension for BLV users. With the rapid recognition of the maximum and range of the chart (between the start point and the end point), the participants could match the pattern in the chart efficiently. In T6 (replicate pie chart) we achieved a TCC of 7/12. While few previous works have required participants to replicate pie charts using haptic feedback [1, 96], participants in our study mainly utilized *trajectory guidance* and *comparison*. In sum, our device facilitated participants in attaining notably high navigation accuracy and task completion when comprehending charts. This may be due to our design leveraging egocentric guidance, in which users establish the coordinates according to their own body's axes [71]. Prior work demonstrated that BLV people found it easier to comprehend egocentric spatial information than allocentric spatial information, especially in small-scale spaces [41]. This rationale elucidates why our device provided high-accuracy navigation for BLV users. Since our findings reinforce earlier research showing that non-visual egocentric navigation using auditory and haptic cues can attain exceptional accuracy [28, 63, 71], future work could consider continuing to leverage this method to support BLV users.

Our device offered a chart exploration mode that was widely used in various charts. For instance, in T3 (find scatterplot's trend) and T4 (identify clusters in the scatterplot), we achieved the TCCs of 12/12 and 11/12, respectively. T3's performance surpassed that of Abu-Doush et al.'s task, where participants only chose the guided presentation mode, in which the robotic arm guided the participants to traverse all the data points [17]. In contrast, all of our participants utilized the *free exploration* and correctly identified the trends in point distributions within scatterplots. T4's performance was notably higher than the 43% reported by Braier et al. [12]. One contributing factor to this difference was their study's large amount of data points, making it challenging to distinguish individual points. Our device, with its ability to precisely differentiate points separated by a distance of more than 0.68 cm and the use of electrotactile reminder to delineate cluster borders, contributed to the higher TCC of our study. When used in T5 (replicate bar chart), we achieved a TCC of 12/12, matching the results of Abu-Doush et al. [17]. Our approach differed from theirs in that our participants did not need to move to the top of each bar to change to another. The participants could navigate freely across the chart. The system provided haptic and audio notifications regarding chart borders and out-of-bar positions, demonstrating that comprehension of bar charts could be achieved without forced movement constraints.

We examined the effectiveness of using audio feedback to supplement haptic guidance via electrotactile stimulations. Although audio cues provided information on specific values for each point, bar, and section, they were insufficient for allowing participants to develop a holistic understanding of the charts. Participants felt that transferring abstract numbers to a mental map required considerable effort, and this process became increasingly challenging as the dataset grew in complexity. On the contrary, relying solely on haptic feedback, without audio, allowed participants to establish a mental map of the figure's layout. However, this layout lacked a meaningful connection to actual data values, rendering the mental map insufficient for obtaining desired information from the charts. In this scenario, while extracting numerical values was achievable through audio screen reader reports, the intuitive comprehension of the chart's structure, especially the relative size of each section, required haptic guidance. Therefore, participants expressed a preference for a combination of haptic and audio feedback to develop a full understanding of common charts. Our findings underscore the potential of supplementing haptic feedback with audio feedback to improve BLV users' chart comprehension, aligning with previous studies [19, 66, 81, 94]. Subsequent research could explore the integration of audio and haptic feedback to enhance assistance for BLV users further.

7.3 The Synergy Between *Trajectory Guidance* and *Free Exploration*

The combination of *trajectory guidance* and *free exploration* emerged as a valuable strategy for participants to obtain a comprehensive understanding of the presented charts. This approach involved utilizing *trajectory guidance* to build an approximate mental map of the chart's layout, then complementing and refining this mental representation through *free exploration*. Interestingly, participants showed different preferences for these two functions depending on the specific type of chart being encountered. For line charts, which participants mentioned they often traversed (e.g., to check stock prices), they employed both functions, allowing them to assimilate key information effectively. In contrast, when confronted with charts they encountered less frequently, such as scatterplots and pie charts, participants typically began with *trajectory guidance*. They found it advantageous to receive guidance initially, enabling them to grasp the fundamental aspects of these unfamiliar chart types. This preference for *trajectory guidance* in the initial stages of interaction was not linked to variations in participants' economic backgrounds, as suggested in previous research [33]. Furthermore, Wall et al. mentioned that their participants easily skipped between pie chart segments, leading to difficulties in touching small sections [96]. This issue was not observed in our study as participants who started with *trajectory guidance* were better equipped to recognize even the smallest section and accurately reported the presence of four sections in the chart. Conversely, participants who did not utilize *trajectory guidance* tended to overlook this particular section, resulting in the report of only three sections in the chart. Our findings underscore the complementary nature of *trajectory guidance* and *free exploration* in ensuring effective chart comprehension.

8 LIMITATION AND FUTURE WORK

Our three studies, involving 12 participants, demonstrated the effectiveness of our electrotactile device in aiding chart comprehension. Although eight out of twelve participants were congenital blind and thus did not have experience viewing charts, we did not explicitly gather such information from all participants. Consequently, it remains unclear whether and how the prior experience of viewing charts among BLV people may affect their usage of our electrotactile device. Future research should investigate how participants' visual condition (e.g., totally blind, low vision) and their prior experience of viewing charts (e.g., exposure before blindness, no exposure due to congenital blindness) may impact their task performance and the perceived usefulness of assistive devices for chart comprehension.

Our current electrotactile system comprises several pieces of equipment and a wearable device, which has some limitations. Firstly, The system is not compact enough to be carried around. Also, despite the FPC being limited by the thickness and bending stiffness of current FPC substrate materials, it is yet to be sufficiently flexible and conformal to the user's epidermis. In these studies, we used adhesive tape and conductive gel to ensure intimate contact. In future work, more compliant substrates, tiny electrodes, and ultrathin interconnects can be used to reduce the flexure rigidity and improve the conformality of the device. To address these limitations, future work can leverage 3D printing to seamlessly conform to different individuals' skin to provide adequate haptic feedback and achieve the design of the control system in an automatic, compact, and wearable manner.

Our device holds potential applications in various domains, including image comprehension, navigation, obstacle avoidance, map reading, touch-screen augmentation, and human-vehicle interaction. In image comprehension, electrotactile feedback can enable BLV users to gain insights into product images on online shopping sites, allowing them to perceive the shape and design of clothing items. For daily navigation and obstacle avoidance, the electrotactile feedback can aid users in identifying the location and size of the nearby door or window in a room. The feedback's intensity variation can notify them of their distance from obstacles and crowds, helping them avoid potential collisions. When reading maps, the electrotactile feedback can convey the distribution of roads, rivers, and points of interest, much like reading line charts and scatterplots using the exploration function. This quick map overview can assist in trip planning before travel. Furthermore, employing haptic augmentation of touch screens, such as those found on smartphones, household appliances, and vehicles, can provide BLV users with a tactile sensation akin to pressing a physical button. This enhancement can improve their interaction efficiency and intuitiveness in various daily tasks.

9 CONCLUSION

In conclusion, we conducted three studies aimed at assessing the effectiveness of our electrotactile device in facilitating chart comprehension for BLV people. We proposed an unobtrusive electrotactile system that applies electrotactile feedback on the fingertip edge based on a two-channel modulated signal. In Studies 1 and 2, we determined the optimal stimulation time and stimulation interval. Study 3 showed that participants achieved a high position and direction recognition accuracy with lower voltage and smaller electrodes compared to prior work. Our investigations demonstrated that our device effectively aids participants in comprehending the four commonly used charts: line charts, scatterplots, bar charts, and pie charts. Moreover, we delved into recognition enhancement, presentation modes, and function synergy. Our work serves as a valuable reference for the future development of electrotactile assistive tools to facilitate the comprehension of commonly used charts for BLV people.

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A APPENDIX

Table 4: The statistic data of calibration voltage in study 1

Stimulation position	Average value	Standard deviation	Median value
1	12.58	5.21	12.5
2	21.58	5.85	22.5
3	20	5.80	20.5
4	22.3	6.98	22
5	22.25	5.94	21
6	19.33	5.52	18
7	15	6.58	12.5
8	13	3.36	13
9	13.08	2.64	13.5
10	10	4.49	10

Table 5: Stimulation direction and pairs options

Direction	Stimulation pair
Rightward	(1,10), (2,9), (3,8), (4,7)
Upward	(1,3), (1,4), (2,4), (10,8), (10,7), (9,7)
Top-left Bottom-right	(3,10), (4,10), (5,10), (6,10), (4,9), (5,9), (6,9), (5,8), (6,8)
Bottom-left Top-right	(1,5), (1,6), (1,7), (1,8), (2,5), (2,6), (2,7), (3,5), (3,6)