# Tactile Accessibility: Does Anyone Need a Haptic Glove?

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## ABSTRACT

Graphical user interfaces (GUIs) are widely used on smartphones, tablets, and laptops. While GUIs are convenient for sighted users, their accessibility for blind people, who use screen readers to interact with GUIs, remains to be problematic. Even the most screen-reader accessible GUIs are far less usable for blind people compared to sighted people, because the former group cannot benefit from the geometric layout of GUIs. As a result, blind people often have to listen through a lot of irrelevant content before they find what they are looking for. *Haptic interfaces* (those providing tactile feedback) have the potential to make GUI interfaces more accessible and usable for blind people. Alas, mainstream computer devices do not have haptic screens that would enable high-resolution tactile feedback, and specialized haptic devices are very limited and/or are exuberantly expensive and bulky.

In this paper, we describe a low-cost haptic-glove system, FeelX, which can potentially enable usable tactile interaction with GUIs. The vision of FeelX is to enable blind users to connect it to any computer or smartphone, and then interact with it by moving their hands on any flat surface such as the desk or table. To establish the practicality and the desirability of using haptic gloves, we evaluated the initial prototype of the glove in a user study with 20 blind participants. Throughout the study, we performed a comparative evaluation of several design options for the tactile interface. The participants were asked to identify simple geometric figures such as lines, rectangles, circles, and triangles that are the basic building blocks of any GUI interface. Although the FeelX prototype is far from being a usable product, the results of the study indicate that blind users want to use haptic gloves.

## CCS Concepts

- **Human-centered computing~Haptic devices**
- **Human-centered computing~Accessibility technologies**

## Keywords

Haptic glove; tactile interaction; haptic display; blindness; GUI accessibility; screen reader; tactile exploration.


ASSETS '16, October 23-26, 2016, Reno, NV, USA

DOI: http://dx.doi.org/10.1145/2982142.2982175

## 1. INTRODUCTION

Computers and mobiles have become ubiquitous in our daily lives, and many of us are interacting with multiple graphical user interfaces (GUIs) on our smartphones, tablets, and laptops throughout the day. While the accessibility of GUIs for blind screen-reader users has improved in recent years, a large gap remains in the efficiency of access for people with and without vision impairments; the latter group spends significantly more time interacting with content in web pages, documents, and apps.

To give a sense of the size of the affected population, according to the World Health Organization, there are 39 Million blind worldwide [35]. In the U.S. alone, according to the American Foundation for the Blind [3], there are over 21M Americans who have significant vision loss. These numbers are growing as baby boomers, already relying on computers, continue to develop vision impairments associated with age-related diseases.

Since the introduction of computers, researchers and practitioners have been striving to make computer interfaces accessible to blind people. The best-known results of their work are assistive technology tools such as magnifiers for people with low vision and screen readers for those who are blind. Magnifiers (e.g., Zoomtext [40] and MAGic [19]), which are primarily controlled either with the touch or mouse input, allow their users to zoom in and even narrate the content of the screen. Screen readers (e.g., JAWS [17], Window-Eyes [37], VoiceOver [33], NVDA[22]) enable blind people to interact with and narrate the content of the screen relying either on the touch or keyboard input.

Due to the limitations of assistive technology interfaces, neither magnifier nor screen-reader users can use GUI interfaces as effectively as sighted people. In our experience, the majority of time ends up being spent on searching the screen for relevant content and controls such as links, buttons, and form fields. Magnifiers require a lot of panning, since only a small portion of the magnified screen can be displayed at a time; so, the efficiency depends on the size of the screen, the type and extent of the vision loss, zoom level, and familiarity with the GUI. In contrast, screen readers require an extensive use of touch gestures and, more frequently, keyboard shortcuts to navigate even the most screen-reader accessible interfaces. The efficiency of screen-reader users can vary drastically based on their screen-reader proficiency, speech rate they use, and the familiarity with a particular GUI.

Over the years, screen readers have come a long way from simple and limited tools [11, 12, 25] to sophisticated productivity applications [17, 22, 31, 33, 37]. Nevertheless, the majority of screen readers continue to operate the same way, allowing users to navigate sequentially by pressing arrow keys on the keyboard, and now also with gestures on touch-screens. If a GUI has accessible tags for headings, buttons etc., then, with additional shortcut keys or gestures, users can “jump" to the next/previous heading, paragraph, button, etc. Alas, due to the limitation of audio modality, using screen readers boils down to navigating a one-dimensional list of GUI elements, thereby losing any semantic information and utility of the two-dimensional GUI layout.

The introduction of touch-screen devices such as iPhones allowed blind users to listen to the content they touch, i.e. the screen reader narrates the text under the finger. Touch screens allowed blind users to benefit from the 2-D layout, i.e. if the user knows where the content is on the screen, s/he can slide the finger right to it, in contrast to navigating through items one by one.

Regrettably, screen reading on touch screens has numerous limitations: (1) just as with keyboard browsing, one can determine if some content is relevant *only* after listening to it; (2) one can go directly to the particular content *only* if one is very familiar with the content layout; however, it is difficult to orient oneself on a flat surface just with the audio feedback; and (3) touch screens are often small, which makes it easy to miss content due to the "fat finger" problem [18, 30]. It should be noted that blind users do not normally use zoom to avoid horizontal scrolling. Our user studies [4] revealed, for example, that non-visual web browsing on touch-screens is not any faster than browsing with keyboards. In the end, any text-to-speech interface is ultimately limited by the inherent throughput of the audio channel and by the speech rate.

*Haptic interfaces* (with tactile feedback) have the potential to overcome some of the above limitations. Haptics engages the sense of *touch*, providing multiple simultaneous channels of information (e.g., one for each finger). If touch screens could render any GUI in tactile form, the user would be able to feel the sections of the interface, or the lines of text, or individual controls such as buttons. Prior studies [21] revealed that understanding webpage layout would be easier if users could feel section borders, enabling them to explore webpages faster than with audio alone. Regrettably, mainstream devices do not have haptic screens that would enable that kind of interaction, and specialized devices have very limited haptic capability (Section 2). Thus, accessible haptic interfaces remain to be the technology of the future.

To enable low-cost tactile interaction with GUIs, we developed *FeelX* – a haptic glove system. The vision of FeelX is to enable blind users to connect it to any computer, tablet, or smartphone, and then interact with the device by moving their hands on any flat surface such as the desk or the table. The architecture of FeelX is briefly reviewed in Section 3.1. The working area (i.e. the surface on which one can use the FeelX glove) can be several feet wide and deep. Therefore, while using the FeelX glove, one can easily avoid the "fat finger" problem, since a larger working area allows for bigger objects and wider space between them. The FeelX glove system is envisioned to be used in conjunction with regular screen readers and audio feedback. The gloves, however, will provide users with more ways of exploring GUIs and will enable users to interact with GUIs more efficiently, in this way, transforming the computer interaction experience for blind users.

In this paper, we evaluated the first prototype of a single FeelX glove with 20 blind participants for the purpose of establishing the practicality and the desirability of using haptic gloves. In our experiments, we have questioned the need to use more than one finger, the orientation of the hand relative to the interface, and we tested the ability of the glove users to tell apart basic geometric figures that are the basic building blocks of any GUI.

# 2. RELATED WORK

The research and development detailed in this paper uses haptic feedback devices for computer accessibility. Our research is based on the prior work on haptic interfaces and requires finger tracking to enable the FeelX system. Prior work has been done in all these areas; so, we provide a representative literature review to demonstrate our knowledge of the state of the art and, at the same time, contrast it with the innovations of the proposed approach.

There are a number of **haptic display** prototypes in existence: displays with electro-vibration (electrostatic) feedback [7, 28] that can give a feeling of varying friction; surfaces with temperature-sensitive hydrogel [26], which are slow and have no touch input or real screen; soft flexible displays with magnet or heological fluid actuated by an array of electromagnets to create different tactile sensations, though with low resolution [16]; etc. Some of these technologies are already making their way to the mainstream market, e.g., Phorm iPad case [32] with fluid-filled dynamically appearing buttons from Tactus Technologies and screens from Senseg [28] with electrostatic feedback. While these solutions are innovative, they are still very limited. Tactus case has large round buttons that can *slowly* appear only in the *predefined* locations and are *too large* to be useful for rendering webpage structure. Electrostatic screens have very small latency, and they could theoretically be used to render a webpage structure; however, 1) the feedback will be limited to the screen size, while the haptic gloves could enable interaction over a much larger area, e.g., the table; 2) existing devices provide the *identical* sense of friction over the *entire screen,* so blind users will be limited to using a single finger, while they naturally explore objects with all of their fingers; 3) the finger has to be moving to feel the friction, while, with the glove, the finger can feel the feedback (including the sense of pulsation) with or without finger movement; and 4) the electrostatic feedback is very subtle and depends on the moisture of the skin, while the proposed glove uses mechanical feedback.

Another type of haptic feedback is based on the tactile belts [13] with embossed dots on them. This sort of feedback is designed to reproduce the sensation of both lateral and rotational slip on the user's fingertip. Unfortunately, such displays are limited to representing only simple graphics and textures and are not suitable for interaction with web pages.

Thus, a number of haptic devices have been prototyped, but none of them can render a computer screen with high resolution and low latency. Perhaps the most relevant haptic technology is the pin-matrix device. For example, BrailleDis [34] can raise mechanical pins to form a tactile picture, <u>but it is not portable, has small resolution</u> (e.g., 120x60 in BrailleDis9000), and <u>is exuberantly expensive</u>, e.g., if an OEM Braille cell with 8 pins can cost around \$100, a Braille display with 20 Braille cells costs \$3K-\$5K, then a pin-matrix device with just 120x60 pins will cost tens of thousands of dollars. In the FeelX glove prototype, we use small matrices of pins attached to each finger of the glove and, in this way, simulate a pin-matrix display that is portable, relatively inexpensive (\$500 for a single glove), and is as wide as practically feasible, limited by the span of hands and the area covered by the hand-tracking camera. The FeelX prototype already supports the resolution of 320x240 pins, with the desk space of only 80x60cm.

Extensive research has been done on **haptic interaction**, both with static objects and dynamic computer screens. The use of tactile textures has been explored in [15]. The effectiveness of vibro-tactile feedback for typing on mobile phones has been investigated in [14]. The use of tactons, which stands for tactile icons, has been explored in [9], where authors investigate the use of varying frequency, duration, and amplitude of tactile pulse, to help the user distinguish icons from one another. In [21], the authors combined a 120x60 pin-matrix display with vibration feedback to enable blind and low-vision people to access complex STEM (Science Technology Engineering and Mathematics) educational materials.

Some early prior work exists even on tactile web browsing. In [27], haptic rendering of web-based images and Support Vector Graphics is proposed on a 120x60 pin-matrix display. In [6], auditory and vibration feedback were used to represent visual effects in web pages, such as the appearance of dynamic content. Unfortunately, all haptic research has been limited by the lack of inexpensive haptic technology that could provide high resolution of dynamic tactile feedback.

A wide variety of haptic glove designs have been proposed in research literature. For example, one of the early gloves, proposed in [39], had plastic tubes, light sources and detectors to record joint angles. The major drawbacks of this type of glove are: the fabric from which they are made is limiting the user movements, and the glove by itself requires complex user specific calibration, but does not provide haptic feedback. The majority of haptic gloves [8, 24] focus on virtual reality scenarios trying to give users the feeling of resistance, when they grab objects, and the feeling of touch.

Simple gloves have even been proposed for accessibility, e.g., [20] describes an inexpensive haptic glove which could be used in combination with a touch screen to interact with basic algebra graphs to enable navigation along the plot. A pager motor is placed on the tip of each finger and the motors are used to indicate the direction in which the hand should move. This setup only allows for guiding the user in the interface. This type of tactile feedback could be added to FeelX, but it would essentially provide only a single tactile dot per finger. Another glove that uses vibration feedback was proposed for way finding [38]. The FeelX glove technology is innovative in that it provides high resolution (2x4 pins for each finger) and haptic feedback to enable blind users to interact with GUIs. However, the existing research gave us useful insights that will help us improve the FeelX gloves and avoid common pitfalls.

The component that is needed for the success of the FeelX sytem is **finger tracking**, which is a well-studied field, offering numerous approaches to identifying finger positions. Finger tracking could be performed in a way it is done on capacitive displays (iPads); however, a large capacitive display would not be cheap or portable. Capacitive displays also suffer from their inability to detect fingers that share (X,Y) coordinates; therefore, where possible, finger tracking is done with cameras. In [10], a single finger was tracked using a bounding box-match method applied to camera video; although this approach assumed a contrast background and had limitations in finger orientations. Multiple fingertips were detected in [23] with the help of a thermal camera and fingertip geometry analysis; the use of the thermal camera made this approach rather expensive. A cheaper approach is described in [29], where two cameras are used to track finger positions, and the multiple graphics filters are applied to detect the edges; unfortunately, this approach is rather intensive computationally and sensitive to the surrounding environment. In [5], the authors use a mobile device camera to detect fingers based on the skin detection approach, which has similar limitations. A simpler approach is described in [36], where a custom-made glove with two infrared light-emitting diodes (LEDs) is used to track finger position. One LED is placed on the tip of the pointing finger, and the other – on top of the hand, which enables the support of simple gestures. Since the hand will be wearing the FeelX glove, we simplify finger detection by placing LEDs on the tips of the fingers, making the fingers easier to track. The FeelX system uses off-the-shelf computer vision libraries [2] to identify finger positions captured by an infrared camera (Section 3.4).

# 3. THE DESIGN OF FEELX

## 3.1 General Architecture

*FeelX*, our Haptic Glove system (Figure 1), is composed of the Camera, Finger Tracker, Controller, Haptic Glove, and Interface Manager. The Camera, set up over the table on a portable foldable crane, sends a live video feed of the glove to the Finger Tracker, which uses a standard computer vision algorithm to resolve the $(X,Y)_i$ coordinates for each finger $i$, and sends the coordinates to the Interface Manager.

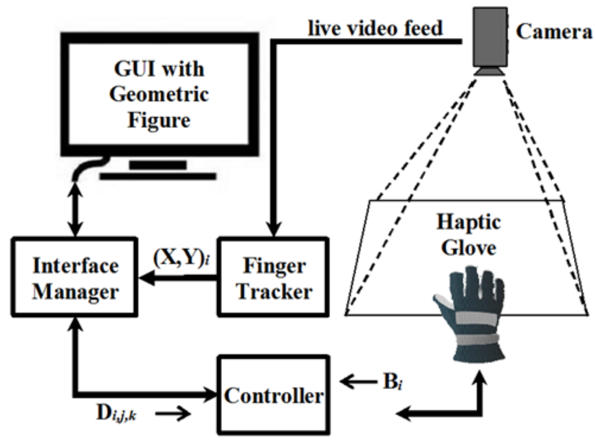


**Figure 1 - The Architecture of FeelX**

The Interface Manager processes geometric figures in the GUI, and maps the $(X,Y)_i$ finger coordinates to the GUI coordinates. Then, the Interface Manager outputs haptic instructions that are sent via the Controller to the haptic gloves in the form of $D_{i,j,k}$, where ($j$, $k$) are the row and column of a tactile "dot" rendered on finger $i$. Each finger in the glove is equipped with a hardware unit capable of rendering a tactile matrix of size $j$ by $k$ on the finger.

## 3.2 Haptic Glove

The FeelX glove is designed in the shape of a human hand (See Figure 2). The first working prototype of the glove, manufactured from laser-cut acrylic parts glued together, is made for the right hand. . Each finger is attached to the palm-platform in a way that allows the user to spread the fingers, as well as extend and collect them by a quarter of an inch. The device can further be adjusted to hands of various sizes by configuring the length of the finger appendages. In addition, the glove has a vertical hand position stabilizer on the left side for the thumb to hold on to. The stabilizer enables a more comfortable placement of the hand on the glove, which results in greater control over the hand movements. Although the glove, to a certain degree, resembles a mouse, each finger can be lifted from the table and moved around individually.

**Figure 2 – The FeelX glove prototype**

The glove integrates four Braille cells (Figure 2), one on each of the four fingertips. We aligned the cells with the *distal phalanx*, which is the most sensitive part of the finger. In our current design, we chose to limit tactile feedback to four fingers because: 1) the thumb wraps around the stabilizer; and 2) when the hand is placed naturally on the surface of the table, the thumb lies on its side, which does not work well with the Braille cell. With the miniaturization of tactile hardware, a future design that engages the thumb as well may be possible.

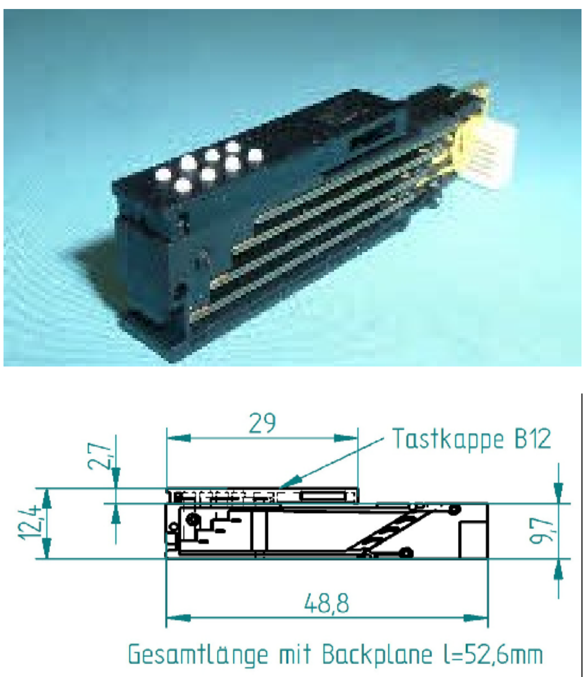


**Figure 3 – Metec Braille cell and specifications**

Each Braille cell is a 2x4 pin matrix with two columns of 4 pins. Each pin is approximately 1.2mm in diameter, and the distance between pin is around 1.3mm. Braille cells are typically operated by piezoelectric actuators that push the pins up or release them to go down. A Braille cell is typically used to render 2x6 Braille characters, with the bottom 2 pins used for other purposes, e.g., the letter case. We use all 8 pins to translate visual information into tactile form. For instance, by activating any two horizontal pins, we can depict a horizontal line; by activating another 4 vertical pins, we can depict two lines intersecting at 90 degrees. Activation and deactivation of horizontal pairs of pins one by one, going from top to bottom, give an impression of a horizontal line moving down. A 2x4 layout can even enable the user to feel lines placed at an angle, and even curves, as illustrated in Figure 4.

We placed two infrared LED lights on each finger to keep track of the finger orientation. We placed one more infrared LED near the thumb on the top of the stabilizer for easier identification of the hand orientation. We believe that, in future designs, this last LED may be eliminated.

## 3.3 Controller

The glove operates via a Controller that is connected to a computer via a USB port. The controller [1] was produced by Metec, a German company specializing in manufacturing Braille devices. We used a Metec's driver to communicate with the cells programmatically via a TCP socket. The payload of one socket transaction is a matrix data structure encoding the information about the pins that should be raised on a particular Braille cell.

## 3.4 Finger Tracker

To enable finger tracking, we removed the infrared filter from a Logitech C210 webcam and converted it into a pseudo-infrared camera. This enabled us to decrease the noise of the picture as well as the camera's sensitivity to the surrounding environment. Then, we made a few standard computer-vision preprocessing steps. Firstly, we converted the camera frame to a gray-white picture and inverted the image. As a result, we received a white image with a black blob representing the positions of the infrared LEDs. The size of the blob depends on the voltage applied to the LED. In our set up, the diameter of each blob was approximately 3 pixels. Then, we smoothed the image using Gaussian smoothing and increased the contrast of the picture to make the borders of the blobs more prominent. After the frame preprocessing, we applied Simple Blob Detection algorithm to detect center (X,Y) coordinates of the blobs on the frame; all image processing steps were made using OpenCV [2], an open source Computer Vision library. If the system lost track of the LEDs, which usually happened when the user moved the hand out of the camera sight range, we raised all pins to notify the user of the fact.

## 3.5 Field Representation

In this paper, we will use the term *field* to describe the GUI that contains a single geometrical figure. We will later refer to the pixel representation of the field as the *field grid*. The resolution of the field is 640 by 480 pixels, limited by the resolution of the camera used in our setup. By using a higher resolution infrared camera, the resolution of the field can be dramatically increased. However, even with the 640 x 480 resolution, blind users were able to recognize geometric shapes successfully, as we will discuss later.

We will refer to the part of the table viewable with the camera as a *working area.* The size of the working area on the table depends on the distance of the camera from the table. The higher above the table the camera is, the larger the working area is. In our setup, the camera was positioned 80cm above the table; the resulting width of the working area was 80cm, and the depth was 60cm.

A Braille cell is represented by a 2 by 4 table of cells in the field grid. Each table cell is a square of 5 by 5 pixels. In addition to Braille cell representation, the field grid contains a geometric figure, represented by one or more line segments or curves.

## 3.6 Interface Manager

The Interface Manager is the mediator of all the modules of the FeelX system. It receives an array of nine point coordinates from the Finger Tracking module: locations of infrared bulbs on the glove. Then the Interface Manager classifies the point coordinates into five categories: the pointing finger, the middle finger, the ring finger, the pinky finger, and the stabilizer bar. The process of classification of points consists of two steps. First, we are looking for the *pivot point*, i.e. a point with the highest cumulative distance from the other points. This point corresponds to the LED located on the hand stabilizer. Then, we sort the remaining eight points based on the distance to the pivot point. Since the position of all the points is dictated by the shape of the hand (i.e. fingers cannot change order), we assign each consecutive pair of points from the sorted array to each of the fingers, in the clockwise order, starting with the index finger.

Using the coordinates of two points on each finger, the Interface Manager builds a representation of the Braille cell in the field. For this purpose, we draw the line connecting these two points and calculate the position of a 2 by 4 grid with that line serving as the main axis of the grid. The resulting grid is the representation of the Braille cell in the field discussed in Section 3.5.

The final responsibility of the Interface Manager is to prepare and send the state of the Braille cells to the Controller to update the state of the pins on the Braille cells. In order to calculate the state of the Braille cells, the Interface Manager is looking for intersections of the grid that represents the Braille cell with the geometrical shape located in the field. If the geometrical shape intersects the (i,j) cell of the Braille cell grid, the corresponding pin on the cell should be raised. Then, the Interface Manager converts this information to the binary matrix and sends it to the Controller.

# 4. STUDY DESIGN

## 4.1 Overview

We evaluated the effectiveness of the Haptic Glove in a user study with 20 blind participants who had to recognize simple geometric figures presented in tactile form.

In preparation for the user study, we singled out 3 possible types of alignment of the haptic feedback grid:

1. Finger-aligned: the haptic feedback grid is always aligned with the user's finger and the field grid is fixed.
2. Field-aligned: the haptic feedback grid is always aligned with the field grid and the field grid is fixed.
3. Field-rotated: the haptic feedback and the field grids are aligned with the finger and the fields are fixed relative to one another.

If the finger is positioned as shown in (Figure 4a), the user gets the exact same haptic feedback in all three types of alignment. However, the feedback changes if the user rotates a finger. The finger-aligned Figure 4b) set up is the most intuitive and represents the way we typically interact with the physical world. The field-aligned set up (Figure 4c) keeps the Braille cell table representation borders aligned with the filed grid boarders. We thought this could decrease the noise of the user feedback at a given point, because, irrespective of the finger position in terms of rotation, the user would get the same feedback from the Braille cell. The field-rotated set up (Figure 4d) attempted to keep the glove and each finger always aligned with the field; so, rotating the hand also rotated the field. This last condition was eliminated during the pilot studies because, when the participants were trying to trace a straight line, their hand invariably rotated and they perceived the line as curved.

To verify if blind users cared about using more than one finger, we evaluated the Haptic Glove by providing tactile feedback to 1 finger (index) and 4 fingers (no thumb). Using the index finger is natural for pointing and touching as it is the most sensitive finger; also, it is the finger that blind people use for reading Braille. The 4-finger condition was chosen to maximize the number of input channels. As already mentioned, when the hand is placed naturally on a surface, the thumb lies on its side and, hence, it cannot be used effectively with the current design of the glove.

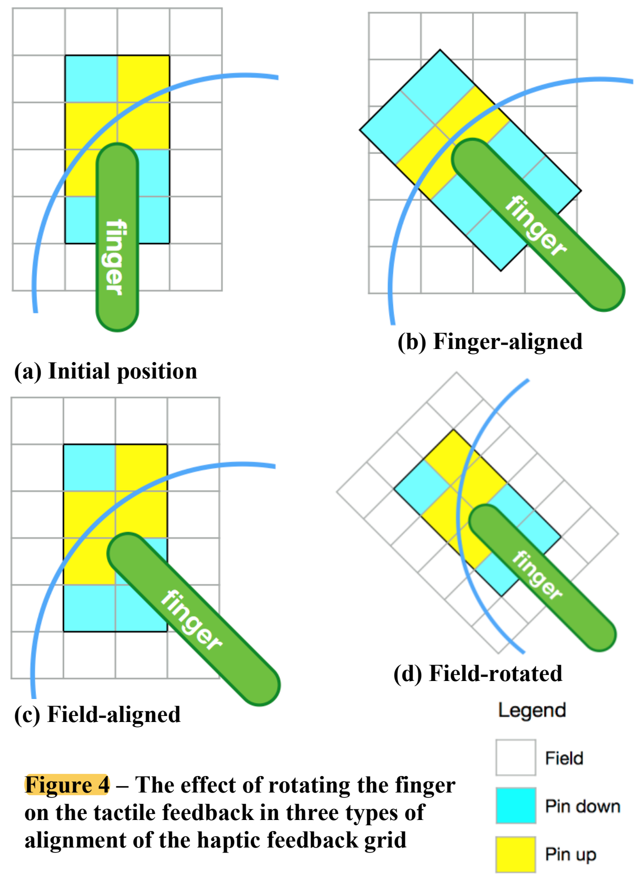


**Figure 4 – The effect of rotating the finger on the tactile feedback in three types of alignment of the haptic feedback grid**

## 4.2 Hypotheses

In the user study, we focused on the following main hypotheses:

**H1**: "Blind users can recognize simple geometric shapes using the Haptic Glove Interface with at least 80% accuracy, in at least one test condition." – This hypothesis tested the overall suitability of the FeelX prototype for interacting with the basic geometric figures – the basic building blocks of any GUI.

**H2a**: "Irrespective of alignment, blind users can recognize simple geometric shapes significantly faster with the 4-finger Haptic Glove Interface compared to the 1-finger Interface."

**H2b**: "Regardless of the number of fingers used in the glove, blind users can recognize simple geometric figures significantly faster with the finger-aligned haptic feedback grid than with the field-aligned one." – H2a and H2b compared the two viable interface design options identified in the preliminary pilot studies.

**H3**: "The haptic-glove interface has an overall good usability rating (an SUS score of at least 75)" – This hypothesis tested the overall user satisfaction with the glove interface.

## 4.3 Subjects

The user study involved 20 blind participants; however, we had to exclude 4 of them; the first one did not have an understanding of what geometric figures are (the participant was elderly and was unaware of the terms "triangle", "rectangle" and "circle"), the second one had an unusually small hand that did not work with our haptic glove prototype, the third one kept falling asleep and was unable to concentrate, and with the fourth participant, we experienced hardware failure. The results of the study are based only on the data collected from the 16 remaining participants.

The participants were pre-screened to be: a) blind screen-reader users, as our user study was concerned only with the participants who had severe vision impairments; b) right-handed, as our Haptic Glove prototype was designed for right-handed users; c) Braille users, as we wanted the participants to have a well-developed sensitivity to subtle Braille feedback, and we wanted to eliminate the advantage that Braille users would have had over the participants who had no previous experience with Braille; however, in the experiment, the participants did not use their knowledge of Braille.

The participants included 43% females and 57% males and were on average 41 years old (median: 36.5). The participants were Hispanic (5), Black (5), White (2), Other (2), Asian (1), Native American (1). Education levels were Graduate (6), Undergraduate (6), High-school (3), and Post-Graduate (1). The participants were, on average, experienced computer and screen-reader users; both average and median experience using computers was 15.5 years. With regard to computer experience, 4 participants considered themselves "experts", 7 – "very confident", 3 – "confident", 2 – "mildly confident". Finally, 4 participants were self-identified "experts" with Braille, 5 were "very confident", 2 – "confident", 3 – "mildly confident", and 2 – "not confident".

## 4.4 Methodology

The evaluation was designed as a within-subjects experiment with counterbalancing. Each task involved using the Haptic Glove to identify a horizontal line, a vertical line, a triangle, a rectangle or a circle; we chose to show one geometric figure per task to keep the experiment focused. Each task was to be performed using either 1 finger or 4 fingers, with either finger-aligned or field-aligned feedback delivery (a total of 2x2=4 conditions). Overall, each participant had to identify each of the 5 figures 4 times, once per each condition, resulting in 20 tasks per participant.

Each time the figure was placed in a different place in the field. The dimensions of the working field were 640x480px. We randomized the positions of the figures to be in central part of the screen from 1/3 to 2/3 along the X-axis and from 50px to 250px along the Y-axis. We did this to have comparable results for different conditions and still have variability of placements. The geometric figures had a consistent orientation. The dimensions of the rectangle were 100x250px, the radius of circle: 100px, the dimensions of the triangle: 250x150x150px. The lines crossed the entire field. Larger figures would be difficult to identify because the user would be sliding the hand out of the field. Smaller figures would be more difficult to identify because of the limited resolution of the field, which could jeopardize the study. We did not attempt to use smaller figures because the goal of the study was not to identify the limitations of the early prototype, but to determine its general feasibility and test several interface design options. In addition, in an envisioned tactile interface, users would be able to zoom in and make the figures the desired size.

Prior to the study, the participants were explained how to use the Haptic Glove, given an opportunity to practice, ask questions, and express concerns. The participants were explained the difference between the finger-aligned and field-aligned glove interfaces. The participants were explained the difference between all evaluation conditions and were asked to practice with all 5 geometric figures listed above. During the practice session, the participants were given the time to find the workflows that were comfortable to them, rather than were forced to follow specific instructions. The practice session lasted between 15 and 60 minutes depending on the participant's ability to adapt to the new technology. The practice session ended when the participants explicitly indicated that they were comfortable with the settings.

The learning effect in somewhat repetitive tasks was mitigated by: (a) having intensive practice sessions that lasted for as long as necessary for the participant to get comfortable with the glove, and (b) randomizing the order of the tasks and conditions.

# 5. RESULTS AND DISCUSSION

In this section, we present our findings, as well as discuss the subjective feedback from the participants. We also present the results of the statistical significance tests we conducted to compare the participants' performances under various conditions.

## 5.1 Analysis of Objective Measure

As explained in the previous section, the participants were asked to identify various geometric figures such as circles, rectangles, etc., under different conditions. Table 1 presents a detailed report on the participants' recognition accuracies for various combinations of figures and conditions. These accuracy measurements were computed based on *successful* task completions, i.e. the tasks where the participants correctly recognized the figure under a given condition. As seen in Table 1, in the 4-finger conditions, the recognition accuracy is over 80% for each figure, which validates hypothesis H1.

**Table 1 Figure recognition accuracy (Avg. w/ Std. Dev.)**

| | *Finger aligned* *1-finger* | *Finger aligned* *4-fingers* | *Field aligned* *1-finger* | *Field aligned* *4-fingers* | ***Overall*** |
|---|---|---|---|---|---|
| *Horizontal Line* | 81% (40%) | 88% (34%) | 94% (25%) | 81% (40%) | **86% (35%)** |
| *Vertical Line* | 100% (0%) | 81% (40%) | 81% (40%) | 100% (0%) | **91% (29%)** |
| *Rectangle* | 56% (51%) | 88% (34%) | 81% (40%) | 88% (34%) | **78% (42%)** |
| *Triangle* | 69% (48%) | 81% (40%) | 81% (40%) | 88% (34%) | **80% (41%)** |
| *Circle* | 75% (45%) | 81% (40%) | 63% (50%) | 94% (25%) | **78% (42%)** |
| ***Overall*** | **76% (43%)** | **84% (37%)** | **80% (40%)** | **90% (30%)** | **83% (38%)** |

It is notable that, with 4 fingers, the recognition accuracy of each shape was above 80%, regardless of alignment. Except when working with vertical and horizontal lines, the participants mostly struggled to recognize the remaining figures under the Finger-aligned 1-finger condition; this is evident from the low accuracy statistics in Table 1. When inquired about the difficulties, most participants mentioned that, under this condition, it was hard and confusing for them to detect the intersection points. The participants struggled to trace the curve of the circle in all 1-finger conditions, especially, in the field-aligned condition. The overall accuracy was the highest in the field-aligned condition.

Table 2 shows the average task-completion times based on the following groupings: (i) the type of alignment (finger-aligned vs. field-aligned); and (ii) the number of fingers used (1 finger vs. 4 fingers). We generated these statistics by merging the data from 4 conditions according to 2 factors: the number of fingers and the alignment paradigm. The statistical t-tests for comparison between groups were performed on the merged data in order to safeguard against Type I errors. We also checked the normality of data in these groups using statistical plots.

**Table 2 Average task completion times**

| Group | Time in ms |
|---|---|
| **Finger-aligned** | μ: 1:06<br>σ: 0:46 |
| **Field-aligned** | μ: 0:59<br>σ: 0:43 |
| **1 finger use** | μ: 1:11<br>σ: 0:48 |
| **4 finger use** | μ: 0:54<br>σ: 0:38 |

As can be seen in Table 2, users could identify figures faster when exploring the geometric figures with 4 fingers, compared to using only 1 finger. Between these 2 conditions, the difference in task-completion times was found to be statistically significant ($p < 0.0001$, paired t-test), thereby validating hypothesis H2a. The difference can be attributed to the fact that it may be easier to find a figure with 4 fingers because 4 fingers can cover a larger surface area in less time. Feeling the shape of the figure with multiple fingers also leaves less chance for a mistake (the difference in accuracies for 1 finger vs. 4 fingers was found to be statistically significant, $p = 0.026$ – paired t-test). In addition, the participants reported that the extra tactile stimulus available with 4 fingers made it easier for them to identify figures.

**Table 3 Participants' task-completion times (avg. w/ std.dev) by shapes and conditions. The winning values are in bold.**

| Shape | *Finger aligned 1-finger* | *Finger aligned 4-fingers* | *Field aligned 1-finger* | *Field aligned 4-fingers* | *Overall* |
|---|---|---|---|---|---|
| *Horizontal Line* | 1:06 (0:44) | 0:52 (0:43) | 0:58 (0:42) | 0:44 (0:41) | **0:56 (0:42)** |
| *Vertical Line* | 0:46 (0:42) | 0:55 (0:43) | 0:55 (0:44) | 0:41 (0:20) | **0:51 (0:38)** |
| *Rectangle* | 1:14 (0:43) | 1:09 (0:46) | 1:13 (0:49) | 0:43 (0:20) | **1:05 (0:42)** |
| *Triangle* | 1:25 (0:47) | 1:05 (0:45) | 1:18 (0:48) | 0:58 (0:45) | **1:11 (0:47)** |
| *Circle* | 1:25 (0:56) | 0:55 (0:41) | 1:29 (0:57) | 0:47 (0:28) | **1:09 (0:49)** |
| ***Overall*** | **1:11 (0:48)** | **0:59 (0:43)** | **1:11 (0:49)** | **0:46 (0:32)** | **1:02 (0:44)** |

The statistics in Table 2 show that the participants, on average, took slightly less time to recognize the figures in the field-aligned condition compared to the finger-aligned feedback. However, this difference was not found to be statistically significant – we conducted a paired t-test, $p=0.102$; therefore, we cannot validate H2b. Although the finger-aligned design may seem to be more intuitive, blind participants had no problem using the field-aligned design. The results demonstrate the viability of both designs, at least, for the types of tasks performed in the user study.

Table 3 presents a more detailed breakdown of the task-completion times, by considering different combinations of figures and conditions. We conducted a 2x2 2-way Anova test, and the results showed that there was indeed a statically significant difference ($p=0.0002$) among the 4 conditions with respect to the Fingers (1 vs. 4) and Alignment (Field vs. Finger) independent variables. Furthermore, there was no significant interaction effect ($p=0.16$) between these two independent variables.

## 5.2 Usability Analysis

At the end of the experiment, we administered several questionnaires to elicit feedback and opinions regarding the Haptic Glove. These included a standard System Usability Scale questions (SUS). The SUS questionnaire is a Likert scale with positive and negative questions, with responses expected to be on the scale from 1-strongly disagree to 5-stongly agree, and 3 being neutral. The average SUS score for the haptic glove, in general, was 62.2 (std. 22.6); therefore, we could not validate hypothesis H3.

The main concerns of the participants were related to the comfort and ergonomics of the glove. Given that it was an early prototype, there were various issues such as the inability to fit the glove on/OR: to small/large hands, insufficient flexibility to bend the fingers, lack of ergonomics, etc. However, the fact that the participants could still achieve a high accuracy (Table 1) indicates the glove's potential to become a viable assistive technology tool.

Since the overall SUS score was influenced by user experience in 4 different conditions, we also administered separate SUS questionnaires for the two types of alignment as well as the number of fingers. However, many participants were getting confused due to multiple SUS questionnaires, and also getting mixed up between the two types of alignment, thereby making the obtained data unreliable. In future, we plan to evaluate different conditions in a between-subjects study to minimize the cognitive load on the participants and obtain more reliable feedback.

## 5.3 User Preferences

Table 4 presents the participant's preferences about the finger conditions. The main takeaway of those results is that the majority of the participants preferred to use 4 fingers; this indicates that the haptic glove is desirable compared to other devices that can only provide tactile feedback for a single finger.

**Table 4 Post-evaluation questionnaire comparing haptic feedback with different numbers of fingers.**

| *Question* | *4 fingers* | *1 finger* | *Both* | *None* |
|---|---|---|---|---|
| *Which number of fingers would you prefer to use?* | 50% | 37.5% | 12.5% | 0% |
| *Which number of fingers did you find the most complex?* | 37.5% | 43.75% | 0% | 6.25% |
| *Which number of fingers did you find the easiest to use?* | 43.75% | 43.75% | 12.5% | 0% |

| | | | | |
|---|---|---|---|---|
| *Which number of fingers would need the most support from a technical person?* | 18.75% | 31.25% | 12.5% | 25% |
| *Which number of fingers was the most well integrated?* | 50% | 18.75% | 31.25% | 0% |
| *Which number of fingers was the least consistent?* | 6.25% | 37.5% | 6.25% | 37.5% |
| *Which number of fingers do you imagine most people would learn to use most quickly?* | 43.75% | 37.5% | 12.5% | 6.25% |
| *Which number of fingers did you find the most cumbersome to use?* | 37.5% | 25% | 0% | 18.75% |
| *Which number of fingers did you feel most confident using?* | 50% | 37.5% | 12.5% | 0% |
| *Which number of fingers did you feel required you to learn the most before using it?* | 37.5% | 25% | 6.25% | 18.75% |

## 5.4 Feature Requests and Opinions

Finally, we conducted a brief questionnaire to get the participants' opinions on the future development of the haptic glove (Table 5). We asked each participant to rate the importance of a prospective feature on the scale from 1 to 5, where 1 was "unimportant" and 5 was "very important". As can be seen in Table 5, the most desirable feature (Avg. 4.31 with the smallest Std. Dev. of 1.13) was the ability to click on the tactile screen to have a more interactive experience with the glove. The participants also favored the ability to spread fingers to help them cover a bigger portion of the working area during the exploration process, the ability to zoom in/out the interaction field for busier GUIs, and the ability to read Braille. The participants were undecided about being able to use two gloves or about using the gloves for typing, but we believe further experimentation is needed to determine the utility and usability of these features, as the participants based their ratings on the experience with the current glove design.

**Table 5 Post-evaluation questionnaire for glove development**

| ***Question*** | **Avg.** | **Std. Dev.** |
|---|---|---|
| *How important is it to be able to spread the fingers* | 3.56 | 1.67 |
| *How important is it to be able to change the zoom level?* | 3.68 | 1.62 |
| *How important is it to be able to use two gloves?* | 2.75 | 1.77 |
| *How important is it to be able to click on the tactile screen while wearing the glove?* | 4.31 | 1.13 |
| *How important is it to be to able to read Braille with haptic gloves?* | 3.68 | 1.74 |
| *How important is it to be able to type using a virtual keyboard enabled by the glove?* | 2.81 | 1.51 |

# TESTIMONIALS

In this section, we present a selection of the testimonials made by the participants during the debriefing session:

*"It is a great generalization tool which can be applied for reading the graphs, images, etc."*

*"The system has a lot of potentials in different areas such as Maps representation, graphics, charts even games such as Maze."*

*"Receiving the information from a hard copy diagram is too slow. Haptic glove is a faster and more efficient solution."*

*"I was never able to follow a straight line [in a computer interface] before using the Haptic Glove"*

The Haptic Glove system has also received a fair amount of criticism from the participants. The major area of concern was the ergonomics of the glove. While we were trying to make the glove configurable to fit any hand size, we still had problems with the participants who had unusually small or large hands.

# 6. CONCLUSION AND FUTURE WORK

In this paper, we presented the FeelX haptic glove prototype. The results of the preliminary user study indicate that haptic gloves could be a viable solution for interacting with GUI interfaces. The experiments showed that, at least with the current design of the glove and the resolution of the Braille cells, the participants could identify geometric figures more accurately and faster when using 4 fingers compared to using a single finger. The observations showed that most of the participants were exploring the figures with multiple fingers at the same time. We hypothesize that, even if tactile resolution increases, blind users would still want to use more than one finger for tactile interactions. Despite being crude, the FeelX prototype received good System Usability Scale scores from the more experienced participants. The majority of the participants wanted to utilize the haptic glove for their everyday computer use despite the limitations of the early FeelX prototype.

Now that we have identified the desirability and the utility of the haptic glove, in our future work, we will improve the design of the glove to be more ergonomic and start 3D printing the prototypes to accelerate the design cycles. We will experiment with using gloves on both hands and explore alternative camera-less approaches to finger tracking. We will enable the glove users to hear the touched content narrated by text to speech. We will test the usability of the gloves with real GUI interfaces such as spreadsheets, web pages, and graphs. We will also experiment with using the gloves as input devices, e.g., clicking and dragging objects in GUIs. Finally, we expect that the tactile technology will eventually undergo miniaturization, which will enable the gloves to become smaller and increase the resolution of tactile feedback.

# 7. ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grants: No. IIS-1447549, CNS-1405641, and IIS-1218570. We would also like to thank Lighthouse Guild for helping us recruit participants for the user study and conduct the experiments. We will like to thank our accessibility consultant, Glenn Dausch, for helping us develop a more accessible technology and formulate the goals for the study.

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