Evaluating the Efficacy of Friction Modulation for Guidance for Blind Individuals

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Graduation Date: October 27, 2023

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Abstract

The emergence of tactile technologies has paved the way for addressing various challenges. Tactile sensing is especially vital for the blind and visually impaired. This study investigates how tactile feedback can enhance mobility and independence among individuals in this community. In today's touchscreen-dominated world, accessibility remains a critical concern for those who are visually impaired, as touchscreens lack the tactile guidance necessary for effective touchscreen use. In addition, it is investigated if the guidance is useful for orientation. Our innovative approach employs a directional friction modulation rendering method, aiding users in finger movement and orientation. The efficacy of the tactile directional cue will be assessed for a tracking task and an orientation task. The tactile cue's shape is determined by the parameter σ, which we optimize in our research. Additionally, in the orientation experiment, we explore the impact of different Field of Feeling ranges, representing the maximum perceivable angles on the actuated glass plate. Our methodology involves blindfolded participants in experiments assessing their ability to interpret and respond to tactile cues generated by an ultrasonic friction modulation device. We use quantitative measures, including response time and directional accuracy, and qualitative feedback from questionnaires to capture participants' experiences with the tactile feedback system. Our findings reveal fascinating insights into the influence of σ and the Field of Feeling. On average the paths were tracked with an error of 9.84 mm. Smaller σ values correlate with improved tracking performance, as evidenced by the lower root-mean-square error between the finger and the reference path. This relationship is described using a logistic function. The directional friction modulation rendering method was shown to be viable for finding the reference angle. On average, this was achieved in 10.79 seconds with a manageable error of 6.28 °. Specific differences between the tested values for σ were not found. In contrast, the Field of Feeling's influence on the results appears more pronounced. A broader Field of Feeling leads to quicker decision times when at the reference angle. These outcomes shed light on the feasibility and effectiveness of ultrasonic friction modulation as a tactile feedback mechanism for enhancing the independence of blind individuals. Furthermore, the successful integration of this technology holds the potential to revolutionize electronic surface haptic devices for a wide range of users.

Index Terms

Surface haptics, friction modulation, ultrasonic vibration, blind guidance, tactile directional cue.

I. Introduction

Human senses are remarkable in processing a wide range of stimuli and providing a rich and nuanced understanding of the world around us. Our senses work together to allow us to perceive and interact with the environment, enabling us to experience the beauty of a sunset, the taste of a delicious meal, or the comfort of a hug. Overall, our senses are a testament to the incredible complexity and capabilities of the human body. However, not everyone has full access to all senses. Globally, 43 million people live with blindness and 295 million people live with moderate-to-severe visual impairment [1]. It is commonly accepted that people with impaired vision can partially compensate for their vision loss with better use of their remaining senses [2]. Studies show that for people who lost sight at an early age, the visual cortex activates when reading braille [3]–[5]. This shows how crucial tactile sensing is for people with impaired vision. There has been a significant amount of research on designing and developing tactile displays for blind individuals, focusing on creating displays that are easy to use, intuitive, and effective at conveying information. O'Modhrain et al. suggest that tactile displays have the potential to enhance accessibility and independence for the visually impaired [6]. One of the tasks where the blind or visually impaired are still dependent on others is navigation; research has been done to find ways to help blind individuals be more independent [7]–[10]. An important aspect of navigation for blind individuals was found to be egocentric representation. Brayda et al. [11] found that the orientation of the map matters for the blind or visually impaired, as an allocentric map (one that is oriented based on the environment) can lead to decreased navigation accuracy and speed compared to an egocentric map (one that is oriented based on the user's perspective). Touchscreens also pose problems however, the guidance of the finger improves the usability of touchscreens for the visually impaired [12]. Guidance for touchscreens was typically achieved using rigid buttons, despite their limited versatility. To get a comprehensive overview of these issues multiple blind and visually impaired individuals were interviewed. The questions and the interviews are visible in Appendix A. Many of these issues can be improved using surface haptics [13], [14], which is the field of providing tactile feedback on touch surfaces. It aims to enhance the user experience by simulating the sense of touch or physical interactions with digital surfaces, such as touchscreens or touch-sensitive devices [15]–[17].

Traditional touchscreens primarily offer visual and auditory feedback, but they lack the ability to provide realistic tactile sensations. Surface haptic technologies aim to bridge this gap by introducing various techniques to recreate haptic feedback on touch surfaces [18]–[23].

Ultrasonic-friction modulation could be well suited for improving the lives of blind individuals [24]. In an ultrasonic friction modulation device, a transparent plate is activated at its eigenfrequency, resulting in tiny vertical displacements of 3 or 4 microns. Although users may not directly perceive these low-amplitude, high-frequency vibrations, they create a squeeze-film effect between the finger and the touch surface [25]. This mechanism effectively reduces the friction coefficient between the finger and the touch surface [26]. By modulating the amplitude of the vibrations, a wide range of friction forces can be generated [27].

Earlier research studies that focus on tactile aid for blind individuals [10], [11], [13], [14], [28] share a common characteristic: the tactile feedback is solely dependent on finger position, providing binary feedback to indicate whether the user is on target or not. However, for more efficient and effective feedback, it is preferred to provide directive feedback as well. Incorporating this additional layer of information can provide valuable benefits. It is worth noting that no research has been conducted on improving performance in tracking tasks using a haptic rendering method that takes the direction of movement into account nor on using this haptic rendering method for the problem blind individuals face with orientation.

In the context of developing technology for blind individuals, it is expected that considering the direction of movement in haptic rendering can significantly enhance the user experience. By integrating this feature, haptic feedback can adapt dynamically to the user's movements, providing more nuanced and informative cues. This approach has the potential to improve tracking tasks and facilitate a more seamless and engaging interaction with digital interfaces. Using this technique the orientation issues might be reduced, by guiding the subject's finger to a location on a glass plate which tells them how they should orientate.

We propose a novel method for rendering directional friction modulation, which enhances user interaction by dynamically adjusting tactile feedback based on movement direction. This tactile directional cue will be evaluated through a human factors experiment. The efficacy of the tactile directional cue will be tested with two experiments, a tracking experiment and an orientation experiment. During the tracking experiment, it is investigated whether subjects can accurately perceive haptic guidance by the tactile directional cue leading the participants along a predefined target path. To gain a comprehensive understanding of its functionality, we will employ both subjective and objective measurements as part of our assessment process. During the orientation experiment, the tactile directional cue's potential to guide participants to reach specific reference angles is investigated. We seek to answer the following question: How can we maximize the effectiveness of the directional friction modulation rendering method, in offering guidance to individuals with visual impairments?

II. Rendering method

Our approach to rendering tactile directional cues differs fundamentally from earlier described surface haptic methods designed for blind individuals. It involves incorporating both finger position and movement direction of the finger, instead of solely relying on finger position. This additional information allows for the generation of a force field sensation, rather than just perceiving sections of high or low friction. It's important to note that there are no active forces used here because, on a friction-modulated touchscreen, it is not possible to generate active lateral forces. Only friction forces opposing the direction of movement can be modulated.

A. Shape and location of the tactile cue

The tactile cue consists of two segments. A segment that firmly guides the participant, represented by the light blue segment in figure 1, towards the Gaussian. In this segment, the finger is considerably distant from the reference position, so maximum friction reduction is employed when moving towards it and no friction reduction when moving away. This strategic approach maximizes the contrast in friction, thereby producing the most robust directional cue possible. The second

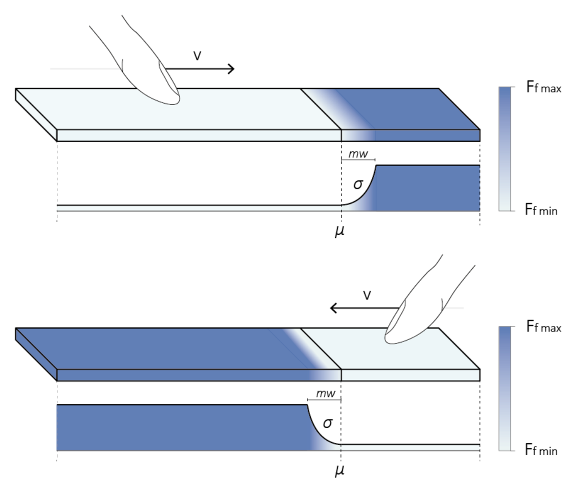


Fig. 1: The tactile directional cue depends on σ, μ, and the direction of the finger movement (v). μ indicates the reference location. σ affects the shape of the Gaussian. Minimal friction is light blue, maximal friction is dark blue. The maximum width of the Gaussian is 3.25*σ, indicated by *mw*.

segment is the Gaussian, the transient colour segment in figure 1. The function of the Gaussian is to indicate the reference location and is determined by formula 1. The parameter σ determines the shape of the curve and the parameter μ determines the location of the Gaussian. To get a clear image of the effect of the shape the maximum amplitude is kept constant using a scaling factor.

$$G(x) = -\frac{scalingfactor}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \quad (1)$$

Because finger direction is taken into account the starting position of the finger does not matter. The finger will always be guided towards the Gaussian. To ensure a smooth transition from the first segment to the Gaussian shape the transition starts at μ. So effectively half of the Gaussian is used to slow down the finger movement, visible in figure 1. The Gaussian ends at x = 3.25 * σ from μ.

B. Field of Feeling

During the orientation experiment the device's functionality is influenced by an additional parameter. The device, shown in figure 2 operates in the horizontal direction, so the width is constant but how many degrees are rendered on the width of the glass plate can be altered to influence the maximum range of degrees that can be perceived by the user. This will be called "Field of Feeling" which refers to the tactile equivalent of the field of view. It says something about the largest possible displayed angle on the glass plate. The field of Feeling will vary between the ranges of (-30°, 30°), (-45°, 45°), and (-90°, 90°). These ranges, visible in figure 2, will be referred to as FoF_{60}, FoF_{90}, and FoF_{180} respectively. Using different ranges will affect the computation of the location of the tactile cue. Because there are more degrees perceivable on the glass plate, a wide range will result in a slower-moving cue while rotating, than when a narrow range is used.

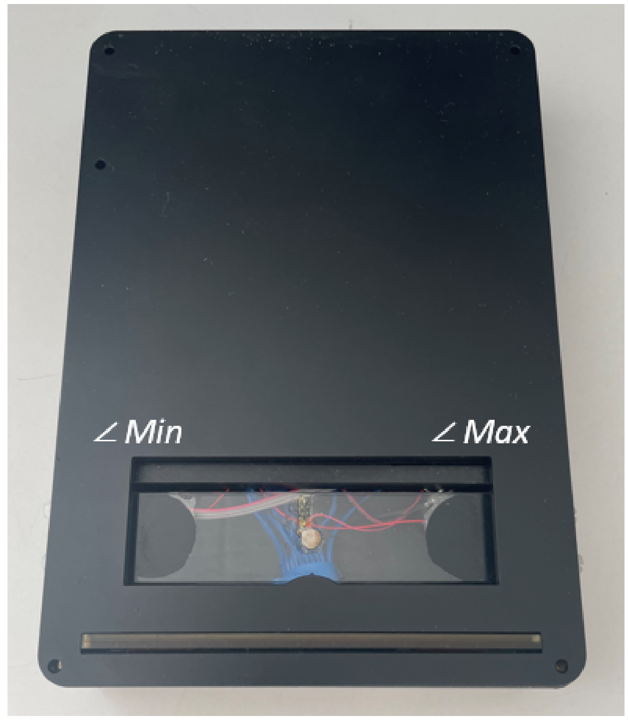


Fig. 2: Photo of the haptic device used for all experiments. The glass plate is actuated to send tactile cues to the finger of the participant. In the centre, there is a physical protrusion designed to help participants locate the device's midpoint blindfolded. On the sides, the minimum and maximum angles are displayed. At the bottom the position sensor is visible.

$$FoF_{180} : \angle\text{Min} = -90,\ \angle\text{Max} = 90$$

$$FoF_{90} : \angle\text{Min} = -45,\ \angle\text{Max} = 45$$

$$FoF_{60} : \angle\text{Min} = -30,\ \angle\text{Max} = 30$$

III. Materials

A haptic orientation test setup is developed for this experimental study. It utilizes the squeeze-film principle generated by ultrasonic vibrations to modulate the glass plate. In combination with a gyroscope and a position sensor, the device will send tactile cues to the participants.

A. Hardware

Wiertlewski et al. [29] developed the foundation for this device. The haptic feedback loop is controlled by a microcontroller (Teensy 3.6 Development Board), which is programmed using the Arduino IDE. The microcontroller is connected to a custom-made printed circuit board (PCB), which uses an AD9838 chip to generate the ultrasonic waveform. The frequency of this waveform is tuned once and the amplitude is actively modulated by the microcontroller during interaction. The output signal is then passed through an $\pm$100V amplifier. The signal is actuating the piezoelectric actuators, which are glued to the glass plate. Also connected to this PCB, is an optical position sensor (TSL 1412s). There is a light present in the encasing, the optical position sensor filters where the light is obstructed to find the horizontal finger position. The position data is filtered analogously with a refresh rate of 5kHz. The optical position sensor is located at the bottom of the glass plate, visible in figure 2.

The main component of this system is the glass plate which is vibrating at its resonance frequency, 34.7kHz [30]. The mode shape is chosen to have only horizontal nodal lines, which makes the amplitude in one dimension constant [29].

Lastly, an inertial measurement unit (SEN0142) is mounted in the enclosure and connected to the Teensy. This way the orientation of the device can be measured. Everything is connected as visualized in figure 3. A laptop is used for logging the data and sending what experiment will be conducted.

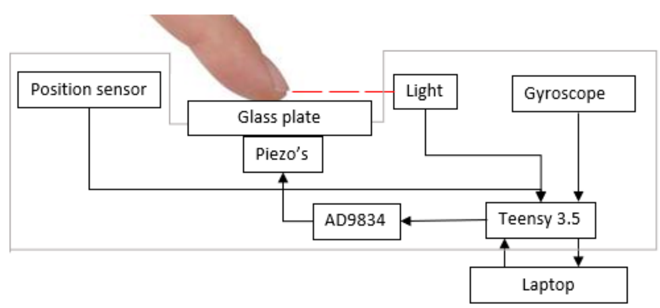


Fig. 3: Schematic representation of the haptic guidance device shown in figure 2. The grey line represents the encasing.

B. Software

The Arduino program running on the microcontroller comprises two main functions, excluding the initialization process. In the main loop, communication with the computer is defined to receive the haptic rendering and experiment conditions. The second function is the interrupt function where the horizontal finger position is read. The interrupt function is triggered when the position sensor indicates that data is ready to be read at a frequency of approximately 5 kHz. The finger position data is then used to calculate the movement direction. In this same interrupt function, the tactile cue is calculated using the location of the finger, the direction of movement, and the orientation measured by the gyroscope.

This results in a closed loop system that incorporates the human using the device, visualised in figure 4.

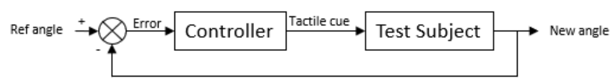


Fig. 4: The location of the tactile cue is calculated using the error with the reference angle

Fig. 5: Experimental setup, with (1) Power supply, (2) Laptop, (3) Haptic Device, (4) Armrest, (5) Blindfold, (6) Noise cancelling headphones

IV. Psychophysical Experiment

In the psychophysical experiment two variables, σ and Field of Feeling, are investigated. Resulting metrics are analysed to find which conditions are best suited for guiding users to a specific target.

A. Participants

6 Women and 14 men, 26.0 years old on average (SD:8.1), were willing to participate in the psychophysical experiment. All test subjects were healthy. None were left-handed. The experimental procedures were approved by the Human Research Ethics Committee at the TU Delft. All participants gave informed consent.

B. Experimental Setup

The device explained in Section III, was used. To investigate the effect of the tactile cue optimally, the participants are asked to wear noise cancelling headphones (Sony WH-1000XM3) and an eye mask. Over the headphones, a pink noise signal would be played to mask any audio cues the device could send. An armrest was present in case the participant was uncomfortable. The setup is visible in figure 5

C. Experimental Procedure

Participants were presented with a brief presentation that explained the purpose and details of the investigation. This was done to ensure that all participants received the same information. Based on initial observations, it was determined that a test phase should be included. This was because it appeared that individuals needed some familiarity with the tactile sensation. Audio cues were played and explained to ensure a clear understanding. Three experiments were conducted in total. The first experiment aimed to find the optimal shape of a tactile cue to guide the test subject's finger to a specific location on the glass plate. This was done by incorporating the preference and looking at the tracking accuracy. The second experiment was done to investigate the tactile cues without taking preference into account. The purpose of the last experiment was to investigate if the directional tactile cues could be used for orientation.

1) Preference of the tactile cue: After the familiarization phase, the first experiment began. The participants sat at a table with the device positioned in front of them. Participants were given 10 seconds to explore the stimulus. The participants were instructed to start with their index finger from their dominant hand on the left side of the device. The objective was to trace a particular path on the glass plate guided by the tactile cue. This was done with four different paths that were used randomly, shown in figure 6. The speed that the paths were guiding the finger with was a constant 17 mm/s [31], [32].

The start of the experiment was indicated by a sound cue, followed by the exploration of the first stimulus. Subsequently, another sound cue marked the exploration of a second stimulus, which had a different σ value. Despite the altered tactile cue, the path remained unchanged from the first. Following this, a two-alternative-forced-choice method was used. After experiencing both stimuli the participants had to determine which stimulus was best for tracking the path. The question that had to be answered by the participants was: ”Which path was the easiest to follow?”

The shape of the signal changed based on a method that is inspired by the up-down staircase method [33]. In the initial two trials, the signal's parameters were set to $\sigma = 5$ and $\sigma = 1$. The values would increase or decrease with 5 dB based on the participant's preference. After conducting preliminary tests, it was determined that $\sigma = 5$ represented a relatively

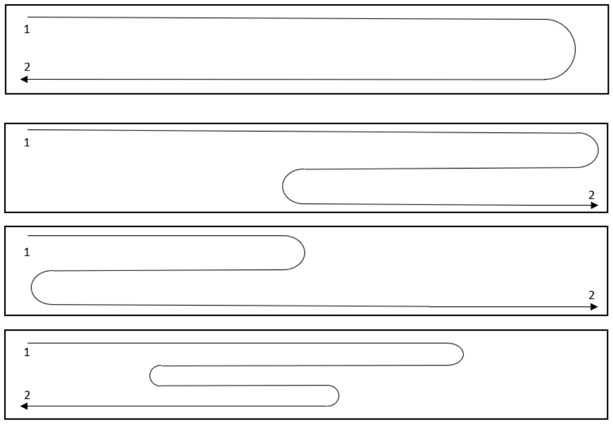


Fig. 6: The four horizontal paths the participants had to follow for the first experiment. 1: starting point, 2: ending point

large and less optimal value. Therefore, it was expected that the participants would first choose $\sigma = 1$. If after the first two trials, $\sigma = 1$ was preferred, then in the third and fourth trials the values would be 1 and $1 * 10^{\frac{-5}{20}}$ in random order. It was possible to choose 5; in that case, the values for the third and fourth trials would be 5 and $5 * 10^{\frac{5}{20}}$. A reversal occurs when there is a change in the direction of progression, transitioning from an increase of σ to a decrease or vice versa. Following the initial reversal, the step size is adjusted to 1 dB. The experiment would conclude if 5 reversals at $\pm$ 1 dB had occurred. An example of the first experiment is visualised in figure 7. After the first experiment, the participant would have a 5-minute break.

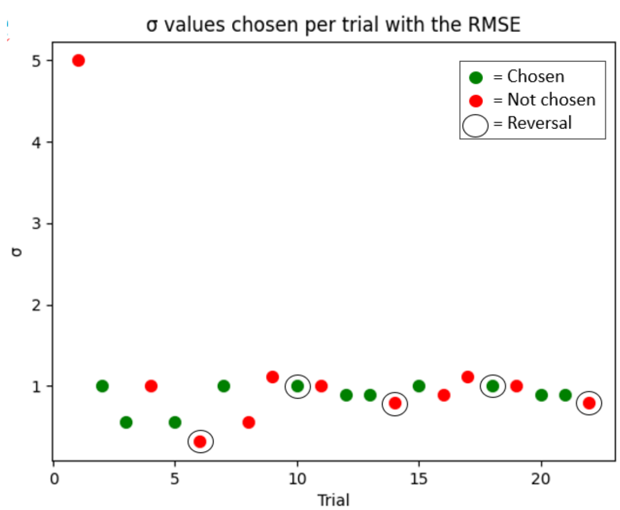


Fig. 7: Example of a result from the guidance experiment. After every 2 trials, the participant had to choose.

This yields two distinct metrics: a psychophysical metric and a behavioural metric. The first metric is determined by the value of σ that participants indicate as the one they comprehend most effectively. The second metric is derived by assessing the accuracy of the path followed, employing the root-mean-square error (RMSE), which describes the average discrepancy between the reference position and the finger position. Narrow shapes, resulting from smaller σ values, are expected to yield lower tracking errors.

2) Tactile cue without preference: For the second experiment, the preference of the participant was not taken into account. The objective of the experiment was still to track the path as accurately as possible. However, three constant values, specifically $\sigma = 0.25$, $\sigma = 1$, and $\sigma = 4$, were employed. This way it will be possible to investigate the effectiveness of σ independent of the preference. To enhance readability, we will use the labels $\sigma_{0.25}$, σ_1, and σ_4 to denote these values. This results in 3 different tactile cues being tested. The four paths from figure 6 were used with the 3 values $\sigma_{0.25}$, σ_1, and σ_4, resulting in 12 paths that were tracked. To see if there was a specific interaction between the paths and values for σ the results will not be averaged. The start of the experiment was indicated by a sound cue, followed by the exploration of the first stimulus. Following by another sound cue the exploration of the next stimulus began. This was repeated until all 12 combinations were tested.

3) Orientation Experiment: The third experiment was conducted dynamically. The test setup was the same as in figure 5, with the exception that the participant was asked to stand up. The objective of the experiment was to find the reference angle, towards which the directional tactile cue was guiding the participants. The participants knew the reference angle was reached when they felt the physical protrusion, shown in figure 2, at the location to which the directional tactile cue was guiding them. This way an egocentric perspective was used. Participants held the device in their hands while standing. In this experiment, the Field of Feeling, σ values, and reference angles were varied. The Field of Feeling ranged from (-90°, 90°), (-45°, 45°), and (-30°, 30°). The σ value varied between the values 4, 1, and 0.25. These variables were combined with reference angles -60°, -30°, 0°, 30°, and 60°. The participants would start from their previous reference angle. This means 4 angular displacements can occur, 30°, 60°, 90°, and 120°. This resulted in 45 combinations which were randomized for every participant. Again to be able to investigate the interactions, every trial was a different combination of σ, the Field of Feeling, and the angular displacement, therefore the data will not be averaged. Consecutive angles were avoided after the randomization, to force movement. Next to this, the first angle at the start and after the break was never 0°. The orientation experiment was divided into 4 parts to avoid the participants getting exhausted. At the beginning of each trial, the start cue was played, and participants were given unlimited time to orient themselves correctly. If they thought the orientation was correct they had to say this and the next trial would then start. To investigate the effectiveness three metrics were chosen. The first metric is the time used to reach the reference angle, indicated by the 1 in figures 8. The second metric is the decision time at the reference angle, indicated by the 2 in figures 8. The last metric is the error of the actual angle at the moment of decision with the reference angle, indicated by the 3 in figures 8. If the reference angle is never reached during the trial, that trial will not be used for analysis. This is because it will be impossible to distinguish between the time taken to reach that reference angle and the decision time. It is expected that there will be a trade-off in speed and accuracy, where a smaller FoF is expected to yield higher accuracy and a broader FoF is expected to result in faster times.

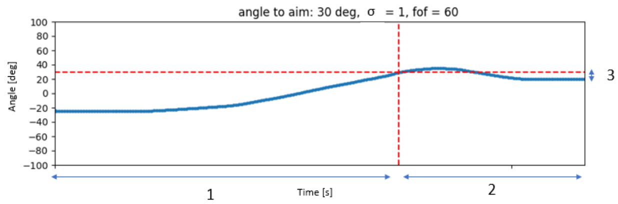


Fig. 8: Example of a result from the orientation experiment. Where 1: Time to the reference angle. 2: Time to decide the reference angle is reached. 3: Error with the reference angle.

On average, the guidance experiments together lasted approximately 9 minutes, while the orientation experiment lasted around 14 minutes. Throughout all experiments, the position of the participant's finger, the angle of the device, and the duration of each trial were recorded for subsequent analysis.

V. Results

The raw data from each trial were examined, and any significant jumps in the finger position and angle data were identified and marked for further review. Jumps in the data, not caused by finger movement were found in the guidance experiment. The jumps were caused by timestamps being logged in the past. This was solved by interpolating between the timestamp preceding the error and the timestamp after the error. Another issue that arose was that some participants reacted too late to the audio cue. This could pose an issue if the last recorded finger position was on the right side of the screen, as it would significantly inflate the average error. To address this, these positions were set to the starting values, which still led to some error, but to a lesser degree. Subsequently, some trials seemed to lack data from the orientation experiment. This was most likely due to accidentally moving on to the next trial prematurely. Those were manually assessed, and those containing data errors were excluded from the analysis. In cases where the reference angle was never reached, the trial had to be removed as well. This occurred 50 times. By excluding unusable trials, 828 trials out of 900 trials were used for further analysis.

A. Preference of the tactile cue

There were two purposes of the guidance experiments, finding what values for σ were preferred by the participants and finding the effect of σ on the tracking ability. The distribution of the preference is shown in figure 9. The effect of σ values on the RMSE is visualised in figure 10. A logistic function, formula 2, can be fitted on the moving average of the error. The values for L, k, and x_0 are 14.11, 0.7, and 0.97 respectively, here x represents σ and $f(x)$ is the expected average tracking error.

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}} \tag{2}$$

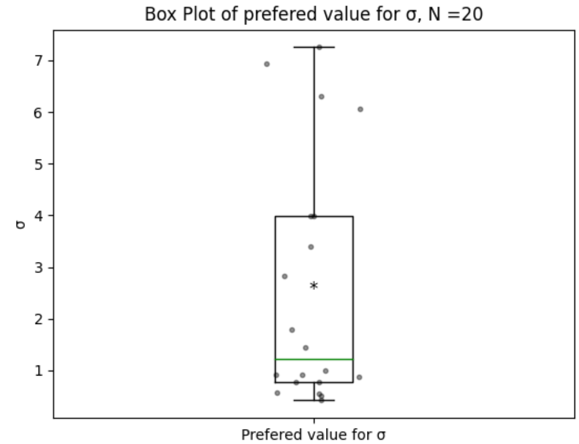


Fig. 9: The distribution of the preference of σ mean: 2.56, median: 1.23, and standard deviation: 2.32.

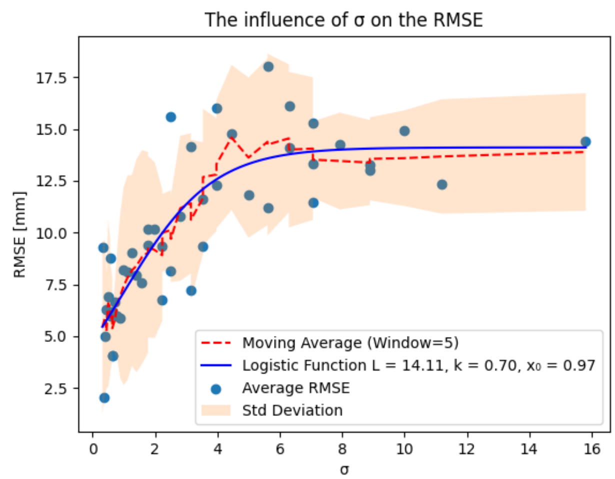


Fig. 10: Effect of σ on the tracking error. The error between the reference path and finger position increases as σ increases

B. Effect of the tactile cue without preference

For the second experiment where constant σ values were tested, a Shapiro-Wilk test [34] showed that the data was not normally distributed ($W = 0.89, p < 0.001$). The robustness of mixed-effects models allows for linear mixed-effects models to be used even if the distributional assumptions are violated [35]. Because of the combination of not normally distributed data and repeated measures, a linear mixed-effects model [36] was used to investigate the effects and interactions of σ and the four paths, visible in table I. The fixed effects for the model are σ and the paths and their interaction. The interaction indicates if the combined effect of σ and the path on the RMSE is different from what would be expected based on their individual effects. The random effect is the possible difference in ability between participants. The coefficients are values that represent the strength and positive or negative relationship between a fixed effect and a dependent variable. The p-values indicate if the coefficients are statistically significant. Since

TABLE I: Results from the mixed-effect model of the effect of σ, the paths, and differences in ability on the tracking error. The interaction is represented by σ : Path.

Table I

	Intercept	σ	Path	σ : Path	Participant
Coefficients	7.79	0.37	0.35	0.00	8.11
p-value	p < 0.001	N.S.	N.S.	N.S.	p < 0.05

there are no significant effects found no post hoc is necessary. The intercept serves as the baseline from which changes in the dependent variable are measured when you manipulate the independent variables.

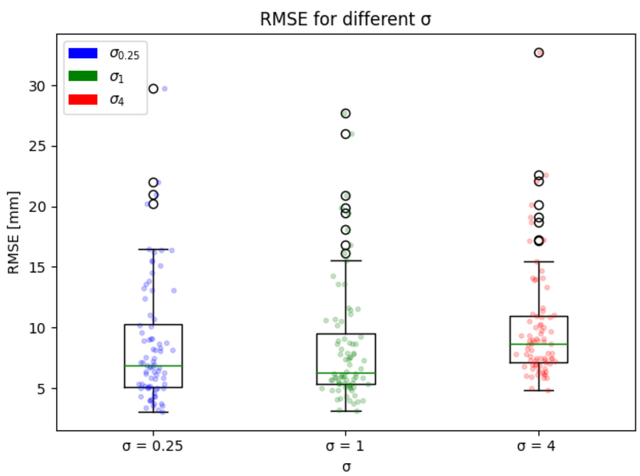


Fig. 11: The error between the reference path and finger position with constant σ values.
$\sigma_{0.25}$ median: 6.92, mean: 8.66, Standard deviation: 5.03
σ_1 median: 6.30, mean: 8.42, Standard deviation: 4.99
σ_4 median: 8.67, mean: 10.00, Standard deviation: 4.67

C. Orientation experiment

In the orientation experiment, our primary aim was to assess the feasibility of directional ultrasonic friction modulation as a means of aiding blind individuals in orientation. Additionally, we examined how the variables σ and Field of Feeling influenced the participants' orientation abilities.

1) Effect on the time to reach the reference angle: There are 3 fixed effects for this metric, σ, Field of Feeling, and angular displacement, visualised in figure 12a and 12d. This results in many different combinations. To properly see the effect and interaction of these three variables the data will not be averaged. Shapiro-Wilk test showed that the data of the time participants needed to reach the reference angle was also not normally distributed ($W = 0.72, p < 0.001$) and displays positive skewness, as one would anticipate when considering an arrival time metric. Once more, due to the presence of non-normally distributed data and a repeated measures design, we employed a linear mixed-effects model to explore the influences and interactions of σ and the Field of Feeling, visible in the second and third row in table II. For the fixed effect angular displacement is a significant effect shown. Therefore, a post-hoc Conover-Iman test [37] with Bonferroni correction [38] was conducted to find specific differences. Differences were found with $p < 0.001$ between all 4 angular displacements.

2) The effect on the decision time: The results from the next metric, the time the participants used to decide they were at the reference angle, are visualised in figure 12b and 12e. The data was not normally distributed ($W = 0.85, p < 0.001$), also with positive skewness. Again, due to the presence of non-normally distributed data and a repeated measures design, we employed a linear mixed-effects model to explore the influences and interactions of σ and the Field of Feeling, visible in the fourth and fifth row in table II. For the Field of Feeling and angular displacement, significant effects are shown. The post-hoc Conover-Iman test [37] with Bonferroni correction [38] showed differences with $p < 0.001$ between all 4 distances. The intercept effect was found to be significant as well, the value represents the estimated baseline of the dependent variable when all other independent variables are set to zero or held constant.

3) Effect on the error with the reference angle: The results for the error with the reference angle are visualised in figure 12c and 12f. When analyzing the effects on the error with the reference angle, the Shapiro-Wilk test indicated that the data did not follow a normal distribution ($W = 0.81, p < 0.001$). The presence of positive skewness can be attributed to the use of absolute error values. Once more, due to the presence of non-normally distributed data and a repeated measures design, we employed a linear mixed-effects model to explore the influences and interactions of σ, Field of Feeling, and the angular displacement. For the fixed effects there were no significant results. However, the difference between participants was strongly present with a coefficient of 33.38, visible in the last two rows in table II.

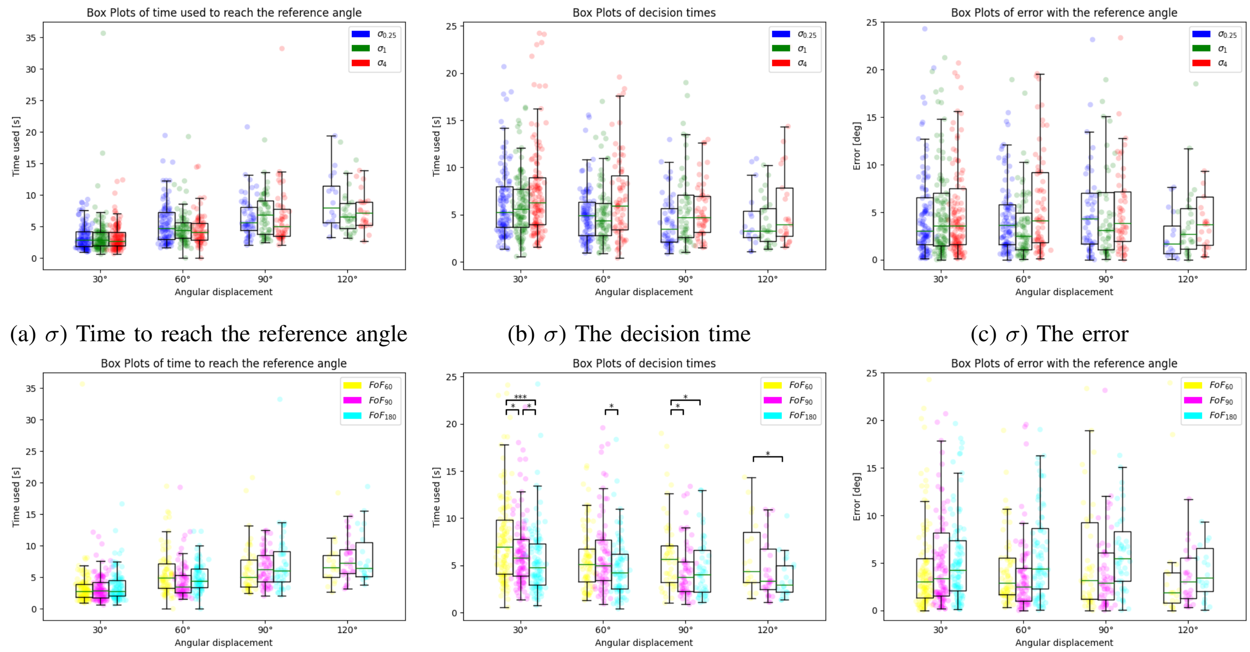
VI. Discussion

A. Performance and Participant Preference

The participants demonstrated an ability to track the path with a manageable average error of 9.84 mm. It was found that as the parameter σ increased, the tracking error also increased. Optimal performance was observed between $\sigma = 0$ and $\sigma = 1$, as shown by figure 10. This observation aligns with the preferences expressed by the participants. Out of the 20 participants, 10 indicated a preference for σ below 1, as illustrated in figure 9. In the second experiment, no significant effects of σ or the paths were found, visible in figure 11. The different paths did not influence the RMSE as was desired. Also, no interaction between the paths and values for σ was found. The absence of a significant effect of σ may be attributed to the close proximity of scores, possibly due to participants not using tactile cues in alignment with their preferences. Participants with preferences for larger σ values might have scored better using σ_4 but worse for $\sigma_{0.25}$. While the opposite may be observed for participants who favoured smaller σ values. The difference in preference can be the result of differences in sensitivity between participants. Some participants seemed to have more difficulty with the task than

	Intercept	σ	FoF	σ : FoF	AD	σ : AD	FoF : AD	σ : FoF : AD	Participant
Time to ref Coefficients	1.404	0.24	0.00	-0.00	0.06	-0.01	0.00	0.00	2.13
P-value	N.S.	N.S.	N.S.	N.S.	$p < 0.001$	N.S.	N.S.	N.S.	$p < 0.001$
Decision time Coefficients	8.61	0.20	-0.02	0.00	-0.03	0.00	0.00	0.00	3.18
P-value	$p < 0.001$	N.S.	$p < 0.01$	N.S.	$p < 0.05$	N.S.	N.S.	N.S.	$p < 0.01$
Error with the ref Coefficients	7.16	-0.81	-0.00	0.01	-0.05	0.03	0.00	0.00	33.38
P-value	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	$p < 0.01$

TABLE II: Results of the linear mixed-effect models, with fixed effects σ, Field of Feeling, and angular displacement (AD)



(a) σ) Time to reach the reference angle

(b) σ) The decision time

(c) σ) The error

(d) FoF) Time to reach the reference angle

(e) FoF) The decision time

(f) FoF) The error

Fig. 12: Results of all the metrics, where * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$

others. This is visible in the linear mixed-effect model results in table I. The p-value for the participant coefficient, indicates a significant effect between participants, meaning that certain participants were performing better than others. People with impaired vision are expected to do even better because of stronger spatial fingertip acuity. The spatial thresholds on the fingertips of young, normally sighted individuals measured between 1.2 and 1.7 mm, while blind subjects have slightly lower thresholds, ranging from 1.0 to 1.5 mm [39]. Since performance increases as more modalities are available [40], [41] it is expected that this technique would function well in multitasking situations because the cognitive load would be reduced when using multiple modalities [42].

B. Strength of Directional Cue

The strength of the directional cue was assessed using the time taken to initially reach the reference angle. Faster times indicate a stronger directional cue. The linear mixed-effect model did not reveal significant interactions or main effects for either Field of Feeling or σ. The effect of the angular displacement was significantly present. The coefficient of 0.06 indicates that for every one-degree increase, the time is expected to increase by 0.06 seconds. It is logical to see an increase in time, as the distance becomes greater. Here the differences between participants are significantly present as well, visible in table II. The mean duration to reach the reference angle across all conditions was 5.90 seconds.

C. Decision-Making

An investigation into the effect on the confidence of the participants was done by examining the time the participants took to decide that they were orientated correctly after reaching the reference angle. On average, participants required 4.89 seconds to determine that they had reached the reference angle across all conditions. The total average time used was 10.79 seconds. Again differences between participants were present. The angular displacement had a significant negative effect on the decision time. This suggests that as the distance becomes greater, the decision time is expected to decrease. This is most likely due to the participants realizing that the likelihood of reaching the reference angle is higher once they've already rotated 60 or 90 degrees. But more interesting was the significant negative effect for Field of Feeling shown by the linear mixed-effect model in table II. The results from the Conover-Iman test that showed significant differences all indicated that bigger Field of Feeling ranges resulted in faster times the participants were able to recognise they had reached the reference angle. Here as well, significant effects between participants were shown by the linear mixed-effect model. Additionally, the linear mixed-effect model showed a significant intercept value of 8.61 seconds, which serves as the baseline for decision time when other factors are set to zero or held constant. Comparing this to the average decision time is 4.89 seconds the fixed effects seem to decrease the decision time.

D. Accuracy of Orientation

The effectiveness of directional friction modulation in aiding orientation was assessed by examining the error with the reference angle as well. The results indicate that directional friction modulation effectively guided participants towards the reference angles. On average, participants achieved the reference angle with an error of just 6.28°. The linear mixed-effect model showed no significant effects or interactions of the fixed effects. This means that the expected trade-off from section IV-C3 could not yet be shown. Interestingly the difference between participants was stronger present in the error with the reference angle. The coefficients representing the differences between participants for both the time taken to reach the reference angle and decision time were similar. The coefficient of 33.375 for the group differences suggests that the greatest challenges were encountered in achieving accuracy.

E. Improvements

The speed was kept constant throughout the finger guidance experiment. Different guidance speeds might result in different preferences. It might be interesting to investigate how the shape of the tactile cue influences the speed-accuracy trade-off. During the breaks and after the experiments the participants were asked how they experienced the experiments. One returning issue was the warmth the device transferred to the index finger. A few participants even lifted their index finger during the experiment because the warmth became unpleasant. This means that this method of orientation at this point in time is not yet viable for improving navigation. During longer routes, the warmth transfer might increase to unpleasant levels. For this investigation, the amplitude was kept constant at the middle of all Gaussians. In the future varying the amplitude at the reference location can be investigated, if the amplitude is lowered dynamically the heath issue might be resolved. After establishing a comprehensive understanding of the effects of these parameters, the next step would be to explore the functionality of tactile directional cues within a two-dimensional framework.

Ongoing research in active force feedback has demonstrated the feasibility of providing lateral forces in directions perpendicular to movement, even when the finger is stationary [43]. This is done by incorporating methods like travelling waves or combinations of standing and lateral vibrations. In the field of active haptic surfaces, it is expected that the principles of directional friction modulation offer valuable insights. This is particularly relevant in the context of employing haptic feedback as a means of directional cues, where systems can apply active forces to users.

It's essential to note that our experiment solely explores two parameters and two applications for this haptic rendering principle. Numerous other parameters can be adjusted to cater to diverse interaction scenarios and haptic stimuli. Directional friction modulation can be integrated into a wide array of human-machine interaction applications. These applications span beyond tactile feedback for blind individuals and include, but are not limited to;

- Aerospace and Aviation: Tactile feedback in aircraft controls can aid pilots in perceiving the aircraft's condition, particularly in scenarios with low visibility or high stress, as it enhances multitasking capabilities.
- Mobile Devices and Touchscreens: Haptic feedback on touchscreens enhances the user experience by providing tactile responses when interacting with buttons, sliders, and virtual objects. It can simulate the feeling of physical buttons, making touchscreens more intuitive.
- Automotive User Interfaces: Haptic surfaces integrated into car dashboard systems enable drivers to interact with controls while keeping their focus on the road, facilitating tactile-level shared control in highly automated vehicles. This feedback can be delivered when making adjustments to climate settings, volume, or navigation.
- Home Appliances: Haptic surfaces can be used on the control panels of appliances like ovens, washing machines, and refrigerators to provide tactile feedback when adjusting settings. In smart home devices, they can enhance the user interface and responsiveness.

VII. CONCLUSION

In this study, the concept of a directional friction modulation rendering method on a surface-haptic screen was introduced. The approach takes into consideration the direction of finger movement to enhance the tactile feedback experience. This rendering method was used for providing tactile feedback for a guidance experiment and for an orientation experiment.

Our findings demonstrate fascinating insights into the effectiveness of tactile directional cues in guiding users along predefined trajectories or toward specific orientations by providing tactile feedback. Smaller σ values result in improved tracking performance, as evidenced by lower tracking errors. We were able to describe this relation using a logistic function. Next to this, in the context of orientation assistance, the influence of σ on the outcomes was not shown. However, our findings revealed that a wider FoF led to quicker decisions when at the reference angle. The findings demonstrated that, within the confines of this study, this technique effectively directs users toward a reference orientation. On average, this was achieved in 10.79 seconds with a manageable error of 6.28°. Nevertheless, it is essential to acknowledge that directional friction modulation rendering methods have certain limitations when applied to orientation tasks. During the orientation finding task, the participants experienced warmth that could get uncomfortable.

In conclusion, our exploration of directional friction modulation on surface-haptic screens provides valuable insights into the realm of haptic feedback with directional cues. While it exhibits promise, our study underscores the need for a nuanced understanding of its limitations. We anticipate that future advancements in active haptic feedback technologies will unlock new possibilities, enhancing the efficacy of this rendering method for a variety of applications. Effective adoption of this technology has the capacity to revolutionize electronic surface haptic devices.

Acknowledgment

I would like to thank Dr. Yasemin Vardar and Dr. Michaël Wiertlewski for their guidance throughout this project. I'm also grateful for the participants who took the time to help with this investigation.

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APPENDIX

A. Interviews

Questions for the blind or visually impaired	Questions for the organisations
What is your age?	Do you work directly with blind or visually impaired people?
Are you fully blind?	What is the level of blindness?
How long do you have trouble seeing?	Are electronic assistive devices used a lot?
Can you read Braille?	Which popular devices only use audio?
Do you use electronic assistive devices?	How many blind or visually impaired people can read Braille?
Do you use electronic assistive devices that only use audio?	Are there devices to assist with reading maps?
Do you use maps to navigate?	Are there many blind or visually impaired people that work with data representations e.g. diagrams and graphs?
Are you familiar with tactile data representations e.g. diagrams and graphs?	With what tasks do they need the most help?
Are there moments you need to ask for assistance to obtain certain information?	
Is there information not accessible at all?	
Is there more you would want to add?	

TABLE III: The sets of questions

Questions	Answers Person 1
what is your age?	69
Are you fully blind?	yes
How long do you have trouble seeing?	40
Can you read Braille	yes
Do you use electronic assistive devices?	iPhone en laptop
do you use electronic assistive devices that only use audio?	orion webbox
Do you use maps to navigate?	no
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	inaccessible websites
Is there information not accessible at all?	inaccessible kitchen appliances
Is there more you would want to add?	Use speech as much as possible very few blind people know Braille

TABLE IV

Questions	Answers Person 2
what is your age?	75
Are you fully blind?	yes
How long do you have trouble seeing?	75
Can you read Braille	yes
Do you use electronic assistive devices?	PC with Braille display and speech software, iPhone with speech and Braille keyboard, Google Home Nest Mini, outdoor Aftershokz headphones (bone conduction), small voice recorder, Webbox, talking colour detector, apps for navigation.
do you use electronic assistive devices that only use audio?	yes googlenest, webbox,colour detector,iPhone
Do you use maps to navigate?	yes,reliefmaps
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	Information only accessible through sight
Is there information not accessible at all?	I don't know. I notice that for sighted people there is an abundance of information. But with the senses I am able to use I am able to obtain a lot of information that sighted people might miss. From that, I filter what I need.
Is there more you would want to add?	It would be a shame if double work was done, so investigate well what solutions are available.

TABLE V

Questions	Answers Person 3
what is your age?	77
Are you fully blind?	no
How long do you have trouble seeing?	40
Can you read Braille	yes
Do you use electronic assistive devices?	iPhone iPad
do you use electronic assistive devices that only use audio?	iPhone iPad
Do you use maps to navigate?	Yes
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	bank transfers, paying by card in stores, scales in supermarkets information signs train stations
Is there information not accessible at all?	-
Is there more you would want to add?	-

TABLE VI

Questions	Answers Person 4
what is your age?	60
Are you fully blind?	yes
How long do you have trouble seeing?	7
Can you read Braille	I could but not anymore
Do you use electronic assistive devices?	reading device, ear camera, iPhone
do you use electronic assistive devices that only use audio?	alle
Do you use maps to navigate?	no, a person helps
Are you familiar with tactile data representations e.g. diagrams and graphs?	no, a person helps
Are there moments you nod to ask for assistance to obtain certain information?	websites
Is there information not accessible at all?	-
Is there more you would want to add?	-

TABLE VII

Questions	Answers Person 5
what is your age?	62
Are you fully blind?	no my eye score is 0.3/0.4
How long do you have trouble seeing?	a few years
Can you read Braille	I am learning
Do you use electronic assistive devices?	app lazarillo iPhone
do you use electronic assistive devices that only use audio?	magnifying glass phone laptop
Do you use maps to navigate?	no I need help
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	doing groceries or shopping
Is there information not accessible at all?	
Is there more you would want to add?	

TABLE VIII

Questions	Answers Person 6
what is your age?	60
Are you fully blind?	yes
How long do you have trouble seeing?	12
Can you read Braille	I could but not anymore
Do you use electronic assistive devices?	iPhone laptop scale blood pressure measurement device liquid indicator milestone smart glasses daisyspeler
do you use electronic assistive devices that only use audio?	All
Do you use maps to navigate?	no
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	Questionnaires groceries reading and filling in tables
Is there information not accessible at all?	
Is there more you would want to add?	-

TABLE IX

Questions	Answers Person 7
what is your age?	64
Are you fully blind?	yes
How long do you have trouble seeing?	20
Can you read Braille	no
Do you use electronic assistive devices?	Mostly iPhone and some kitchen appliances
do you use electronic assistive devices that only use audio?	All
Do you use maps to navigate?	no
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	Navigate
Is there information not accessible at all?	Difficult question I don't know
Is there more you would want to add?	

TABLE X

Questions	Answers Person 8
what is your age?	72
Are you fully blind?	yes
How long do you have trouble seeing?	25
Can you read Braille	no
Do you use electronic assistive devices?	iPhone
do you use electronic assistive devices that only use audio?	All
Do you use maps to navigate?	no
Are you familiar with tactile data representations e.g. diagrams and graphs?	no
Are there moments you nod to ask for assistance to obtain certain information?	Some internet pages, and during navigation
Is there information not accessible at all?	
Is there more you would want to add?	

TABLE XI

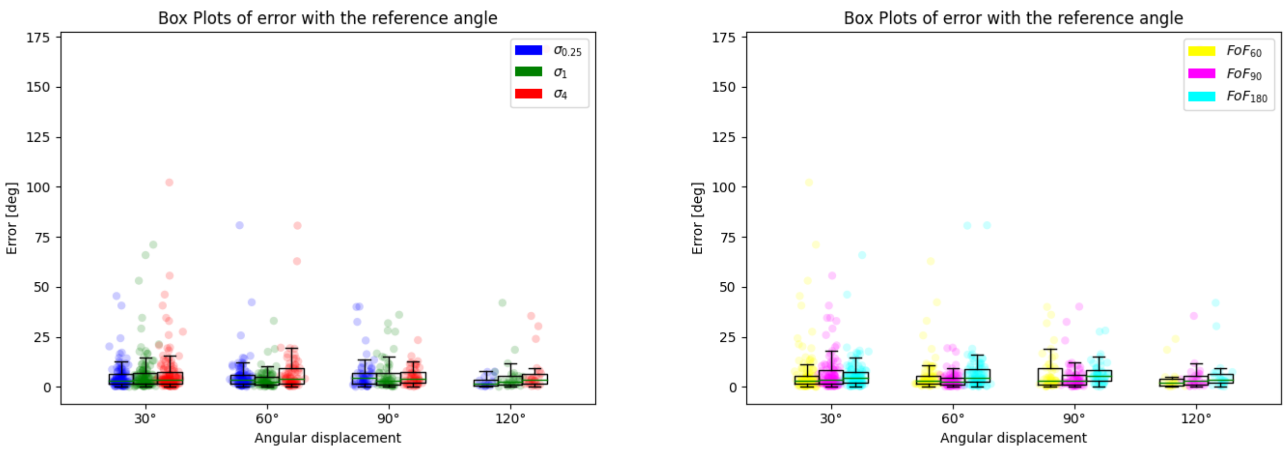
Questions	Answers Organisation 1
Do you work directly with blind or visually impaired people?	Yes through phone and email.
What is the level of blindness?	Both
Are electronic assistive devices used a lot?	Both
Which popular devices only use audio?	iPhones are popular, android is used too but not as much
How many blind or visually impaired people can read Braille?	Not that many
Are there devices to assist with reading maps?	Yes but only by using audio
Are there many blind or visually impaired people that work with data representations e.g. diagrams and graphs?	Not that I know of
With what tasks do they need the most help?	newer devices, some solutions are pc's, Braille keyboard's webbox,daisylezer

TABLE XII

Questions	Answers Organisation 2
Do you work directly with blind or visually impaired people?	Yes via phone and email.
What is the level of blindness?	Both
Are electronic assistive devices used a lot?	Both
Which popular devices only use audio?	Everybody needs different help
How many blind or visually impaired people can read Braille?	Everybody needs different help
Are there devices to assist with reading maps?	No
Are there many blind or visually impaired people that work with data representations e.g. diagrams and graphs?	No
With what tasks do they need the most help?	There is no specific general issue, every person finds different solutions, a lot of solutions can be found on websites, worldwidevision optelec

TABLE XIII

B. Normal scale figures



(a) Figure of the error with the reference angle for σ

(b) Figure of the error with the reference angle for FoF

Fig. 13: Normal scale figures of the error with the reference angle

C. Explanation Arduino code

Code snippet 1) Here the direction of the finger is calculated, if s_signvel=-1 the direction is to the left and if s_signvel=1 the direction is to the right

```
//Find the sign of velocity with hystheresis
if ((f_velocity_foaw > 0) & (f_sgnvel < 100)){
  f_sgnvel++;

}
else if ((f_velocity_foaw < 0) & (f_sgnvel > -100)){
  f_sgnvel--;

}
//Find the sign of velocity
s_sgnvel = (f_sgnvel > 0) - (f_sgnvel < 0);
```

Fig. 14: Code snippet 1

Code snippet 2) This is the reference location if the first experiment is conducted, the paths are defined at the start and different paths are selected when there is a task sent to the Arduino.

```
if(CaseVal==1){
    midDip=aimAngle;
  if (pathcount<999) {
    midDip=path[pathcount];
  }
  else{
    midDip=path[999];
  }
}
```

Code snippet 3) Here the reference location is calculated for the orientation task, the shape of the gaussian looked a bit like a dip so that's why its called the middle of the dip.

```
else{
  if (aimAngle<=mpu.getAngleZ()-FOV/2){ //
    midDip=0.1*aimSize;

  }
  else if (aimAngle>=mpu.getAngleZ()+FOV/2){
    midDip=0.9*aimSize;


  }
  else{
    //Error between aim and acutal angle multiplied by the amount of pixels that fit in 1 deg
    midDip=((aimAngle-int(mpu.getAngleZ()))*MAXMAP/FOV)+6000;
    midDip=midDip/100.0; // 100.0 is because MAXMAP/aimSize = 100 but it needs to be a float

  }
```

Code snippet 4) s_ouput = the output that is sent to the piezo's is calculated, it ranges from 0 to 4000. 0 is full friction reduction, 4000 is no friction reduction. Caseval==1 means first experient S_signvel==1 means the finger moves to the right F_position_filt= the location of the finger midDip= the reference location the finger is guided to dcFriction= a constant that can be changed to shift the amplitude output, but this is never changed. aimArray= an array full of the value 2000, this means that the finger either perceives maximum friction reduction if it moves in the right direction or no friction reduction if it moves in the wrong direction

```
if(CaseVal==1){
  if(s_sgnvel==1){
   if (f_position_filt < midDip) {
    s_output = (uint16_t) (dcFriction - s_sgnvel*aimArray[f_position_filt]);
   }
   else if(f_position_filt > midDip+sizeDip/2){
    s_output=(uint16_t) (dcFriction + s_sgnvel*aimArray[f_position_filt]);
   }
   else{
   s_output=(uint16_t) (dcFriction + dipMap[f_position_filt-int(midDip)+sizeDip/2]);
   }
  }
  else{
   if (f_position_filt < midDip-sizeDip/2) {
    s_output = (uint16_t) (dcFriction - s_sgnvel*aimArray[f_position_filt]);
   }
   else if(f_position_filt > midDip){
    s_output=(uint16_t) (dcFriction + s_sgnvel*aimArray[f_position_filt]);
   }
   else{
   s_output=(uint16_t) (dcFriction + dipMap[f_position_filt-int(midDip)+sizeDip/2]);
   }
  }
```

Code snippet 5) This is the second experiment so the only difference is in the lines where the finger location is compared to a reference location. MidDip is calculated in Code snippet 3 and needs to be scaled back using maxmap, which is the maximum amount of pixels and aimsize, which can be changed to investigate field of feeling.

```
else {
  if(s_sgnvel==1){
   if (f_position_filt < (int(midDip) * MAXMAP / aimSize)) {
    s_output = (uint16_t) (dcFriction - s_sgnvel*aimArray[f_position_filt]);
   }
   else if(f_position_filt > (int(midDip) * MAXMAP / aimSize)+sizeDip/2){
    s_output=(uint16_t) (dcFriction + s_sgnvel*aimArray[f_position_filt]);
   }
   else{
   s_output=(uint16_t) (dcFriction + dipMap[f_position_filt-(int(midDip)*100)+sizeDip/2]);
   }
  }
  else{
   if (f_position_filt < (int(midDip) * MAXMAP / aimSize)-sizeDip/2) {
    s_output = (uint16_t) (dcFriction - s_sgnvel*aimArray[f_position_filt]);
   }
   else if(f_position_filt > (int(midDip) * MAXMAP / aimSize)){
    s_output=(uint16_t) (dcFriction + s_sgnvel*aimArray[f_position_filt]);
   }
   else{
   s_output=(uint16_t) (dcFriction + dipMap[f_position_filt-(int(midDip)*100)+sizeDip/2]);
   }
  }
```

D. Communication Python to Arduino

Code snippet 7) An example of how data is read by the Arduino. If in the python code P is sent to the Arduino this will be triggered. First, it will read sizeDip then FOV then aim angle then caseVal. Then dipMap is read but in multiple segments because it is an array. Then kk is updated indicating that a new piece of information will be sent.

```
case 'P':   //Prepare to receive some new profiles
  uint16_t InfoIn;
  int16_t byte11; int16_t byte12;
  if (debug) {
    Serial.print(F("Send Stuff "));
    Serial.println(Serial.available());
  }
  //Load all table with .5s timeout in case it's needed
  timeoutSerial = 0; kk = 0;
  while ((timeoutSerial < 500) & (kk < sizeDipMax + 4)) {
    if (Serial.available() >= 2) {
      byte11 = Serial.read(); //read 2 bits at once
      byte12 = Serial.read();
      InfoIn = (uint16_t) (byte11 << 8) + byte12;
      if (kk == 0)
        sizeDip = InfoIn;
      if (kk == 1)
        FOV = InfoIn;
      if (kk == 2)
        aimAngle = InfoIn+offsetAng;
      if(kk==3)
        CaseVal = InfoIn;
      if ((kk >= 4) & (kk < sizeDipMax + 4))
        dipMap[kk - 4] = InfoIn;
      kk++;
    }
```

Code snippet 8) In the python code the sending will look as follows:

```
sizeInt=int(size)
fovInt=int(fov)
angleInt=int(angle)
caseint=int(2)
ser.write(b'P')
ser.write(sizeInt.to_bytes(2, byteorder='big', signed=True))
ser.write(fovInt.to_bytes(2, byteorder='big', signed=True))
ser.write(angleInt.to_bytes(2, byteorder='big', signed=True))
ser.write(caseint.to_bytes(2, byteorder='big', signed=True))

numSent = 0
while(numSent < size):
    chunk = 10
    rs232buf = bytearray(2*chunk)
    for ii in range(chunk):
        if numSent+ii == size:
            break;
        value = int(diptosent[numSent+ii])
        rs232buf[2*ii] = value.to_bytes(2,byteorder='big',signed=True)[0]
        rs232buf[2*ii+1] = value.to_bytes(2,byteorder='big',signed=True)[1]
    ser.write(rs232buf)
    numSent+=chunk
```

E. Shape of tactile cue

Code snippet 8) diptosent determines the shape around the reference location, it is created like this so it can be different widths. dipMap is the formula for a gaussian. The first for loop finds the width. The second for loop fills diptosent, so it contains exactly the guassian but no values that are negligible. Scaling = 4000 so it's scaled to the 0,4000 input range for the piezo signal. DcFriction is a variable that shifts this input but it's always 2000. The value 1980 is chosen as a cutoff so it's cut of at 3.25 * sigma from mu.

```
x = np.linspace(0, 120, MAXMAP)

dipMap =  -np.exp(-0.5 * ((x - mu) / sig)**2)*scaling+DcFriction;
for ii in range(MAXMAP):
    if dipMap[ii]<1980 and k==0:
        hval=ii
        k=1
    if dipMap[ii]<1980:
        size+=1
for i in range(0,size):
    diptosent=dipMap[hval:hval+size]
```