It’s like Google Maps, but better than Google Maps.

tac.tic

Tactile design language for
indoor - outdoor pedestrian navigation

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tac.tic

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Thank you, Molly, for the constant support and encouragement.

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ABSTRACT

People navigate through indoor and outdoor spaces all the time, and these environments are rich with visual and audio information, and noise. This poses a challenge to someone trying to navigate in a new environment. While GPS services like Google Maps help, they demand visual attention in an already visually stimulating environment. It is not possible to navigate while talking on the phone. They also keep one hand busy. Audio-based turn-by-turn navigation, while useful in certain scenarios, temporarily mutes the outside world for a pedestrian. In addition, these services do not work very well for people with visual and hearing impairments.

tac.tic is a tactile design language for indoor-outdoor pedestrian navigation. It consists of a sleeve with 9 vibrotactile motors in a 3 X 3 grid, that navigates a user through complex environments, by drawing patterns on the forearm. Apart from communicating directions that help navigate people, the design language aims to communicate the complexity of indoor environments, such as going left vs. going up the stairs to the left vs. going down the stairs to the left. Through a process of iterative prototyping and testing with people, the result is a preliminary language for navigating pedestrians within the built environment. It also paves the way for designers to design experiences beyond the audiovisual.

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INTRODUCTION

Almost everyone is faced with the task of navigating the built environment, many of which are to unfamiliar places. People not only walk to, and in, places they don't know, but also have to find their way around complex indoor spaces. Finding the way to the right gate in an airport, a particular store in a mall or a room in a hospital can be just as hard as finding a restaurant. GPS services like Google maps, while initially designed for driving, have been extended to include walking directions.

There is no doubt interactive location-aware maps have been a boon to people navigating outdoor environments, a leap from static maps. However, indoor navigation faces the challenge of localization. GPS signals are scattered by solid structures inside a building, making the resultant location highly unreliable indoors. This is an ongoing, widely researched field, with studies using a range of sensors including those already present in smartphones and bluetooth beacons. Localization technology is outside the scope of this thesis, but, the work done in this thesis is largely dependent on the success of widespread accurate localization methods.

Apart from the challenge of localization, the user-facing interface for such products have largely been audiovisual. Visual turn-by-turn navigation forces the user to shift their attention, both visual and cognitive, between the interface and the physical environment. They also require the user to hold the phone while walking, rendering the hand unavailable for other tasks. Audio directions are impractical for a pedestrian considering the surrounding noise, and using headphones cuts off the user from the environment.

The answer to this could lie in tactile interfaces, interfaces that communicate through skin using the sense of touch. The tactile sense is an integral part of our everyday experience. When used for navigation, tactile displays could potentially guide the user in a subtle, non-intrusive fashion. This has been the area of research for multiple studies. While these studies have been successful to various degrees, a common shortcoming is that they only communicate simple turns like left and right. This does not address the complexity of indoor spaces that may need people to take the stairs, walk down a ramp, or change floors.

Indoor navigation is complex

The tac.tic design language aims to navigate pedestrians, both indoor and outdoor, by communicating wayfinding instructions to the user through easy-to-learn patterns. Not only directions like left, right, straight, behind, northeast and northwest, but tac.tic can communicate architectural elements like stairs, escalators, ramps, elevators and doors. It can direct a user to go up the stairs to the left, or down the ramp to the right. While this makes navigation in complex indoors spaces easier, it is particularly helpful in situations where there exists a straight path, stairs going up straight ahead and stairs going down straight ahead. Tac.tic can communicate exactly which way to go, by variations in vibration pattern, intensity, and duration. The prototypes were tested with people, and were able to successfully navigate them to their destination.

This thesis advances the field of tactile interfaces by designing and evaluating a range of patterns that communicate information necessary for navigation. The remainder of this document is organized as follows: the next section is a review of the state of the art in audiovisual navigation, localization and indoor navigation and tactile navigation. It also briefly talks about tactile sensors in the body and tactile illusions. This is followed by the design process, which includes scoping, method and sketching in hardware. It also involves a section on evaluating the design. Lastly, the tac.tic design language is explained in detail, followed by conclusion and future possibilities.

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RELATED WORK

The related works are divided into three primary categories:

Audiovisual navigation: Today, pedestrian navigation mostly relies on audiovisual interfaces. Apart from popular GPS services, there has been work on using technology like augmented reality and designing audio-based navigation that take very little attention of the user.

Localization and Indoor navigation: Work on optimal localization methods for indoor navigation is on-going, and forms a big part of indoor navigation research.

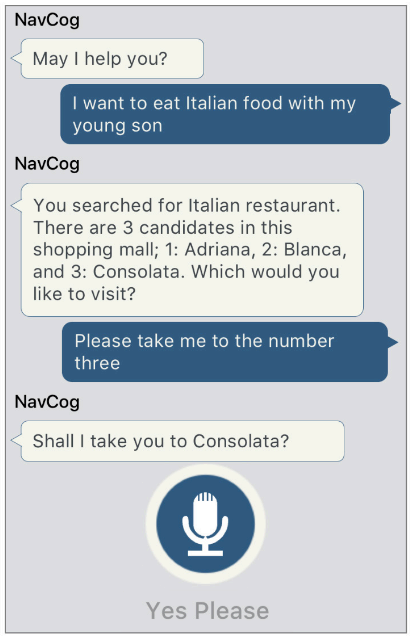
Tactile navigation: A significant body of work has been done to navigate people through indoor as well as outdoor environments, using tactile displays on various parts of the body.

Audiovisual navigation

As with most technology, GPS was first developed for the military as early as 1960s. More precise and advanced versions were in use in the early 80s. However, it was not until the 90s that the first consumer GPS devices (in-dash) were available, for cars. The mid 2000s saw a number of players like Garmin and Tomtom launch standalone GPS devices [1]. The advent of location-aware smartphones led to the widespread use of this technology. Even today, apps that make use of the GPS capability on smartphones, like Google maps [2], are widely used. These services can be used as an interactive visual map, or for audio-based turn-by-turn navigation. While they were initially targeted at automobile use, pedestrian navigation capability has been added in the last few years. An app called Walc [3] has been designed exclusively for pedestrians, and makes use of landmarks to help people orient themselves with respect to the environment. There are also GPS devices whose sole purpose is navigation. An example of this, built primarily for those visually impaired, is the Humanware Victor Reader Trek [4] which apart from giving clear audio-based instructions, can also play audiobooks and podcasts.

There have been explorations in the field of navigation using technologies like augmented reality and virtual reality, by taking advantage of its ability to present information contextually. Mulloni et al. [5] designed an augmented reality mobile interface that guides people indoors by telling them the number of steps to the next turn. The direction is presented in the form of an arrow on the screen, overlaid on the real world. Ishii et al. [6] proposed a virtual reality system which displays images of the environment as if the head-mounted display was see-through, and control's the pedestrian's direction by superimposing a visual illusion onto the image. Rukzio et al. [7] have designed a system that makes use of a public display to point to the right direction when the user's mobile phone is nearby. The user is notified of the turn by vibration of the mobile phone. GazeNav [8], by Giannopoulos et al., relies on the user looking towards the correct direction, which then causes the phone in the users pocket to vibrate. These approaches aim to alleviate the problem of pedestrians having to consciously map the navigation information provided to the surrounding world.

Mulloni et al. [5]



Sato et al. [12]

Holland et al. [9] have developed AudioGPS, a spatial non-speech audio-based navigation system with minimal attention interface. The direction is communicated by panning a sound source with respect to the user. A sharp tone is used if the direction is in front of the user and a muffled tone, if it is behind. The number of pulses of sound, and their rapidity indicate the distance to the next turn. The farther the turn, the sound pulses are more widely spaced. Strachen et al. [10] have built gpsTunes by integration a GPS and a music player. Users walk towards the direction of the music, and the volume increases as the user moves closer to the destination. Audio-based interfaces are especially common for the visually impaired. Wayfindr, a non-profit organization, has developed the Wayfindr Open Standard [11], a guide for designing accessible audio-based indoor navigation to ensure it is usable by the visually impaired. Sato et al. developed NavCog3 [12], a wayfinding system for the visually impaired, which uses a conversational interface as the interaction method. While the primary output is speech, directions are also displayed on the mobile phone screen, for those who can see.

Audiovisual wayfinding interfaces have a number of issues including taking the user's attention off the physical environment, needing to be held in the hand and unavailable to be used by the visually impaired, among others [13, 14, 15]. A number of studies have shown how how using a smartphone while walking can be potentially dangerous around traffic [16, 17, 18].

Localization and Indoor navigation

While GPS systems continue to be popular for outdoor environments, they do not work indoors because satellite signals are blocked or are unreliable. A considerable amount of work has been done on localization in indoor environments, starting in the early 90s. Some of the early work done to this effect includes the Active Badge-System [19] and BAT [20] which locate the user based on a number of ultrasonic beacons deployed across the indoor environment. Bahl et al. worked on RADAR [21], a radio-frequency based system that operates by recording and processing signal strength as multiple base stations located inside the building. Cricket [22], a location-support system by Priyantha et al., combines radiofrequency and ultrasonic beacons to help mobile devices learn where they are with respect to the environment.

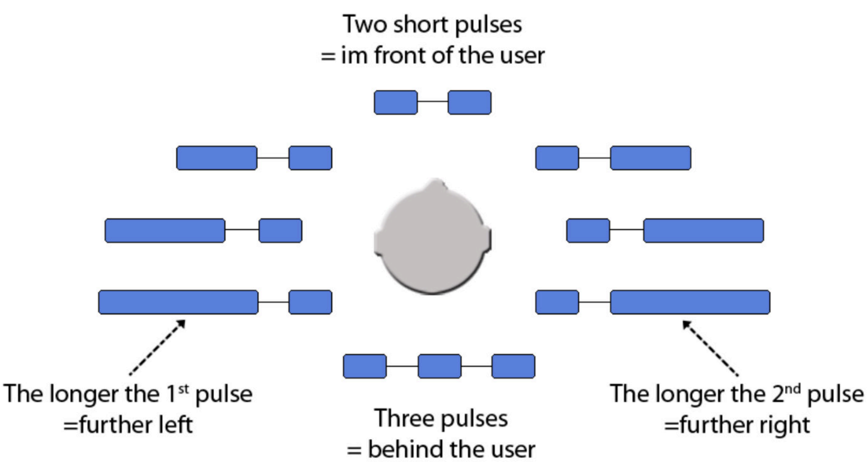
Apart from the radio and ultrasonic based systems, there are many works which use a range of sensors. Mulloni et al. [23] used the phone's camera to detect optical markers placed in the environment. Woodman et al. [24] used a foot-mounted inertial unit, a detailed building model and a particle filter to provide absolute positioning. Yeh et al. [25] took the approach of equipping the user's footwear with force, ultrasonic, orientation, RFID sensors and an accelerometer to produce a wearable location tracking system. PINwl [26], by Lochtefeld et al., makes use of the camera, compass and accelerometer on a mobile phone to navigate users by clicking a picture of an indoor (you-are-here) map. Cheng et al. [27] propose a wi-fi based positioning system which does away with the need for deployment of specialized infrastructure. Luca et al. [28] and Ahmetovic et al. [29] propose the use of low-energy Bluetooth beacons to help in localization. Work by Fallah et al. [30] uses the sensors available in mobile phones and combines them with the tactile sensing capabilities of visually impaired people to help navigate them through indoor environments. It requires users to confirm the presence of landmarks along the way. Work has advanced enough in this area that companies now sell bluetooth beacons so people can easily make high quality localization information.

While the above mentioned work on localization is concentrated on humans, a large body of work on localization is for navigation of robots in indoor environments. DeSouza et al. [31] provide a good overview of the work in this space.

Tactile navigation

Even though visual and verbal cues can provide more accurate commands than tactile interfaces, there are a number of advantage of communicating through the skin which has made it a highly researched topic. Researchers have not only designed various ways of using tactile communication, but have explored various parts on the body to provide such tactile information.

A number of researchers have explored tactile devices that have to be held in the hand, including smartphones. NaviRadar [14] uses a radar metaphor to communicate turns through vibration patterns on the user's mobile phone, while being held in the hand. While "I did it my way" [13] also requires the user to hold their phone in their hand, it vibrates to communicate in the general direction of the destination, allowing users to explore and take their own paths towards the destination. Traxion [32], by Jun Rekimoto, is comprised of a handheld tactile actuator which contains an electromagnetic coil, a metal weight and a spring. The user feels like they are being pulled in a particular direction. Hemmert et al. [33] worked on shape-changing and weight-shifting handheld devices which directed the user by either changing shape in the required direction, or by shifting an internal weight towards the required direction. The Animotous [34] is also a shape changing device which extends its body to indicate the distance from the turn and twists to indicate the direction. Handheld devices are an impractical approach to tactile navigation in everyday situations as they require the user to hold the device in a particular orientation, while taking up a hand and hindering real world tasks.



Rumelin et al. [14]

When devices are in the pocket, it frees up the hand to do other tasks. Pocketnavigator [35] and NaVibration [36] use a mobile phone to encode vibration patterns that communicate directions, while it is in the pocket. The reliability of communication of tactile patterns with devices in the pocket depends on factors like how tight the phone is against the thigh, the thickness of the pocket cloth, and the need to keep the phone in the pocket, as against in a purse or bag.

Vibrotactile belts have been widely explored. Activebelt [37], by Tsukada et al., consists of 8 equidistant vibration motors placed under a user's belt. Each motor maps to the respective direction. Heuten et al. [38] have used a similar tactile belt with eight vibration motors, but the device can communicate slight deviations in the path by activating two adjacent vibration motors. NAVI [39] uses a Microsoft Kinect to see the environment and helps the user do both, micro-navigation (communication of obstacles and other people on the path using a tactile belt) and macro-navigation (using audio). Cosgun et al. [40] present a way to navigate humans using a tactile belt by making use of ROS local navigation planner to find an obstacle free path by modelling the human as a robot.

The feet are most directly involved in the act of walking. This has led to a number of explorations. Velazquez et al. [41] worked on an on-shoe tactile display that communicates with the user through a 16-motor grid to communicate directions, as well as other important messages. CabBoots [42] consists of a pair of shoes equipped with sensors and mechanics that change the topography below the user's foot to indicate the right path. When going off-path, the sole lifts up in an angle to indicate the edge of the path, and steers the use back onto the path. Lechal [43], one of the few commercially available tactile navigation products, are a pair of GPS insoles that indicate turns using vibrations.

The shoulder is a great place to communicate tactile directions, much like a friend tapping on the shoulder to steer someone. Gemperle et al. [44] designed a tactile vest with tactors wrapped around the shoulder. Designed for walking and cycling, the Navigate jacket [45] was designed by Wearable Experiments, a wearable-tech company in Australia. Accompanied by a smartphone app, the jacket transforms turn-by-turn navigation data from the app into vibrations on the shoulder. LED's built into the sleeves tell the user how far they are from the next turn.

The wrist is a popular location for tactile displays for its easy access and high sensitivity. Kammoun et al. [46, 47] and Panëels et al. [48] have used actuators on wrist bands, using either one band or one on each hand, to indicate turns. Wayband [49] is one of the few commercially available tactile navigation bands designed particularly for the visually impaired, using a patented haptic language.

Most of the work reviewed on tactile navigation either communicates simple directions like left and right, or indicate the general direction of the destination. However, indoor environments can be particularly peculiar and needs much more than just basic directions. Paths could be at various angles and not necessarily at 90 degrees to each other. Also, communicating architectural elements becomes a major part of pedestrian navigation, particularly indoors. How does a user know whether to go straight, straight up the stairs, or straight down the ramp? What about taking a U-turn?

Navigate jacket, Wearable Experiments [45]

The Human Body

The tactile sensors in our skin that sense vibration are called mechanoreceptors (there are four main kinds in the human body). They are unevenly distributed among different parts on the body, leading to changes in the resolution of the stimuli. As a general rule, parts of the body involved in exploration and manipulation have a higher sensor density [50]. In other words, resolution of tactile stimuli increases as we move away from the torso.

Tactile illusions

Just like visual illusions, there exist tactile illusions. A tactile illusion is the marked discrepancy between a physical stimulus and its corresponding perception [51]. Some of these illusions, individually and in combination, have played an important role in the development and design of the vibrotactile patterns.

Illusion of Distance - Tau and kappa effects

Tau effect: If the temporal interval between stimuli presented to the skin is very small, the stimuli are perceived to be closer together spatially than they really are.
Kappa effect: The faster a stimulus moves across two or more points, the closer the points are perceived to be.

Illusion of Movement - Tactile apparent motion

When a number of stimuli are presented sequentially on the skin within a short interval, it is perceived as a single stimulus moving across the skin.

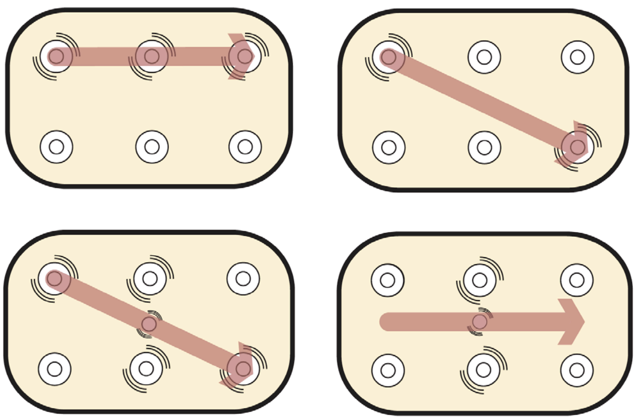
Errors of localization – Sensory saltation illusion

When a series of short pulses are delivered successively at three different points on the skin, it is perceived as a stimulus that is progressively moving across the skin.

Errors of localization – Sensory funneling illusion

When stimuli are presented simultaneously at closely spaced points on the skin, they are perceived as a single focal sensation in between the stimuli.

Poupyrev et. al [52] investigated the apparent motion and funneling illusions to develop Tactile brush, an algorithm that produced high resolution tactile strokes on the skin with a tactile grid display. This was the first attempt at developing tactile displays by combining tactile illusions.



Poupyrev et al. [5]

DESIGN PROCESS

Scoping

This study started off with an interest in how people attach human characteristics to inanimate objects. Why do some people feel bad while throwing away their old shirt or feel that an object can 'get hurt' when it falls down? I wanted to investigate this human behavior of having feelings for inanimate objects. Parallely, I was thinking what if these inanimate object actually had feelings and could reciprocate? What if a toaster communicated how useless it felt when used for a long time? I briefly looked at conversational interfaces to see how personification of an inanimate object affects people's relationship with products. What if everyday objects like an umbrella or a table had the ability to 'communicate'? Can that lead to better human-product relationship? All of the above questions came together in the form of understanding anthropomorphism. I wanted to use this understanding to develop ways in which designers could consciously influence relationships between people and interactive media. A deeper reading on anthropomorphism introduced me to the concept of social presence. I started wondering how social presence can be used to communicate the awareness and capabilities of smart products in our environment, what the product is doing, whether it is listening and what it is collecting. I wanted to design IoT products that were socially present in the environment by clearly communicating their 'thoughts' and 'intent'.

While researching on objects communicating intent, I landed inside the space of autonomous vehicles. On one hand, I looked at the communication of intent between an autonomous vehicle and its passengers. How does an autonomous vehicle communicate intent to its passengers? How does it tell them where it is going, what it is going to do next and when it wants the human driver to take over? On the other hand, I explored how autonomous vehicles could communicate intent to people outside the vehicle. How does an autonomous car signal to another human driver? How does it communicate with a pedestrian in the scenario of crossing the road? After reading about past studies in this area, it became clear that it would become difficult to prototype, test and prove that the work has truly advanced the topic, without having access to autonomous vehicles. However, I was still interested in the concept of social presence, both of people and products. How can products make people aware of their ability to perceive a situation and act accordingly? How can these “situation-aware” products in turn help people be more socially present? The area of navigation seemed to lend itself well to this. A quick review of the current state of navigation for driving, cycling and walking showed that the primary method for pedestrian navigation was services like Google Maps. These were were initially designed for driving and later adapted for pedestrians. Also, while there were a large number of studies on localization for indoor navigation, there was not enough exploration of the output methods. The problems with the using audiovisual interfaces for navigation while walking, like switching attention between the environment and interface, led to the identification of tactile navigation for pedestrians, as a potential area of study. An extensive search of existing work on tactile navigation did not lead to a study that involved communicating the complexities of indoor navigation. As discussed in the related work section, most work communicated only basic directions like left, right and straight, or communicated the general direction of the destination. It became clear that there was scope to explore complex navigational communication, and in the process, testing boundaries of tactile interfaces. This study takes up the challenge of successfully navigating a person through a combination of complex indoor and outdoor spaces.

Design. Make. Test. Repeat.

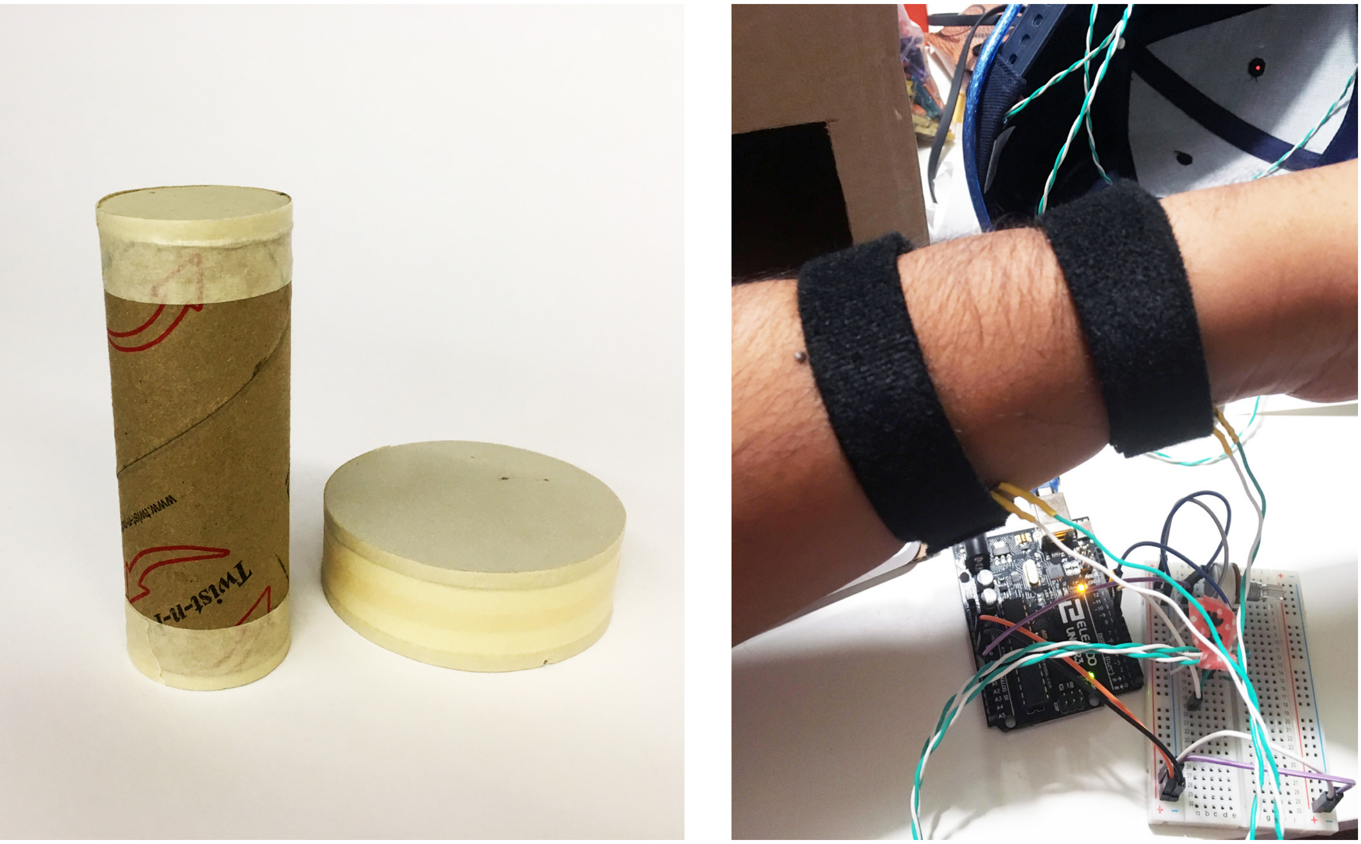
The method

Despite being an established research field [53, 54, 55], designers lack the knowledge of designing tactile interfaces due to the lack of experience working with the medium [56]. This has led to an absence of design patterns and norms to guide interested designers, and turned into a chicken vs. egg problem. Additionally, multiple works of research have noted that the vocabulary around the subject is limited, making it hard to verbalize and communicate our experiences from the tactile sense [57, 58, 59, 60]. The nature of this subject and its reliance on the sense of touch makes it extremely difficult to explore without being hands-on. Keeping this in mind, ‘Make to Learn, Learn to Make’, is the ideal to learning adopted for this study, from Camille Mousetti's work on Simple Haptics [61]. 'Make to learn' pertains to the making and building activities which are essential in exploring tactile interactions. Currently available commercial tactile interfaces allow for limited exploration. Following a practice of sketching in hardware and building various prototypes allow for a wider range of tactile experiences. 'Learn to Make' deals with gaining the skill and knowledge to build tactile prototypes. I had no experience working with tactile interfaces or in electronics prior to starting this study. It was a cyclic process of making from what I know and learning what I want to make. Throughout the year, prototypes were built (most times semi-working), tested with people, and changes made based on the observations, moving from design to making to testing and back within the same day on many occasions.

Early exploration

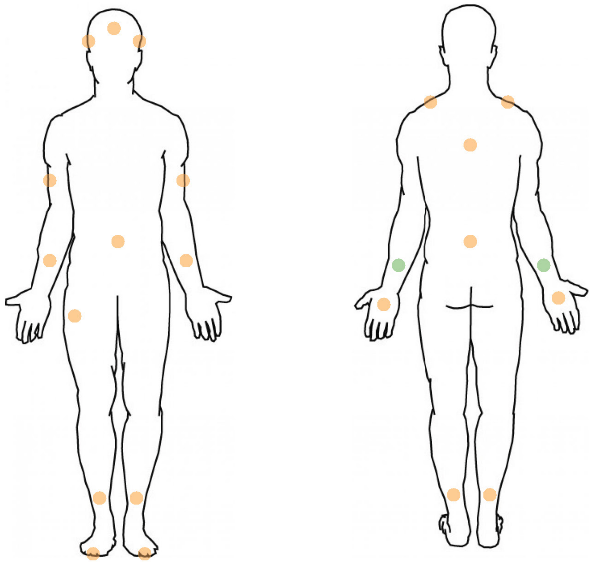
A tactile interface is a device that communicates information to the wearer by stimulating the perceptual nerves of the skin [44]. This involves modalities like temperature, air-pressure, electric stimulation, weight-shift, shape-change and vibrotactile stimulation. Initially, a couple of low-fidelity prototypes were built by adding weights to one side of a hand-held device. The movement of these weights from one side to the other could convey directions. However, this, and most other modalities are limited in their communication as well as hold technical complexities. Vibrotactile motors appeared to be the most versatile for exploration, as well as cost-effective and easy to work with. This narrowed down the study's focus on vibrotactile interfaces.

While I could have narrowed down on locations on the body based on information discussed in the related work section, I wanted to investigate if the sense of direction is better perceived in certain locations. This prompted me to test how vibrations from a vibrotactile motor felt around the head, neck, on the shoulders, back, upper arm, forearm, wrist, thighs, shin and foot. Based on this investigation, I found the forearm, foot and shoulders to have a decent sense of perceived direction, as well as good sensing capabilities. Of these, the forearm was the ideal location for a wearable and was also the easiest location to constantly test prototypes.



Early prototypes, weight-shift and vibrotactile bands

The initial explorations involved learning to activate and stop a single vibrotactile motor. Once I was comfortable with the Arduino platform and using the motors, I started replicating the tactile illusions previously discussed. This was greatly helpful in leading the way to prototypes that were built later. I also tested how the patterns felt on different parts

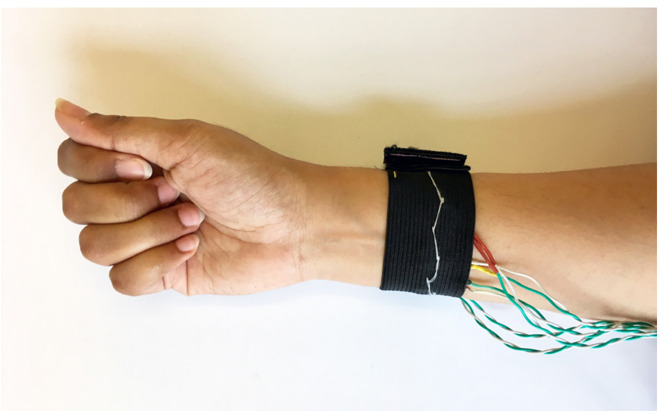


Locations explored on the body for vibrations

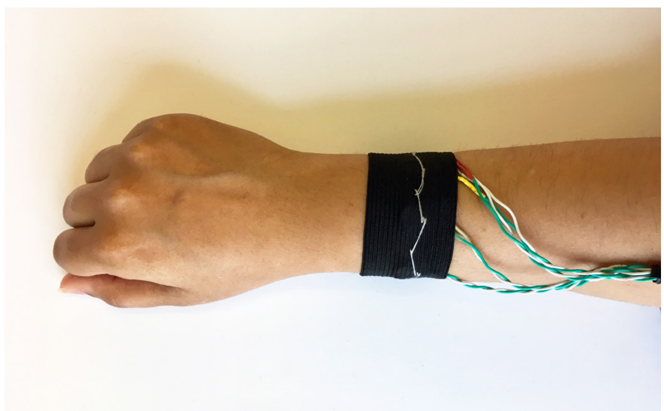
of the forearm, and realized that they were best localized closer to the wrist. This led to an option of building the interface for either the anterior forearm (on the same side as the palm) or the posterior forearm (on the same side as knuckles).

Anterior vs. posterior forearm: A quick trial was done to test the ideal location for a navigational tactile display, between the anterior and the posterior part of the forearm. Studies have been done to observe localization on the two sides of the arm [62], and have found that there is no significant difference in the localization capabilities of the two sides. A better sense of direction and the mappability of the communication to the environment were the factors for choosing the posterior forearm over the anterior part.

Anterior arm



Posterior arm

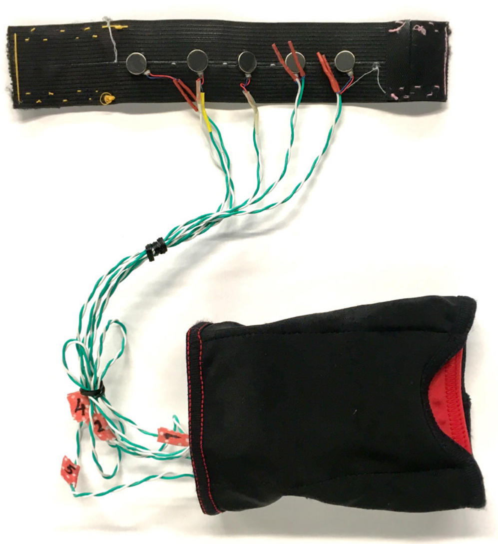


Sketching in Hardware, Part 1

1 X 5

The first attempt at navigation a person using a tactile interface was made using a prototype with 5 vibrotactile motors. These were placed collinearly on an elastic band. The motors were stitched onto the band with a distance of 1.5cm in between each motor. Velcro was stitched onto the the ends of the band so that it can be strapped on the wrist. Other than the Arduino, the electronics consisted of a bluetooth module to help control the prototype wirelessly. The electronics were packaged in a pouch which was strapped onto the upper arm using velcro.

1 X 5 prototype

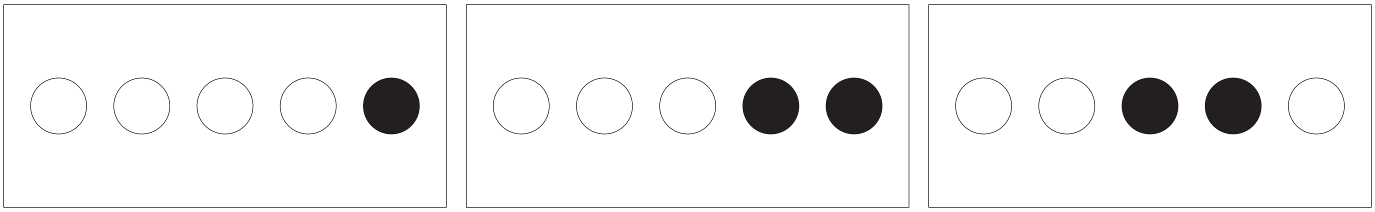


Prototype on the arm

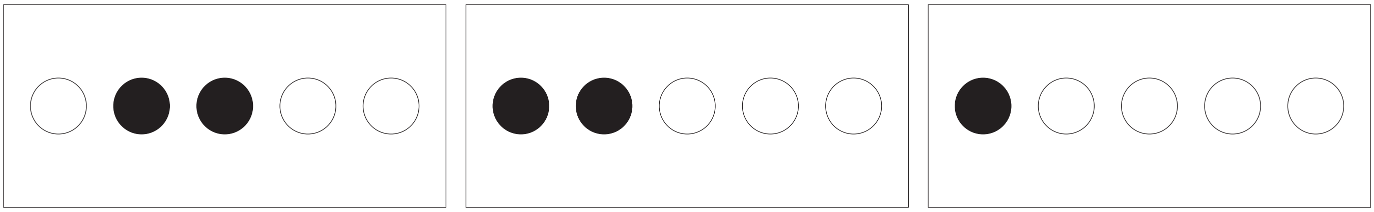
A set of 13 patterns, called hapticons were tested using the prototype. The patterns were designed by manipulating the direction of movement, speed of movement, rest period in between successive vibrations, intensity of vibration and duration of vibration. They were: left, right, straight, stop, stairs (going up to the left, going down to the left, going up to the right and going down to the right), ramp (going up to the left, going down to the left, going up to the right and going down to the right) and doors (push and pull).

> *The patterns were designed by manipulating the direction of movement, speed of movement, rest period in between successive vibrations, intensity of vibration, and duration of vibration.*

Left

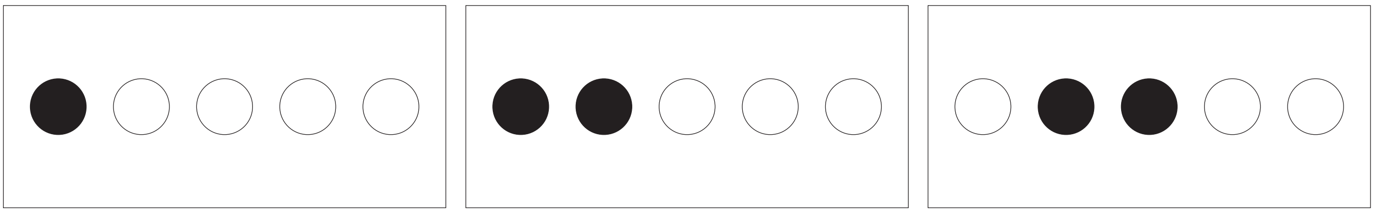


1 *150 milliseconds* 2 *150 ms* 3 *150 ms*

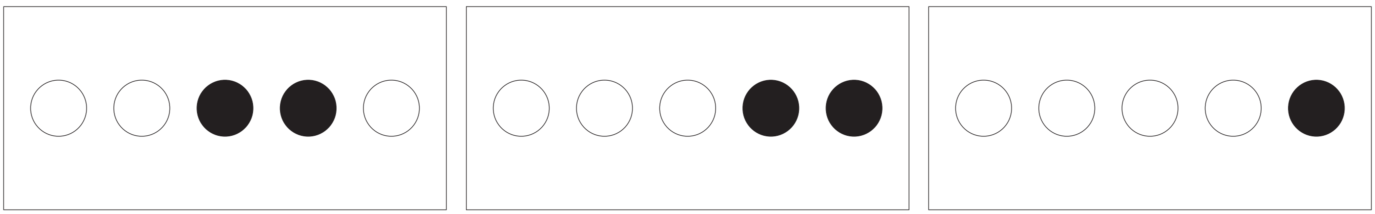


4 *150 ms* 5 *150 ms* 6 *150 ms*

Right

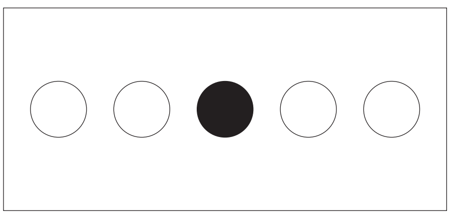


1 *150 milliseconds* 2 *150 ms* 3 *150 ms*



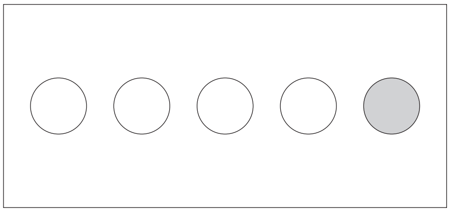
4 *150 ms* 5 *150 ms* 6 *150 ms*

Straight

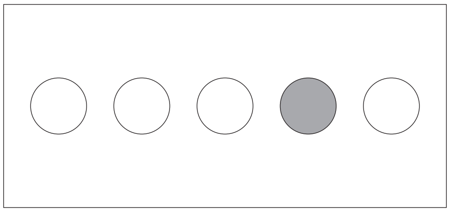


1 second

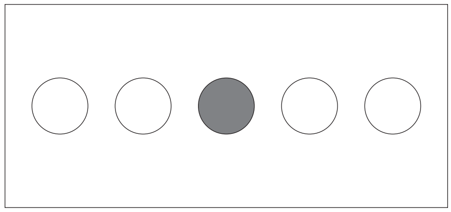
Up the stairs, to the left



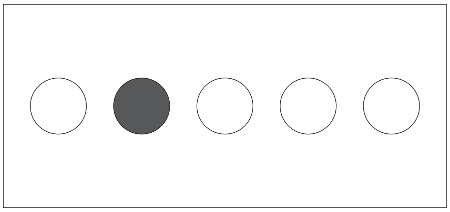
1 100 milliseconds



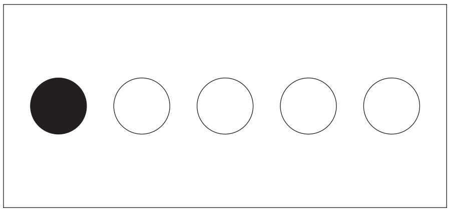
2 200 ms



3 300 ms

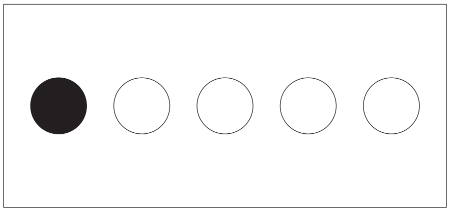


4 400 ms

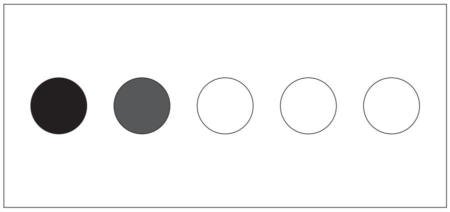


5 500 ms

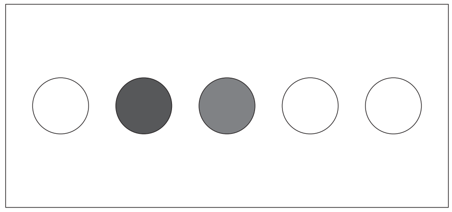
Down the ramp, to the right



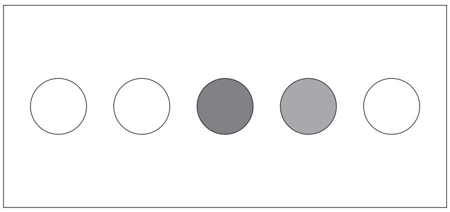
1 1 second



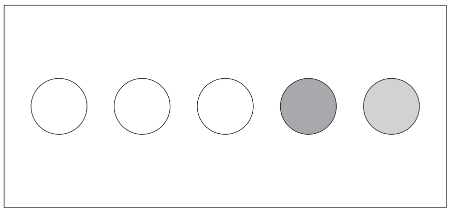
2 100 milliseconds



3 100 ms

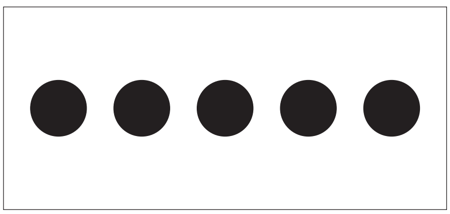


4 100 ms



5 100 ms

Stop



1.5 seconds

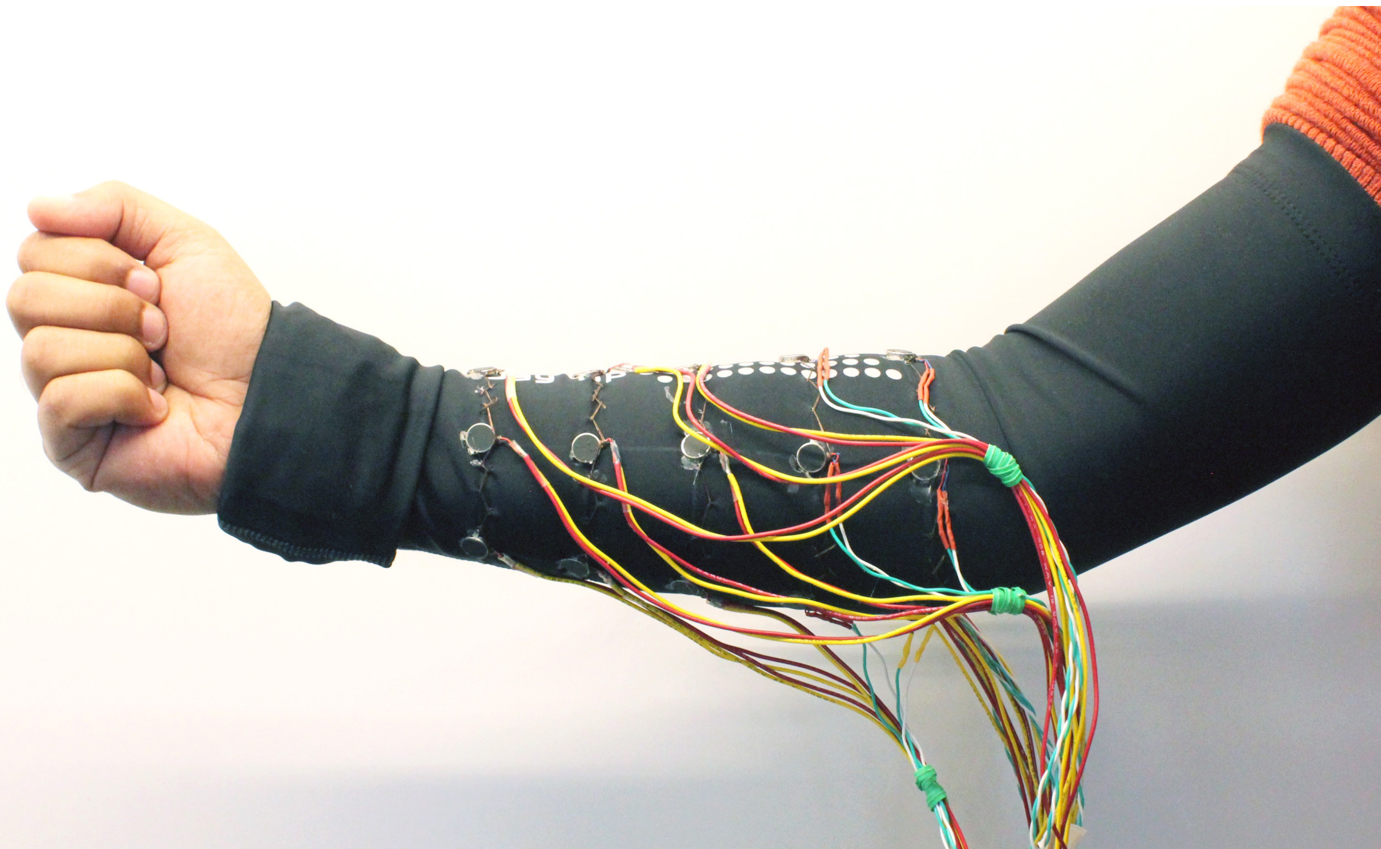
The prototype was tested by training participants to learn the patterns, and then they were navigated to a predetermined destination not known to them. The path was specifically selected such that it passed through indoor and outdoor environments which included some complex directions that included diagonals, stairs and a ramp.

The pattern for left and right, based on the tactile apparent motion illusion, were very easy to understand. They "drew a line" on the wrist from right to left to indicate left, and left to right to indicate right. Only the motor in the center was activated to indicate straight. This was easily understood by the participants too. Activating all the motors at the same time was an intuitive signal to ask the participants to stop. Basic directions (left and right) were distinguishable from complicated ones (stairs to the left or ramp to the right).
However, It took the participants a while to distinguish between going up the stairs and going down the stairs. Similarly, it took some trial and error to distinguish between stairs and ramp. Also, the prototype had some limitations. Because of its horizontal colinearity, it could not convey directions like go up the stairs straight or take the ramp behind you, which are possible situations in indoor navigation. It also could not communicate diagonal directions. This could be addressed by placing the motors in a grid with multiple rows and columns. While the pattern for doors was understood, it was hard to distinguish between push and pull. It was also observed that doors did not have to be necessarily communicated even when navigating a person indoors. If the instruction was to take a right and go through the doors, just a basic right direction was enough for the participant to go through the doors.

5 X 5

Since the prototype was not expressive enough, and could not communicate all the necessary directions, it was decided to build a prototype with 25 vibrotactile motors. These were placed in a 5 X 5 grid, stitched onto an arm sleeve so that they envelope the forearm and sit tightly. Since the Arduino Mega only had 15 PWM outputs, they could only control 15 of the motors. Two PWM servo drivers were added to increase the number of PWM outputs to 32, enough to control the 25 motors in the prototype. However, the prototype ran into multiple issues. The stitches could not hold the motors in place since the arm band stretched when being worn. Hot glue was added to secure them. The high number of motors required a larger external power source. Multiple power options were tried including AA, D and coin-cell batteries, but they all failed to work the motors in a predictable fashion. Although covering the entire forearm with vibrotactile motors seemed promising and could have led to new observations, I was not up to the electronic challenges that came up. Also, I believed that just increasing the number of motors was not the primary goal and decided to abandon this prototype and move on to another that I could handle electronically.

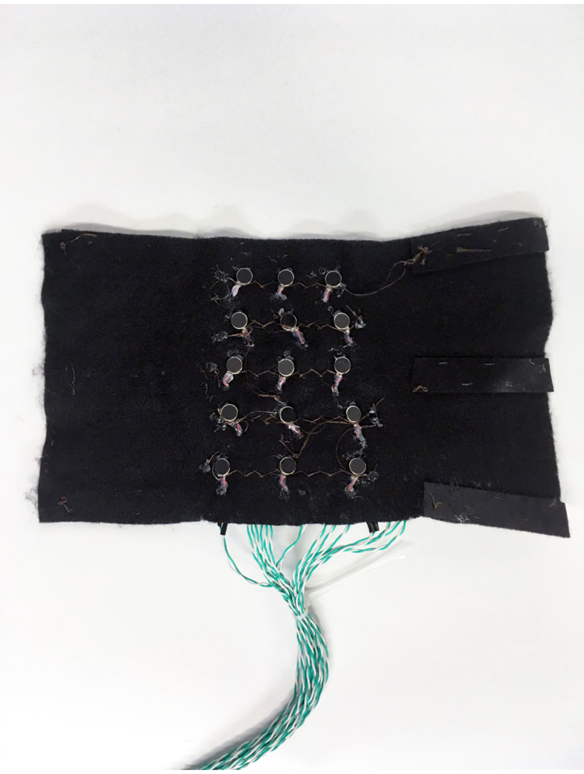
5 X 5 prototype on the arm



5 X 3

I decided to use as many motors as were possible just using the Arduino Mega (without PWM divers), which was 15. These were hot glued in a 5 X 3 grid onto a large piece of felt which can be strapped around the arm using velcro. The electronics including the batteries were placed in a bag that can be carried on the shoulder when the motors were strapped onto the arm.

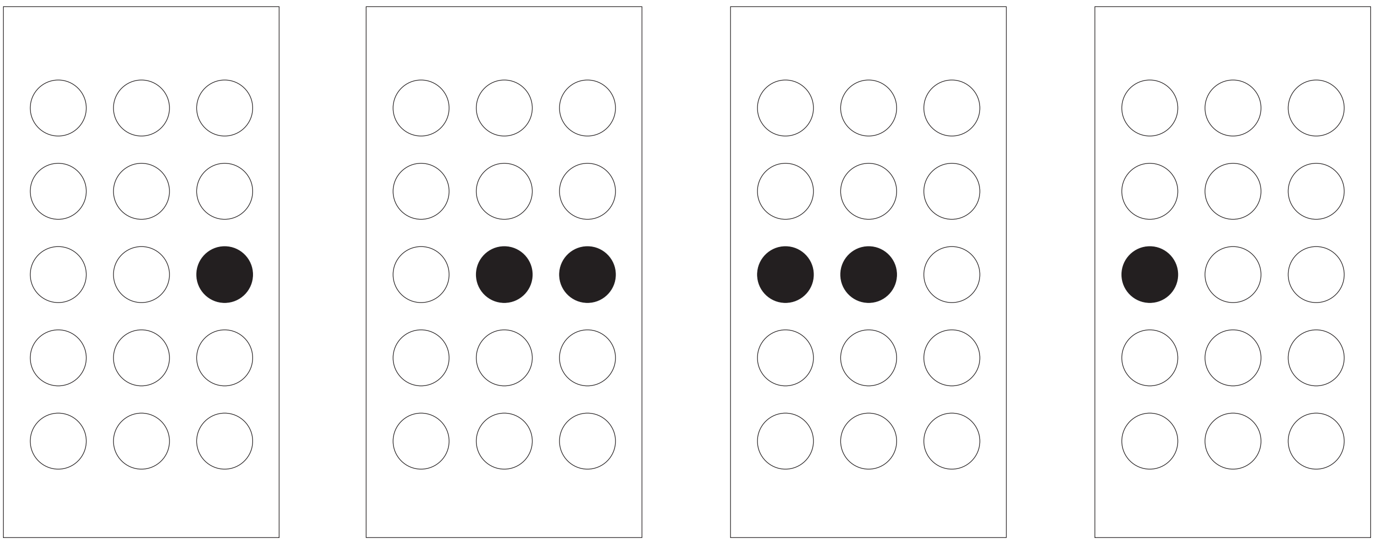
5 X 3 prototype



Prototype on the arm

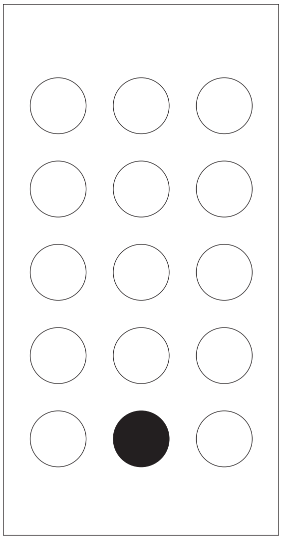
The larger grid opened up the possibility of communicating complicated directions like go in a diagonal direction or go up the stairs to the left. Extensive trials were done to select the best of multiple possible patterns for the each navigational instruction based on the ease of understanding and distinguishability from other patterns. The trials were done by Guerilla testing with participants so as to quickly evaluate and iterate the patterns. 28 patterns (out of more than 60) were built into this prototype. These patterns were representative of the entire language and someone who could identify these could identify most other patterns. The included the basic directions (like left, right, straight, behind and diagonals) and the different variations of stairs, ramp, escalator and elevator. This prototype could communicate whether to go up the stairs to the left or go down the ramp to the right. It also included patterns for stop, on track and destination reached.

Left

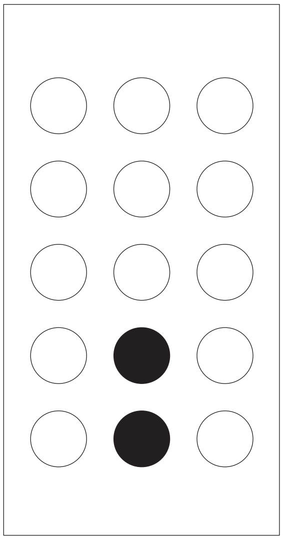


1 150 milliseconds *2 150 ms* *3 150 ms* *4 150 ms*

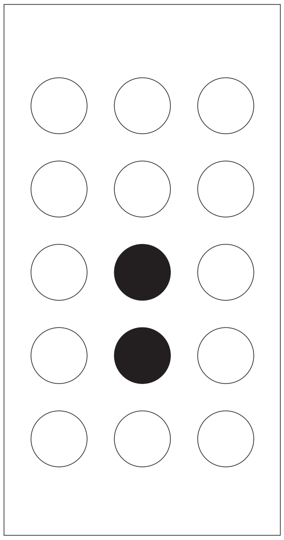
Straight



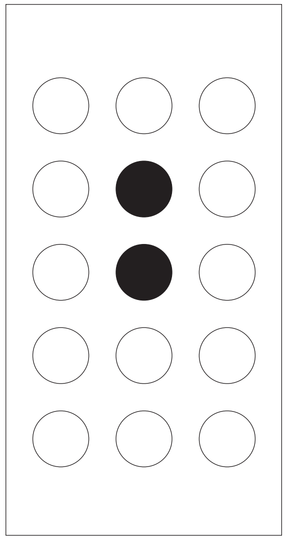
1 *150 milliseconds*



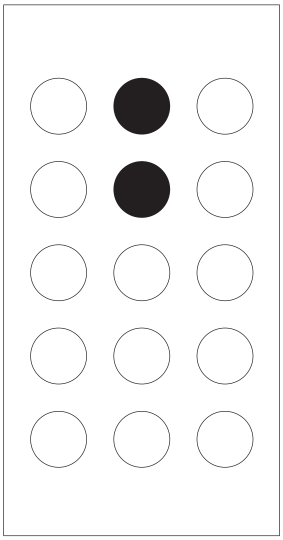
2 *150 ms*



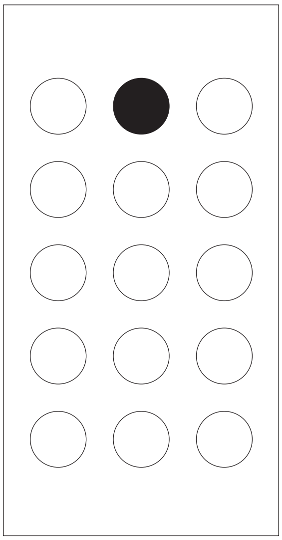
3 *150 ms*



4 *150 ms*

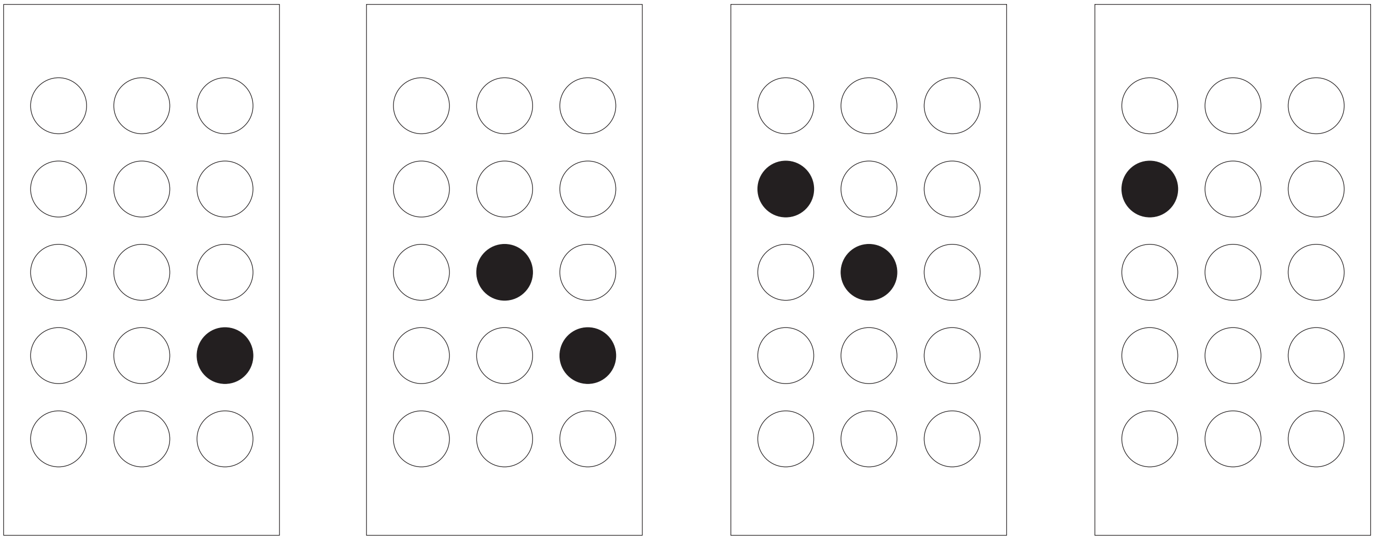


5 *150 ms*



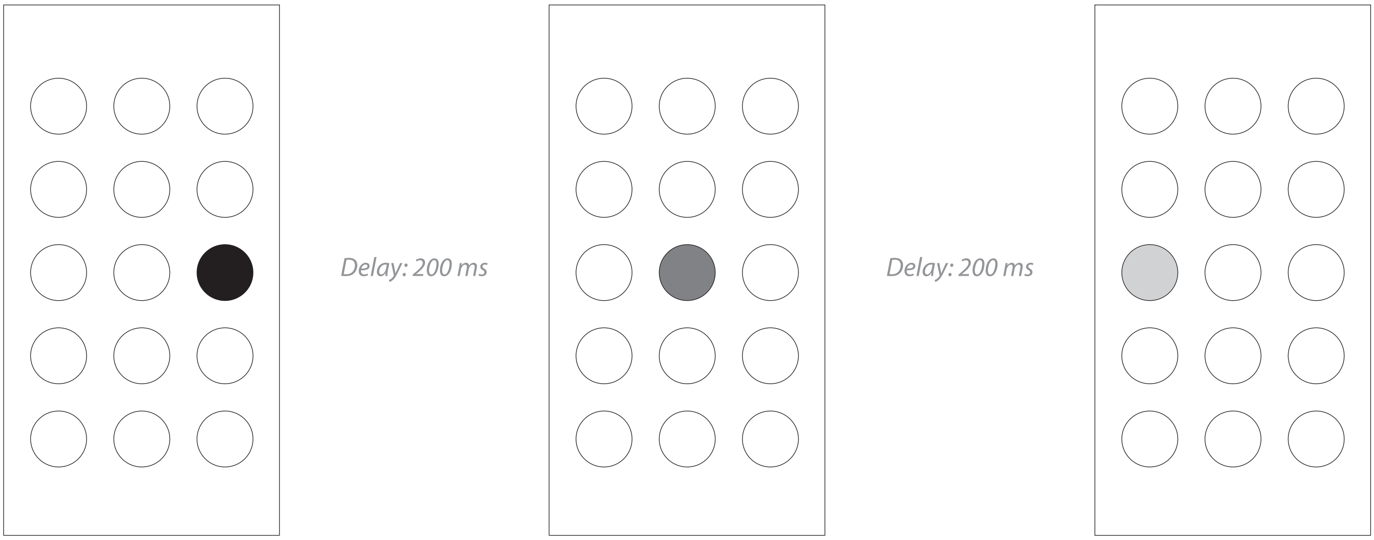
6 *150 ms*

Diagonal towards the left



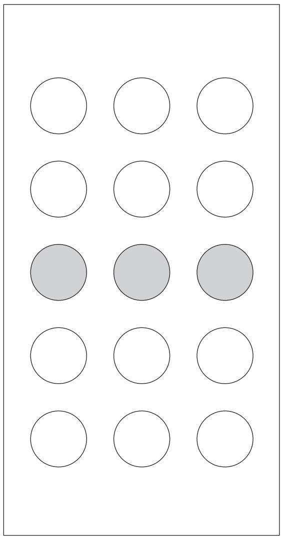
1 150 milliseconds | 2 150 ms | 3 150 ms | 4 150 ms

Down the stairs, to the left

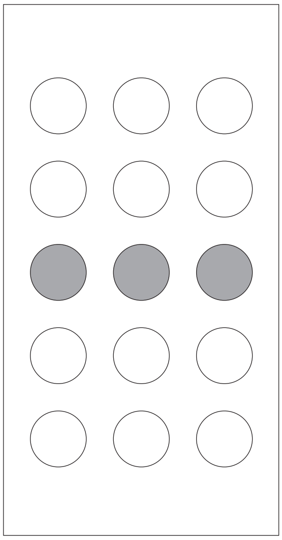


1 700 milliseconds | 2 550 ms | 3 400 ms

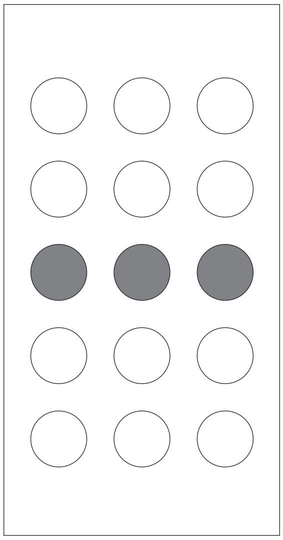
Up the elevator



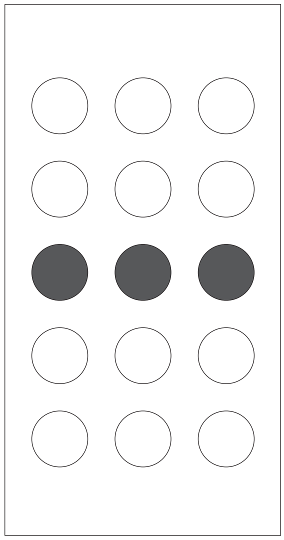
1 300 milliseconds



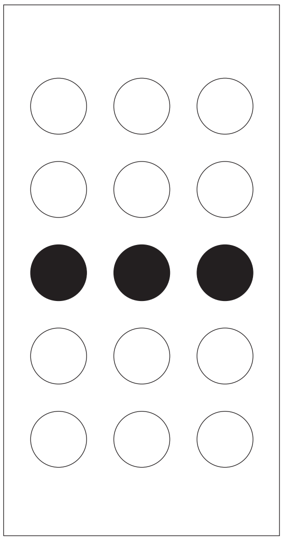
2 300 ms



3 300 ms

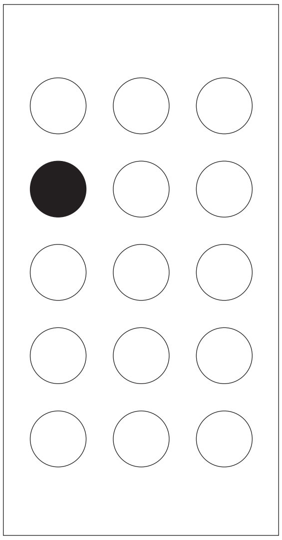


4 300 ms

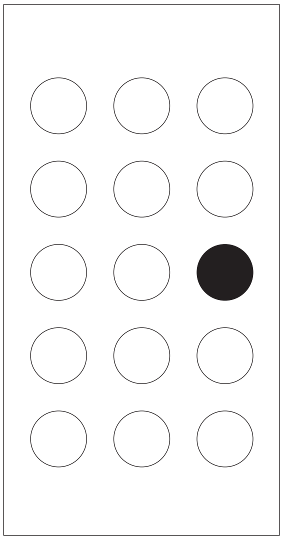


5 300 ms

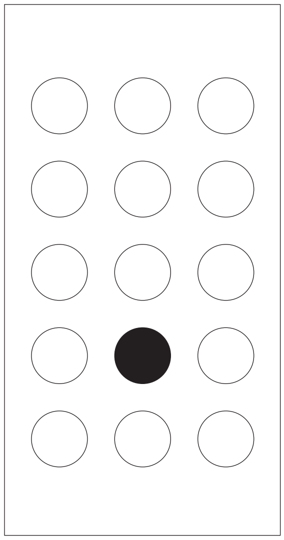
Destination reached



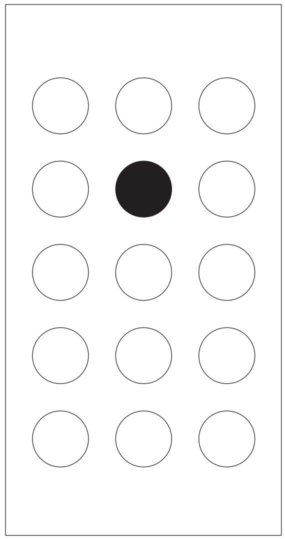
1 150 milliseconds



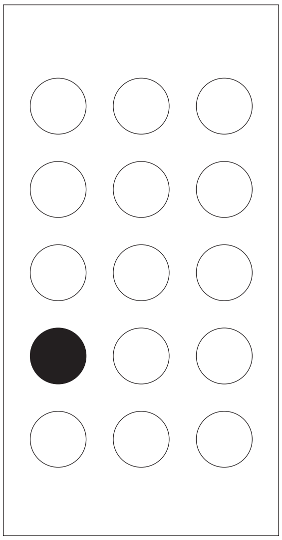
2 150 ms



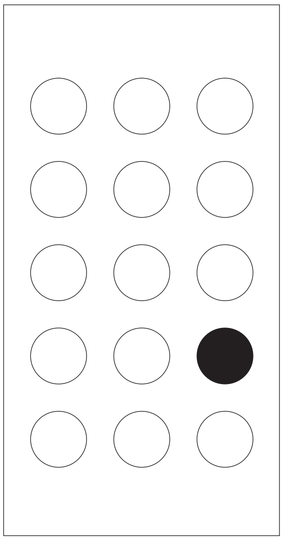
3 150 ms



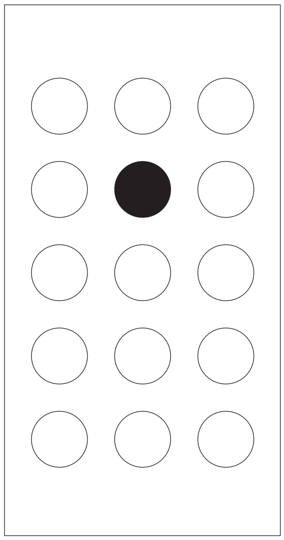
4 150 ms



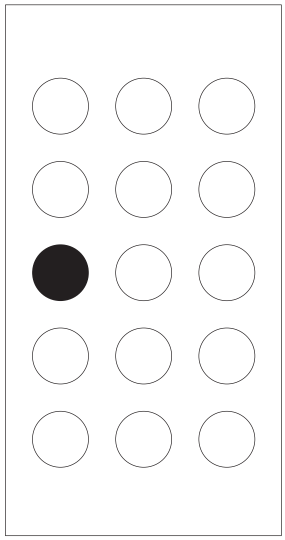
1 150 ms



2 150 ms



3 150 ms



4 150 ms

Evaluation

Overview

Although there have been multiple studies on vibrotactile interfaces for navigation, most of them have been tested in controlled lab environments [63]. There were two primary goals for this evaluation. Firstly, I wanted to know if tactile navigation can work for pedestrian navigation. Would people be able to map what they feel to what they are seeing? Second, if people are able to understand the patterns and can navigate complex indoor environments successfully. As discussed previously, there have been multiple studies on basic directions, but complex directions pose a challenge. Additionally, I also wanted to investigate if and how the perception of direction changes when the arm is in different positions. Are the patterns identifiable only when the arm is in the front? How do people interpret the same pattern when the arm is behind?

For this study qualitative data was gathered based on observations. This included observing if the participants took the correct path, the points on the route that were hard to navigate and if the direction had to be communicated multiple times. The participants were questioned during the study to understand their rationale behind the decisions they took. This gave a good amount of input on their experience navigating with the help of a tactile interface, which was used to further refine the language. The participants were all students at Carnegie Mellon, and from different parts of the world. While this may not be completely representative of the population, it was enough to understand their perception while using a tactile device. Also, being students who are at the center of technology made them more open to the tactile medium even if they haven't experienced anything similar previously.

Study: Communicability of the patterns

A comprehensive 3-part evaluation protocol was followed to test if participants could successfully navigate the path to reach the destination, particularly if they could traverse the complex turns in the path.

Training: Participants were introduced to the patterns, and trained to distinguish between them. They were encouraged to form mental connections between the tactile pattern and what came to their mind when they feel it. This took about 20 minutes per participant on average.

Video navigation: Once the participants felt comfortable with the patterns, they were introduced to a point-of-view video of navigating an indoor-outdoor route. At decision-making points on the route, the video was paused and the tactile navigational patterns was communicated to the participant. The participant had to say where they thought they had to go, and the video resumed. This was done to acclimatize the user to understand the patterns in context. Identifying the pattern in the presence of context turned out to be much simpler than without context.

Navigation to predetermined destination: By now, the participants seemed to be able to successfully identify and distinguish between patterns. They were navigated to a predetermined destination through a particular path without being told where they were going. I wirelessly controlled the prototype to communicate patterns, while following the participants. They were told to follow the navigational instructions communicated by the tactile interface, and speak aloud what they thought the instruction was. The path selected path consisted of both indoor and outdoor environments, and included multiple complex turns. It started in a hallway, where they had to take some basic turns, go down the stairs and exit the building. Once outside they had to walk through a diagonal path, make a sharp turn, take a slightly obscured path to walk on a sky bridge and enter another building. As soon as they entered the building, the path involved a complex diagonal ramp that spiraled down and required them exit the ramp midway to a connected building through a bridge.

Here, they had to take a right and immediately go down the stairs, and walk behind to reach the destination.

Patterns communicated: The list of patterns in the order it was communicated through the path were **(Indoor)** Left > Straight, down the stairs > Straight > Right > **(Outdoor)** Left > On track > Left > Diagonal to the right > On track > Right > Left > Straight > Right > **(Indoor)** Diagonal to the left, down the ramp > On track > Right > Left > Right > Left > Right > Right > Right, down the stairs > Behind > Straight > Destination reached.

Selected images and directions from the navigated path

Results: All five participants successfully reached the predetermined destination, and they could understand majority of the patterns without requesting for the communication to be repeated. Four participants mentioned that they were surprised at how communicative and easy to understand most patterns were. One participant mentioned that the whole experience was intimate, and that it felt like her husband was guiding her by holding her hand. Another participant talked about how the tactile language will be helpful when navigating in pairs or groups, because they don't interrupt conversations. Even if a participant only partly understood a complex pattern, it didn't stop them from taking the right path. This could be seen in the case of 'Diagonal towards the left, down the ramp'. None of the participants understood the 'diagonal' but they took the ramp going down because they either understood 'ramp' or 'down'. The available visual context helped them make the right decision. However, there was only one ramp going down and it might have been confusing if there were more than one close to each other. This also led to the observation that a single pattern communicating whether the participant had to go up, or go down was enough, and communicating stairs and ramps was not required. E.g.: Go up towards your left worked fine irrespective of whether there were stairs or a ramp to the left.

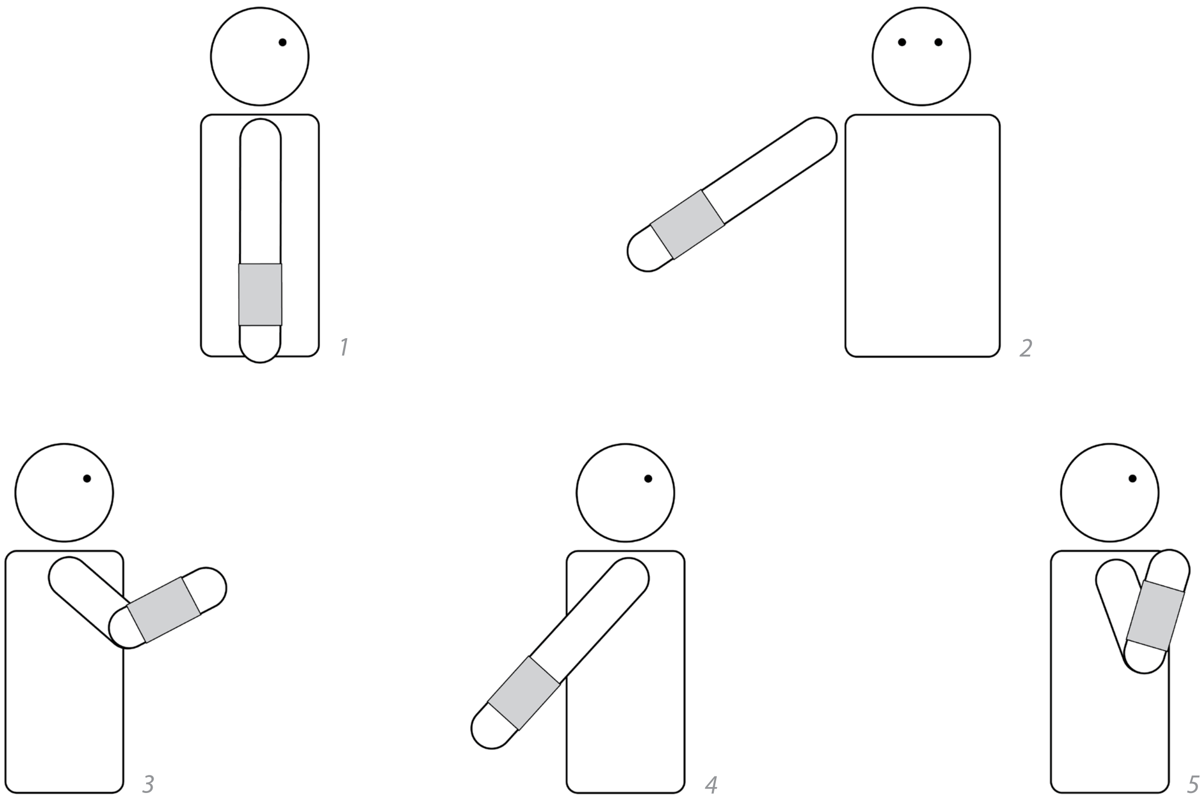
Since the motors were in a 5 X 3 grid, the patterns for left and right consisted of 3 motors, whereas straight and behind consisted of 5 motors. While this did not lead to confusion in identifying the direction, participants mentioned that they did not seem to belong to the same family of patterns (since the pattern for straight and behind felt longer than left and right). Using a square grid can potentially help make the patterns seem consistent. Two participants mentioned that it was not clear how much in advance the pattern was going to be communicated before the turn arrived. The communication when someone was 'on track' was perceived to be very helpful by the participants, especially when they had to walk for longer distances without a change in direction, and when navigating complex indoor environments. However, two of them said they were unclear under which conditions this communication would happen, and when it would not. It would help to detail the condition for the 'on track' pattern. Each pattern for a particular direction was repeated thrice. It was observed that the first instance of the pattern took the attention of participants, and the second and third instances helped identify the direction. It might help to take the user's attention through a generic vibration before communicating the direction. Apart from the pattern itself, the direction of movement of the pattern along the hand was also interpreted as meaningful, even for the left and right directions. Pattern moving up the hand was thought of as going up, and pattern moving down the hand was considered going down. Though this did not hinder their understanding of the pattern it may be helpful to eliminate the movement along the hand to avoid confusion.

None of the participants could understand the pattern for 'diagonals'. 'Diagonal towards the left' was confused with 'left' and 'diagonal towards the right' was thought to be 'right'. These patterns will have to be significantly different from 'left' and 'right' to be successful. There was a point in the path where the participants were required to go down the stairs and then turn and walk behind them to reach the destination (Image below). For this, the pattern for 'behind' was communicated as soon as they got down the stairs. However, all participants started walking back up the stairs, even though the communication for that would have been 'behind, up the stairs' and not just 'behind'. This shows that 'behind' makes people go back the same way they came. Such scenarios require a different pattern that communicates going ahead, taking a turn and walking in the direction behind the user. In a couple of places where there were two turns very close to each other (Image below), there was not enough time to communicate the second direction once the participant has taken the first turn. In such cases, it might help to communicate the next two directions at once.

Images from the evaluation

Study: Multiple arm positions

As discussed previously, the forearm was chosen over other locations on the body due to its decent sensitivity to vibrations, good perceived sense of direction and ease of prototyping and evaluation. However, the challenge of locating an interface on the forearm is that the arm can be in multiple positions while walking, which could affect the orientation of the direction communicated by the tactile pattern.



Arm positions, (1) Relaxed to the side, (2) Stretched to the side, (3) Folded in the front, (4) Stretched behind, and (5) Folded close to the shoulder, flipped

To understand if the position of the arm affected the perceived direction, the basic directions (left, right, straight and behind) were tested with the same participants at the end of the study on the communicability of the patterns. After they had navigated to a predetermined destination, they were brought back to the indoor test area. They were shown a point-of-view video of navigating an indoor space. This video was of a path that had multiple turns through a corridor. Their arms were placed in one of the four positions shown above. As the video played, directions were communicated through the tactile interface. The participants were expected to say out loud, as soon as possible, the direction communicated by the pattern.

Images from the evaluation

Results: It was seen that when the arm was relaxed to the side (Image 1), stretched outward to the side (Image 2) and folded to the front (Image 3), there was no effect on the perceived direction. However, when the arm was stretched behind the body (Image 4), participants had some trouble between identifying straight and behind. Likewise, when the arm was folded close to the shoulder and the posterior side was facing outwards (Image 5), there was confusion between left and right. While the participants did not always make a mistake in these two scenarios, they were processing the pattern and consciously flipping the direction as they knew their arm's position. However, this may not be the case when a pedestrian navigates, which calls for inertial measurement unit (IMU) sensors in forearm arm-based tactile navigation interfaces that can detect the position of the arm before the direction is communicated.

Reflection

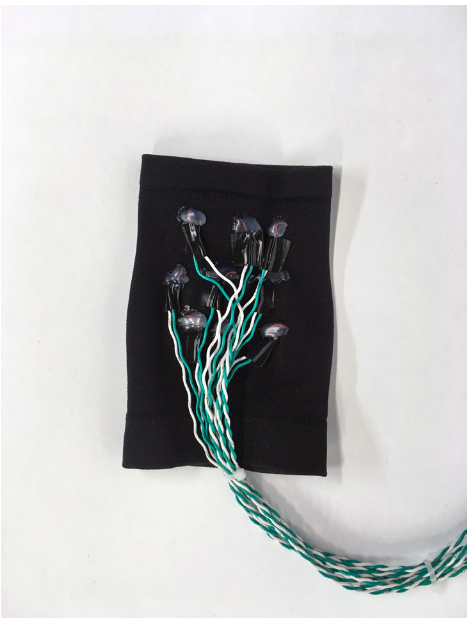
The participants for the study were all students at Carnegie Mellon. These are people who embrace technology and open to new ways of doing things. This makes the participant pool not necessarily a representation of people who might want to use such a device to navigate our built environment. Furthermore, most people are generally wary of such new methods, especially when there are successful and established pre-existing methods (services like Google maps in this case). The number of participants who tested the design was a small number (5). While this was good enough as the findings started to overlap by the fourth participant, the language will have to be tested with many more people to judge its capabilities completely. Also, the language was tested in only one route during the study. While an attempt was made to include as many different kinds of turns as possible, testing the design in new routes might lead to new findings.

Sketching in Hardware, Part 2

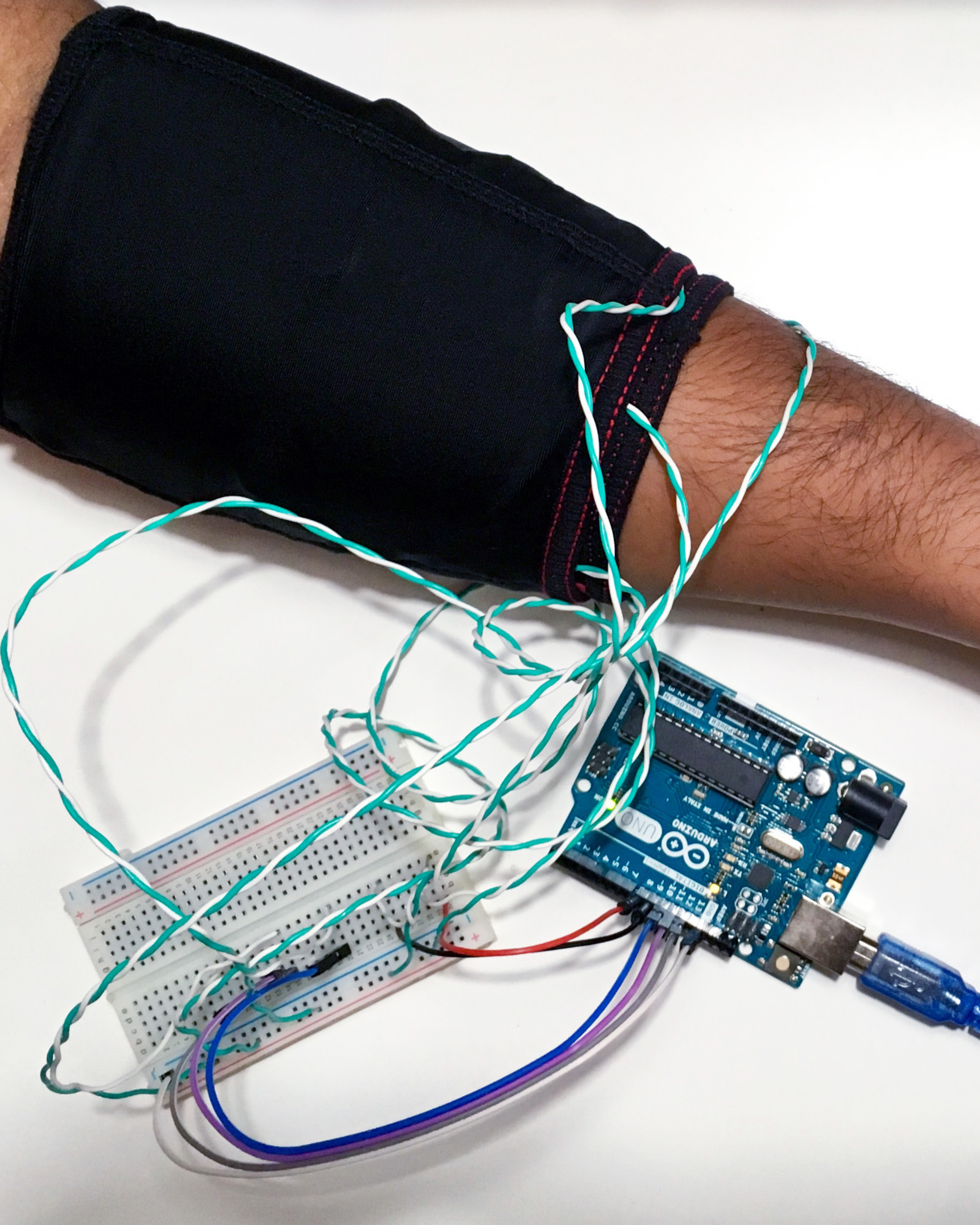
3 X 3

The study results led to the prototype of a 3 X 3 grid of vibrotactile motors. The rectangle grid in the previous prototype led to inconsistency in the duration of the different related patterns (left and right felt shorter than straight and behind). A square grid was used to overcome the inconsistency. The motors are glued on the underside of an elastic arm band. The motors are in direct contact with the skin, while the arm sits tightly on the forearm. The electronics is placed inside a bag that is worn while walking. A laptop communicated wirelessly with the prototype, to initiate patterns, using a bluetooth module.

3 X 3 prototype



Prototype on the arm


ARDUINO
UNO

tac.tic Design Language

Tac.tic is a design language for a tactile sleeve that navigates pedestrians through complex indoor-outdoor environments. It uses a 9-motor 3 X 3 square grid to communicate different navigational instructions on the forearm, in the form of a felt pattern.

The language can produce more than one hundred patterns, identifiable without experiencing a steep learning curve. Each pattern consists of three parts - Direction, Feature and Level change. Direction consists of the 8 basic cardinal directions which tells people which direction to walk in. These are left, right, straight, behind and the four diagonals. Eg: 'Go left' can be communicated using only the direction. Feature communicates the architectural element like stairs, escalator, ramp and elevator, and is always combined with the level change which communicates whether to go up or down. The direction, feature and the level change come together to communicate complex directions.

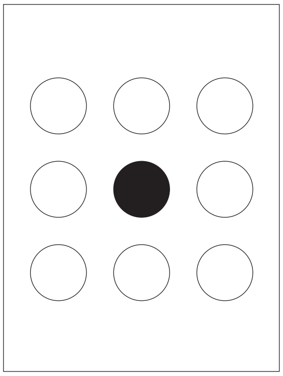
Direction	Left, Right, Straight, Behind, Diagonals
Feature	Stairs, Escalator, Ramp, Elevator
Level change	Up, Down

Direction (Left) = Go left

Direction (Left) + Feature (Stairs) + Level change (Up) = Go up the stairs, to the left

During the evaluation, it was observed that the first time people felt the pattern, it only took their attention. They identified it the second and third time they felt it. In this regard, most patterns (except on track, stop and destination reached) are preceded by a vibration. The motor at the center of the grid vibrates for 1 second, followed by the pattern. This proved helpful to take people's attention, and then communicate the direction.

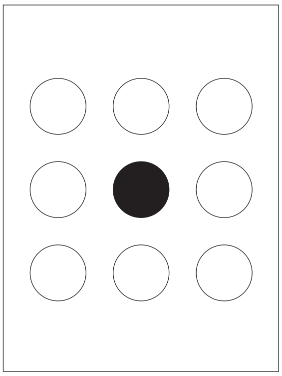
Get attention



1 second

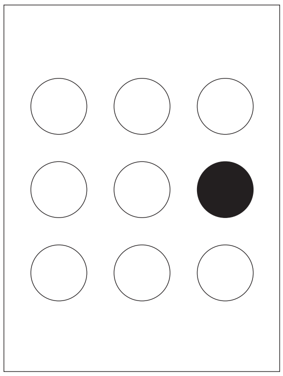
The vibration takes attention, and the direction follows. The basic directions (Left, Right, Straight, Behind & Diagonals) are communicated by drawing a line on the arm, in the respective direction.

Get attention, Left

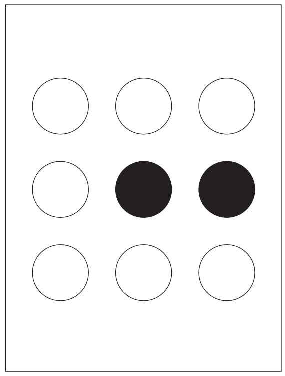


1 1 second

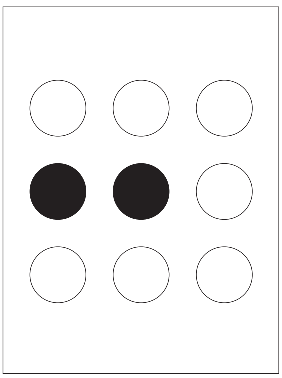
Delay: 200 ms



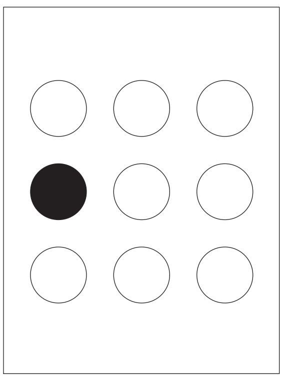
2 150 milliseconds



3 150 ms



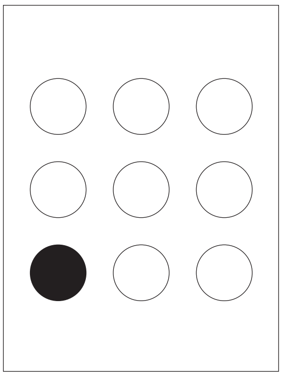
4 150ms



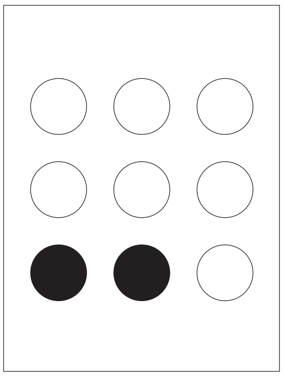
5 150ms

The pattern for diagonals was not identifiable during the prototyping and evaluation sessions. The new pattern takes advantage of the sensory funneling illusion which helps create a virtual vibration at a particular location even though no vibrotactile motors are present in that location. This helps the pattern draw a curved line towards the diagonal direction. This iteration of the pattern can be distinguished better from the patterns for 'left' and 'right'.

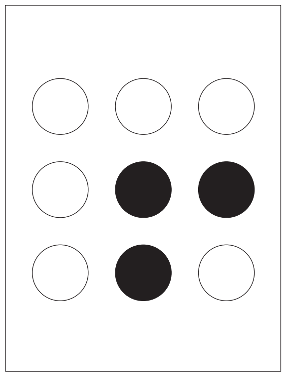
Diagonal, towards the right



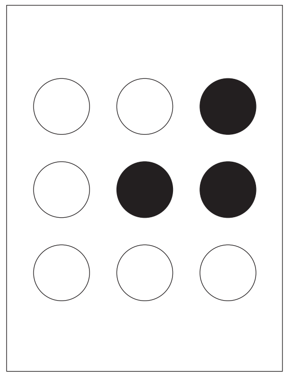
1 150 milliseconds



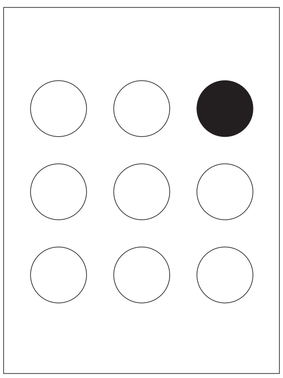
2 150 ms



3 150 ms



4 150ms



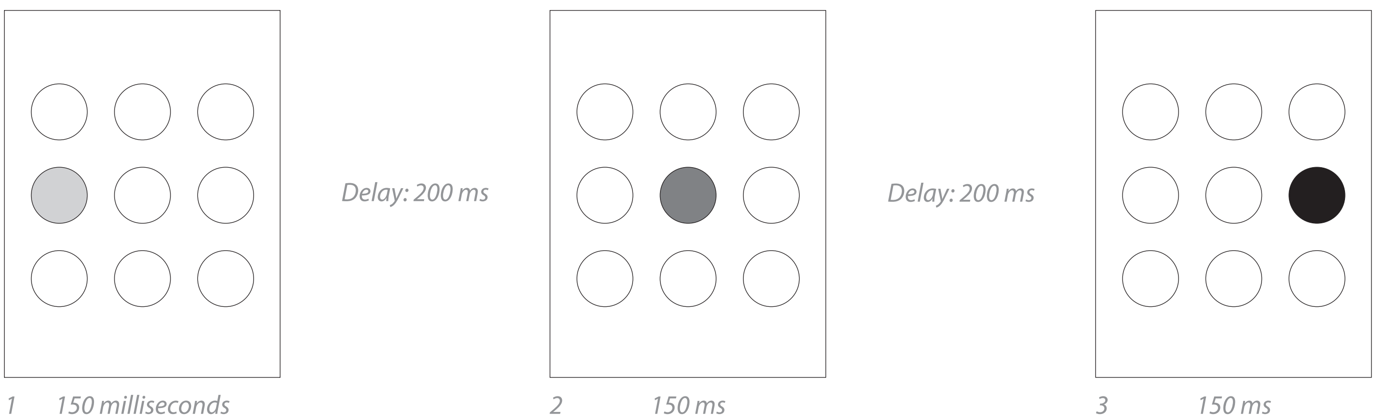
5 150ms

The language communicates more complex directions through the sequential expression of the direction, feature, and level change. While the basic directions are communicated by drawing a continuous tactile line on the arm, the feature and level change are communicated by varying the timing in between vibrations, direction of movement, duration, and intensity of vibrations. Going up is communicated by increasing intensity and duration of successive vibrations in the respective direction, while going down is communicated by decreasing intensity and duration of successive vibrations. This is explained further using multiple examples.

> *Factors manipulated: Direction of movement, time in between vibrations, duration of vibrations and intensity of vibrations.*

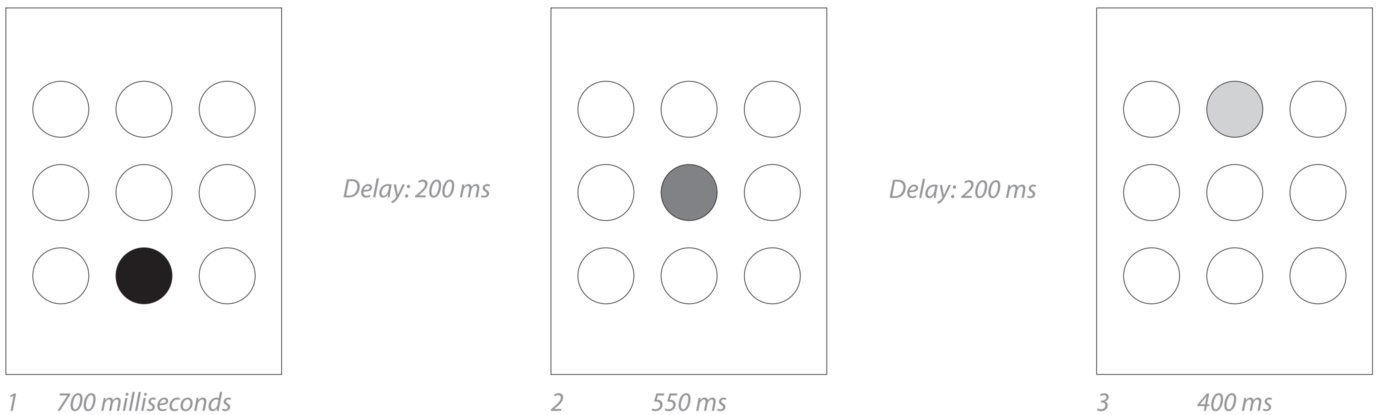
‘Up the stairs, to the right’ is composed of Right (pattern moves from left to right) + Stairs (successive vibrations are not continuous, they are activated one by one) + Up (the duration and intensity of each vibration increases).

Up the stairs, to the right



‘Down the stairs, straight’ is composed of Straight (pattern moves from bottom to top) + Stairs (successive vibrations are not continuous, they are activated one by one) + Down (the duration and intensity of each vibration decreases).

Down the stairs, straight



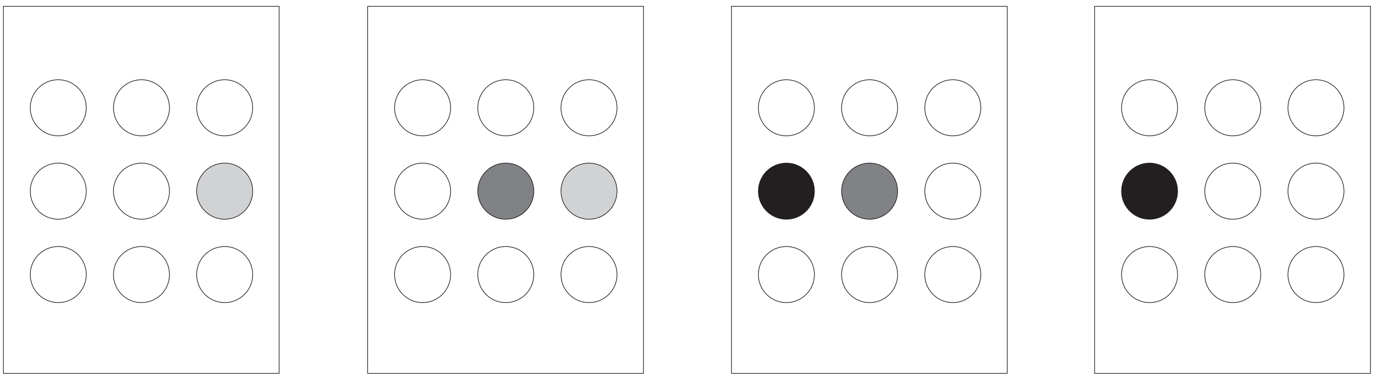
Escalators follow a similar pattern to stairs, but the duration in between vibrations and duration of each vibration is shorter. As a result, ‘Go up the escalator, to the right’ is a faster ‘Go up the stairs, to the right’. The patterns are distinguishable once the user has felt them a few times.

Ramps form a different pattern on the skin. It is a combination of an individual long vibration that defines the level change and a line drawn in the respective direction. If the individual long vibration precedes the line drawn, it denotes going down. If the individual long vibration follows the line drawn, it denotes going up. The rule stays consistent across patterns - higher intensity and duration of vibration indicates a higher ground and lower intensity and duration of vibration indicates a lower ground.

> *Going up: Increasing intensity and duration of vibrations.*
> *Going down: Decreasing intensity and duration of vibrations.*

'Up the ramp, to the left' is composed of Left (pattern moves from right to left) + Ramp (a combination of an individual longer vibration and a line drawn on the skin) + Up (the individual long vibration is felt at the end of the pattern).

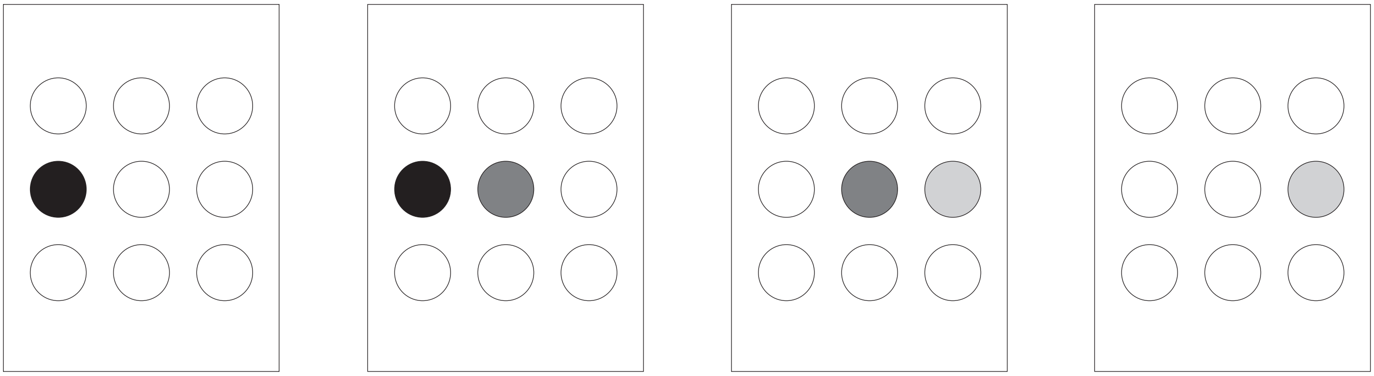
Up the ramp, to the left



1 100 milliseconds | *2 100 ms* | *3 100 ms* | *4 1 second*

'Down the ramp, to the right' is composed of Right (pattern moves from left to right) + Ramp (a combination of an individual longer vibration and a line drawn on the skin) + Down (the individual long vibration is felt at the beginning of the pattern).

Down the ramp, to the right

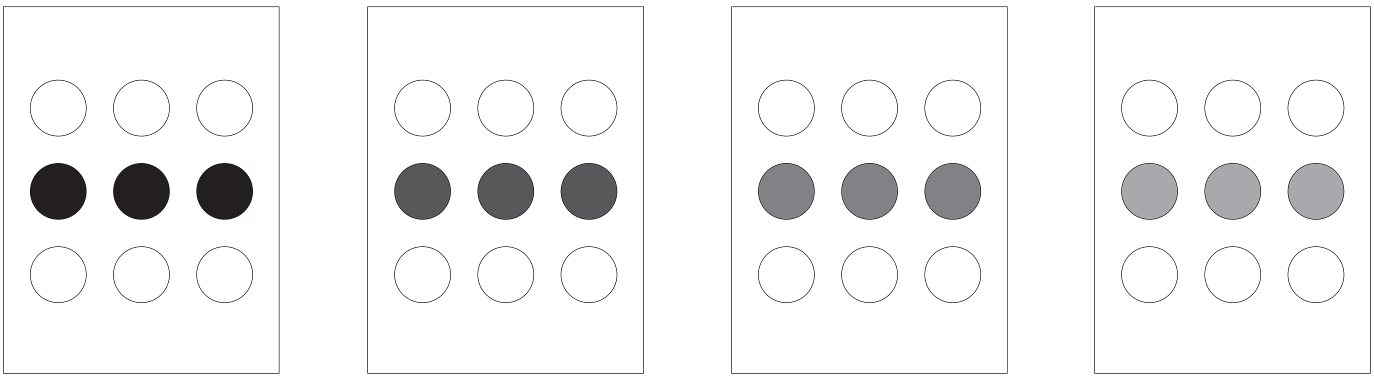


1 1 second *2 100 ms* *3 100 ms* *4 100 ms*

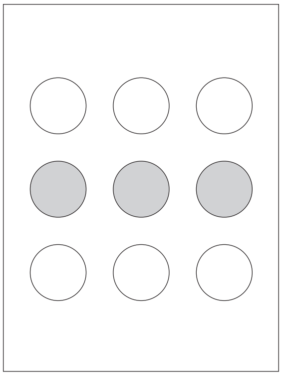
Elevators are communicated by increasing and decreasing intensity of vibrations, as well as the movement of the pattern along the arm. Elevators are the only patterns where each pattern in the sequence (directions are a series of 3 patterns as discussed previously) moves along the arm.

'Up the elevator' is communicated by gradually increasing the intensity of vibrations as well as the pattern moves up along the arm. 'Down the elevator' is communicated by gradually decreasing the intensity of vibrations as well as the pattern moves down along the arm. The current iteration does not communicate the destination floor.

Down the elevator



1 300 milliseconds *2 300 ms* *3 300 ms* *4 300 ms*



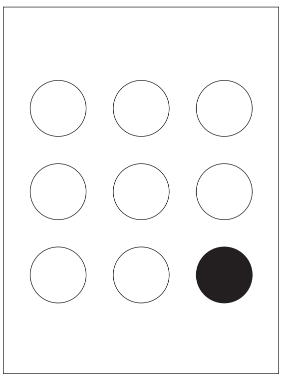
5 300 ms

As mentioned in the study results, in most cases, it is not necessary to communicate whether the one should go up the stairs, escalator, ramp or elevator as long as the communication for going up is clear. However, the individual patterns were still maintained as part of the language so it can be used in scenarios that need the clarity. It also shows how people are able to identify tens of patterns and distinguish between them over a short time.

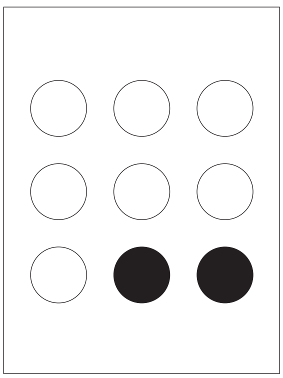
The evaluation revealed a critical need communicate the next two directions at the same time in certain scenarios, such as when there is not enough time to communicate the second pattern after the user has taken the first turn. To address this, I developed patterns that could communicate two turns at once. There is a pause in between the two turns to indicate that they are two distinct actions for the user to take.

'Left, then right' is a combination of the pattern for 'left' and the pattern for 'right'.

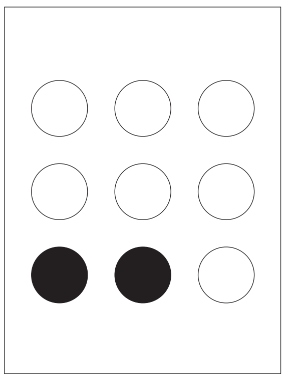
Left, then right



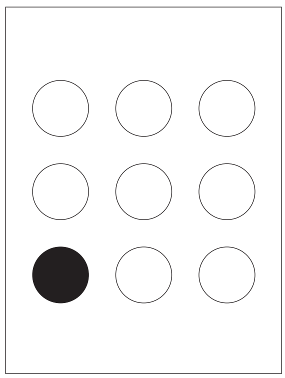
1 150 milliseconds



2 150 ms

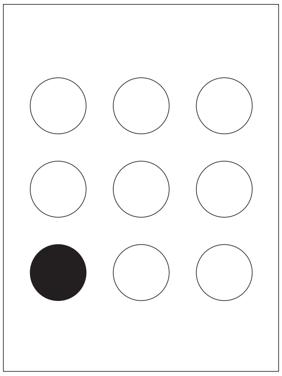


3 150 ms

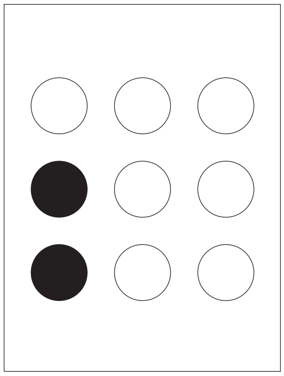


4 150 ms

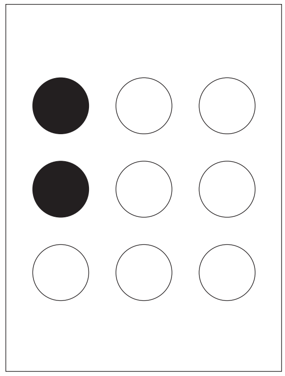
Delay: 300 ms



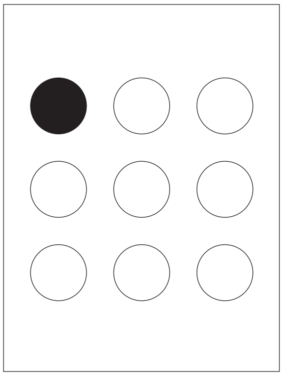
5 150 ms



6 150 ms



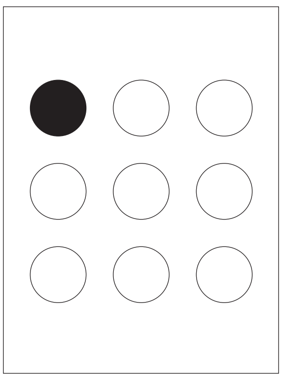
7 150 ms



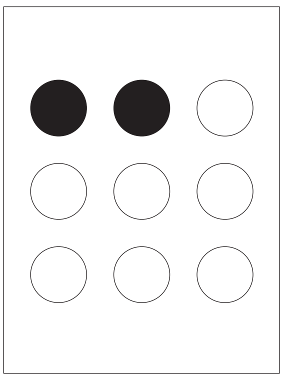
8 150 ms

‘Right, then up the stairs to the right’ is a combination of the pattern for ’right’ and the pattern for ‘Up the stairs to the right’.

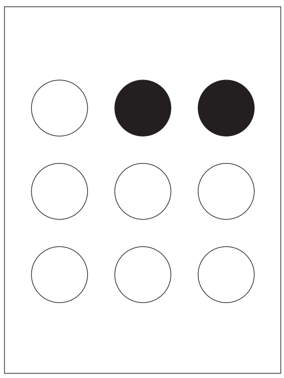
Right, then up the stairs to the right



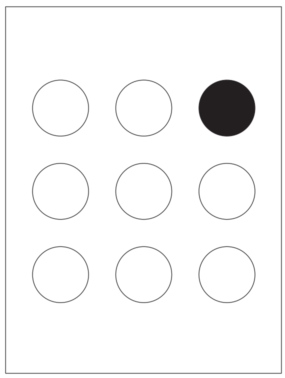
1 150 milliseconds



2 150 ms

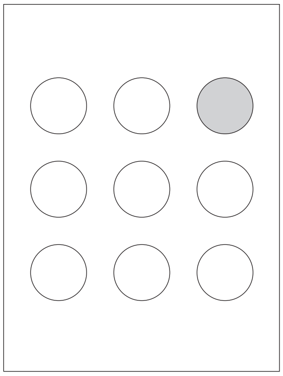


3 150 ms



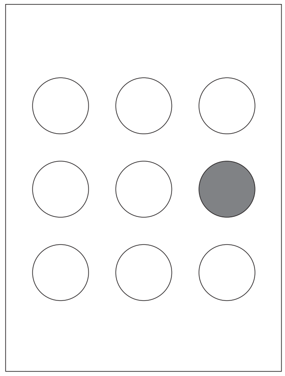
4 150 ms

Delay: 300 ms



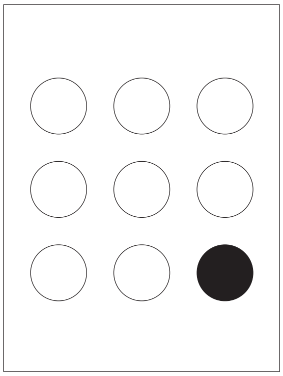
5 400ms

Delay: 200 ms



6 550 ms

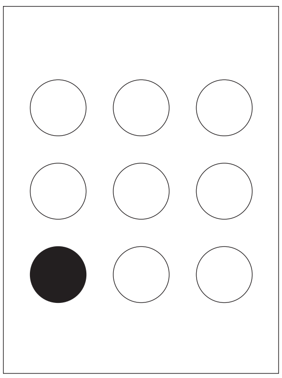
Delay: 200 ms



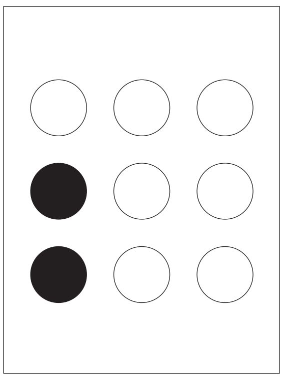
7 700 ms

A pattern for 'U-turn' was designed for scenarios that involved turning 180 around and walking in the direction behind the user. This is a combination of straight, left or right depending on the side of the turn, and behind. There is no pause in between the patterns to indicate that it is a single direction, and not three different directions.

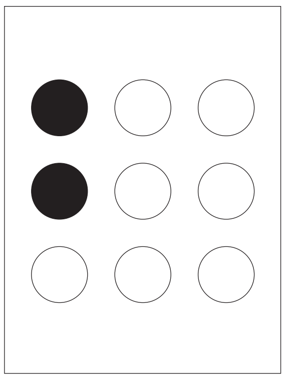
U-turn



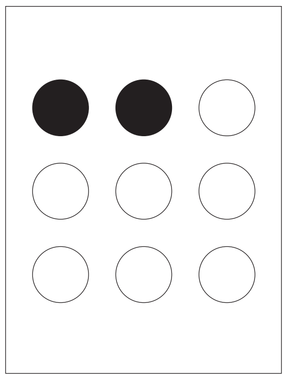
1 150 milliseconds



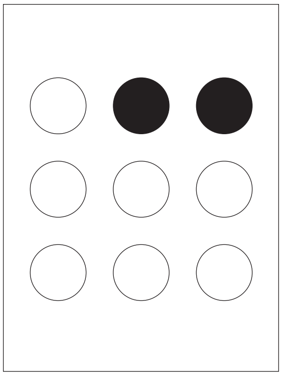
2 150 ms



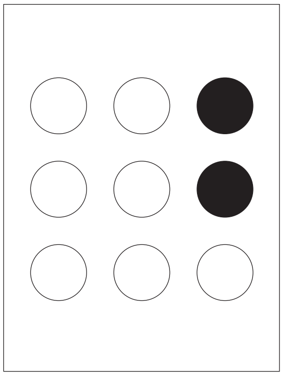
3 150 ms



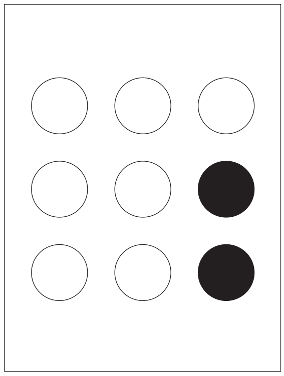
4 150 ms



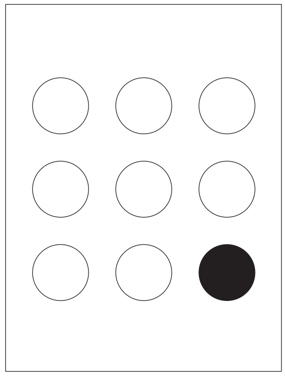
5 150 milliseconds



6 150 ms



7 150 ms

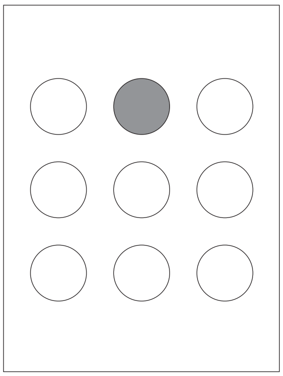


8 150 ms

Apart from these, three patterns designed that are important in the context of navigation were 'On track', 'Stop' and 'Destination reached'.

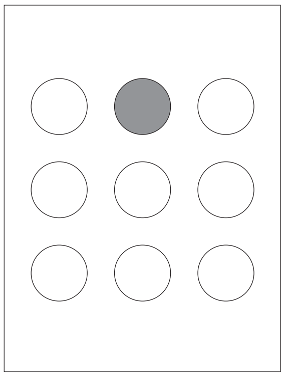
'On track' is composed of successive vibrations of low intensity, of a single motor, to indicate to the user that they are on the right path. This proved to be a hugely liked pattern during the study. This will be communicated every 25 meters when the user is expected to walk over 50 meters on the same path. Also, this is used when there is only one path ahead. In the case where there are multiple path possibilities, 'straight' is used to indicate moving forward.

On track



1 200 milliseconds

Delay: 200 ms

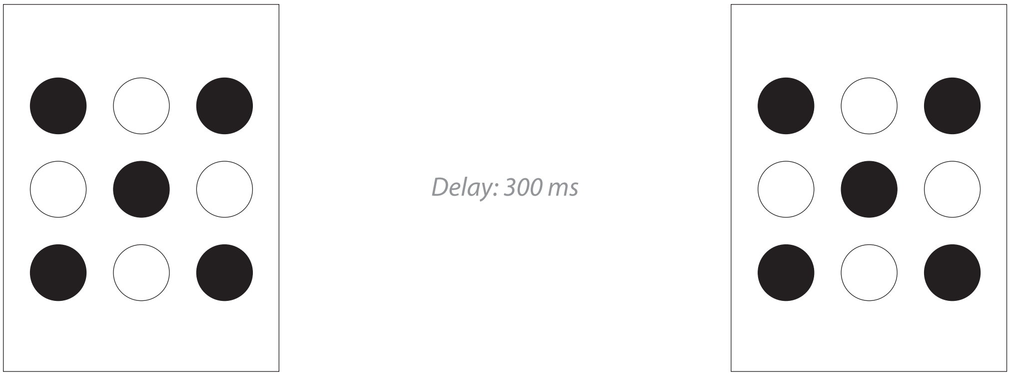


2 200 ms

'Stop' is composed of 5 simultaneous vibrations of highest intensity for a longer duration.

This tells the user to stop. The most common use case for this pattern is when the user goes in the wrong path.

Stop

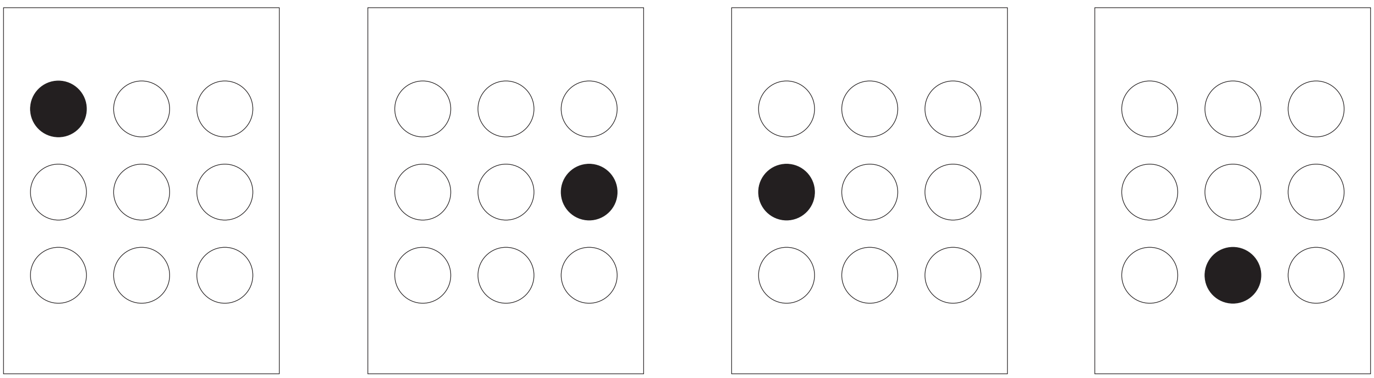


1 2.5 seconds

2 2.5 seconds

'Destination reached', another favorite of the study participants attempts to replicate a 'happy dance' using vibrations. Each of the 9 motors vibrate one after the other in a random order.

Destination reached

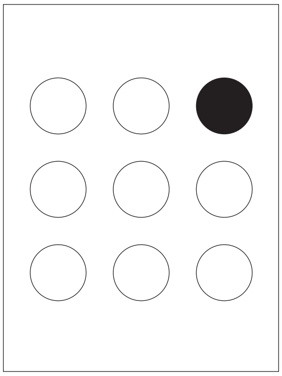


1 150 milliseconds

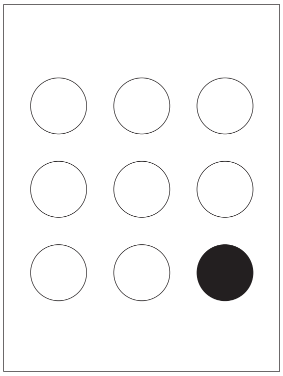
2 150 ms

3 150 ms

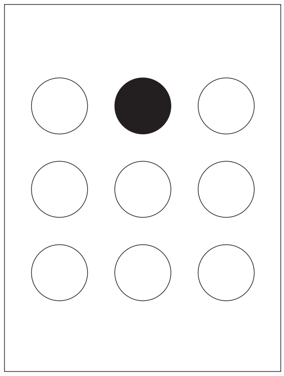
4 150 ms



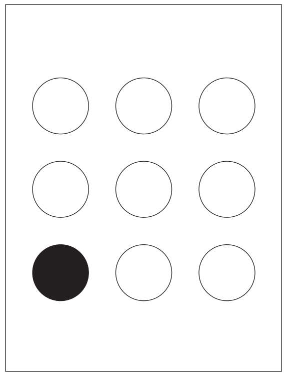
5 150 milliseconds



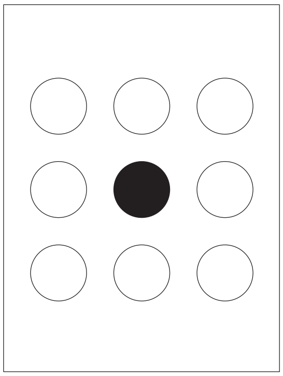
6 150 ms



7 150 ms



8 150 ms



9 150 ms

Reflection

Indoor navigation is dependent on improvement in the field of localization. While a lot of work is currently being done towards improving the accuracy, the design will not work successfully at the current state of the technology. The design itself was heavily based on the hardware that I could build with my amateur experience with electronics. The inclusion of an expert to the project may take it a in different direction. Learning to distinguish between and identify the patterns involves a learning curve, albeit not very steep. While the interface does not demand the user's visual attention, it still requires their cognitive attention in identifying the pattern and mapping it to the environment. Also, the language was designed for the built environment, and will not work in organic environments (Eg: While hiking in the mountains) in its current state.

Conclusion & Future Work

This paper investigated tactile navigation for pedestrians, both indoor and outdoor. A prototyping-first approach was employed because of the difficulty in conducting research in the tactile space without actually feeling what is being discussed. The process involved making multiple iterations of the physical prototype as well the tactile patterns that make the language. When the design seemed to work, the design was tested with participants. The study comprised of an extensive protocol to find as many broken points in the system. Based on this work, tac.tic, a tactile design language for indoor-outdoor pedestrian navigation was presented. While this language can communicate simple directions, its novelty lies in its ability to navigate a pedestrian through complex environments.

Future work could start with addressing its limitations; testing with a larger audience, in multiple paths and exploring the possibilities of using a higher number of motors, or even exploring a tactile sleeve for each hand. In the past, tactile interfaces for navigation have largely been explored for the visually impaired. tac.tic in its current state does not consider this population, but, further work in that direction could lead to an inclusive design. While navigation a pedestrian through complex environments was this projects scoped goal, the larger idea is to surface the potential of tactile interfaces, display people's ability to identify tactile patterns, and introduce designers to an unfamiliar interaction medium. The learnings from this project can be used to design tactile languages for areas other than navigation. Imagine you reach the airport and you are guided to the respective airline's counter using vibrations, as the tactile wearable knows your flight details. You check in, recieve your boarding pass which is accessed by the wearable to navigate you to your gate. While waiting at the gate, you are notified that your flight is delayed, again through tactile communication. You call your friend at the destination to notify them of your delay, and then the device navigates you to the nearest coffee shop. As you are having coffee, vibrations notify you that Bitcoin has jumped up by more than 10% in the last hour. You take out your laptop to make some transactions. Once you are done, you are taken back to your gate. People are more likely to adopt such designs if it can support multiple functions. The medium can be seen as a platform for silent, non audiovisual attention taking communication; a ***physical manifestation of digital information.***

Photo by Glen Noble on Unsplash

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