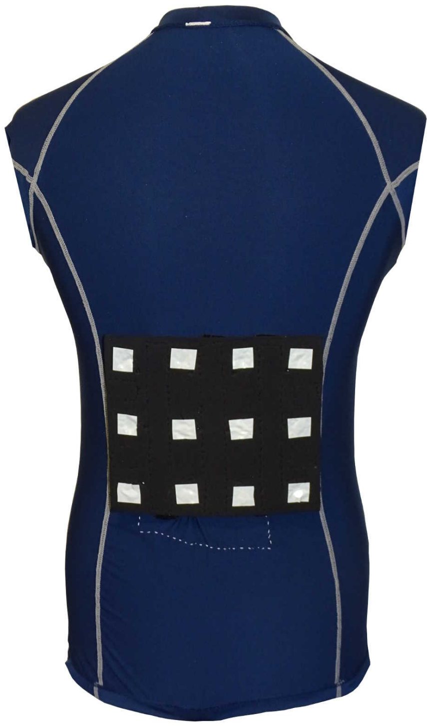
Imperial College London

Department of Electrical and Electronic Engineering

Final Year Project Report 2017



Project Title:	**The Sixth Sense - Electronically Augmented Perception**
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Abstract

The human brain processes vast amounts of information about the world around us using signals from our biological senses; sight, hearing, smell, taste and touch. The development of small, low power electronic sensors gives rise to the possibility of extending a person's perception of the world around them to include additional information. Not only does this provide the opportunity to replace or extend our current senses but also to create completely new senses.

This report proposes, designs and evaluates an item of wearable technology that communicates a sense of direction, via the channel of touch. Following an investigation into the use of vibrotactile communication to give directions, a working prototype embedded with vibratory motors was constructed. The device assisted volunteers with navigation tasks, achieving a 98% accuracy rate.

Acknowledgements

I would like to thank my supervisors, Prof. R. Spence and Dr. M. Witkowski, whose guidance and suggestions have been invaluable, as well as their assistance with the preparations for Imperial Festival.

I would also like to thank all the volunteers who acted as test subjects for the experiments. In particular I would like to thank David Salmon and Rosalind Booth who acted as models for some of the images in this report.

Contents

1. Introduction

Our brain is constantly overloaded with information about our surroundings: receiving and interpreting signals from our natural senses, it is able to form a picture of the world around us. However, our perception of the world is limited to the types of information we can receive from our senses. In order to extend our perception we need a sixth sense to capture new information.

With the development of technology, we have attempted to increase the amount of information we can access. Using the Internet and smart phones we have any information we need at our fingertips wherever we go. However, the majority of technology relies on displaying this information visually, to be captured by the sense of sight. This results in a problem; in order to retrieve information from these different sources we overload our sense of vision, making us less able to use our most dominant sense [1] for its basic purpose, awareness of what it happening around us.

A safety problem that we face today is the use of mobile phones affecting the awareness of activities in their environment. Recently a US study found that the number of pedestrians receiving emergency care in hospital due to the use of mobile phones has increased dramatically [2]. A particularly topical example of these occurrences is the recent emergence of the game Pokémon GO. The game led to a large rise in the number of accidents and injuries resulting from people concentrating on their mobile phones and not on what was going on around them. Many people were involved in road traffic accidents because they did not see oncoming traffic, or obtained injuries from walking into obstructions, tripping and falling or unintentionally walking into dangerous areas such as cliff tops [3].

Another common example of this problem is the use of GPS navigation mobile phone applications: pedestrians are often unfamiliar with the area and so focused on the map or directions their phone is displaying to them that they are unable to pay enough attention to the traffic. Not only pedestrians but cyclists, horse riders and drivers are often seen using their phone

(a) Pedestrian

(b) Cyclist

(c) Horse rider

Figure 1.1: Potential users

for directions in illegal or dangerous situations. In order to improve the safety of road users navigating unknown areas this paper proposes a wearable device to communicate this direction information via another channel, releasing the user's vision to detect dangerous situations such as traffic.

The idea presented in this paper is to use the sense of touch as a channel of communication with the brain, a sense which is not receiving large amounts of information nor playing a significant role in the detection of danger in this situation. The sense of touch can be exploited in 3 different ways: stretch, temperature and vibration. The detection of temperature by the skin has poor localisation and temporal acuity whereas objects that can apply stretch are not compact and so would not be suitable to be embedded in a wearable device. However methods for applying vibration are inexpensive, commonplace and small making them an ideal solution.

The prototype created is formed of a wearable device with embedded vibratory motors controlled by an application running on a smart phone. An important factor of the project is to make the wearable independent of the application allowing the possibility of the wearable being used to create multiple new senses. The application designed to give the user a new sense is a GPS navigational aid to relay directions to the user via patterns of vibration. Potential uses of the device include navigation for pedestrians, runners, cyclist, horse riders and drivers, making them safer by providing them with the directional information they need without distracting their sense of sight. Should the user need directions to travel to their destination, they simply put on the wearable device, enter the destination into the application on the phone, place their phone back in their pocket and proceed as they would for a known destination.

This project was undertaken in two parts, the first was an investigation into whether it is possible to communicate information with the brain through vibrations. This part of the project saw the creation of gloves embedded with vibratory motors, built for an experiment run at the Imperial Festival to discover how patterns of vibration could be used to convey a sense of direction. The second part of the project was to build a practical wearable device which could be used to give the wearer a sixth sense through the use of vibration patterns. This included the development of a smart phone application which, using the wearable device, provided the user with a sense of direction through GPS navigation.

The report structure is as follows: Chapter 2 describes existing work surrounding the replication and creation of senses using a variety of different methods and technologies. Chapter 3 outlines the aims and requirements of the project and the design decisions made in order to follow these requirements. Chapter 4 details the first part of the project, the investigation undertaken to discover how a new sense could be communicated using vibration, describing the design of the experiment undertaken at Imperial Festival, the creation of wearable devices and a smart phone application with which to conduct the experiment and the results obtained. Chapter 5 describes the second part of the project, detailing the creation of a new wearable device, more suitable for communicating a number of different senses, and the testing of the new sense of direction. Chapter 6 presents the conclusion of the project and details the future work.

2. Background

The brain is incredibly complex and is able to use signals from our biological sensors, such as our skin and eyes, to perceive the world around us. However, these senses are only capable of detecting a very small subset of all the information available in our surroundings, for example our eyes can only detect visible light which only makes up a tiny portion of the electromagnetic spectrum. Despite our natural sensors limiting the information we can sense, the brain has the capability to interpret streams of data that are unfamiliar, communicated via existing channels [4]. An example of this is the use of retinal implants to restore the sight of blind patients. The implant stimulates the retinal nerve cells with a signal imitating that which a healthy eye would send and, even though these signals is not identical to those which the brain would naturally receive from an eye, after a period of time the brain learns to interpret the signals and can restore vision to the patient [5].

The ideas behind replacing senses is not a new concept: in 1969 Bach-y-Rita and his team at the Pacific Medical Center in San Francisco ran an experiment to find if visually impaired people could have the sense of sight restored in an alternative way [6] . The subjects sat in a modified chair with a grid of solenoids controlled by the video feed from a camera. An object would be placed in front of the camera and the solenoids would form a tactile pattern which the subjects would feel through their lower back. After a number of training hours, the test subjects were able to distinguish an object from a selection of 25 common objects such as a chair or a cup. This idea from Bach-y-Rita was extended towards a smaller and more mobile solution using an electrotactile grid on the forehead which would form an image of the surrounding world which the wearer was able to interpret [7].

Instead of replacing sight with touch, there have been a number of investigations into replacing sight with sound: sonic glasses detect the depth perception in front of the wearer and produce sound to inform the wearer of objects within the field of view [8]. With training 90 percent of the test subjects found the glasses to be useful for their mobility [9] and this idea has even been extended to guide and help visually impaired people navigate around objects in their environment [10].

In the reverse situation, the visualisation of sound has also been used to provide people with impaired hearing another channel with which to detect sound in the world around them [11]. Using this idea the Invisibilia project [12] visualises sound using a virtual reality (VR) headset to display sound waves from a radio. The wearer can manipulate and interact with the sound waves using intuitive hand gestures. The idea behind the project was to allow someone to remotely demonstrate how to use equipment, to provide visual cues and demonstrations rather than simply attempting to describe to the user what to do. The prototype was tested in an experiment where subjects were asked to interact with a radio which could be operated by hand gestures or by manual control. The image of the sound wave output by the radio was superimposed on the camera image and displayed by the VR headset, the subject could then stretch and pinch the sound wave image to change the pitch and amplitude.

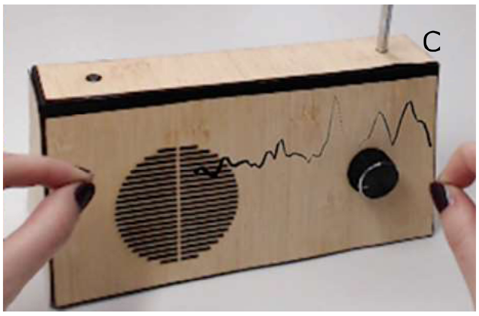


Figure 2.1: The image projected by the VR headset in the Invisibilia project [12]

More recently, with the development in electronics making sensors and actuators significantly smaller and more portable, projects to replace senses have become even more advanced, resulting in the possibility, not only to replace senses that have been lost of damaged, but to extend our natural senses. There have been a variety of projects investigating the extension of our senses, primarily focusing on the extension of vision as it is often identified as our most dominant sense [1]. SpiderVision [13] is a wearable device that extends the range of human vision to allow the wearer to see behind them without confusing the them or distracting from their normal view. Although vision is the most dominant sense, it only covers about a 200 degree sweep in front of the person. The prototype uses a virtual reality (VR) headset with front-mounted and back-mounted cameras. The headset displays the view from the front-facing camera, the image captured by the rear-facing camera is analysed for approaching objects and this activity is blended with the front-view image. There have been various different projects to attempt to extend the range of human sight. FlyVIZ uses a head mounted display to display the image from an omni-directional camera [14] meanwhile Virtual Chameleon uses two cameras which the wearer can control independently [15]. However both of these projects require the user to use significantly more effort to understand due to a large amount of extra visual information to process. The advantage of SpiderVision is that it does not distort the normal view of the user and only extends the field of vision when there is relevant information in the areas outside the normal field of view.

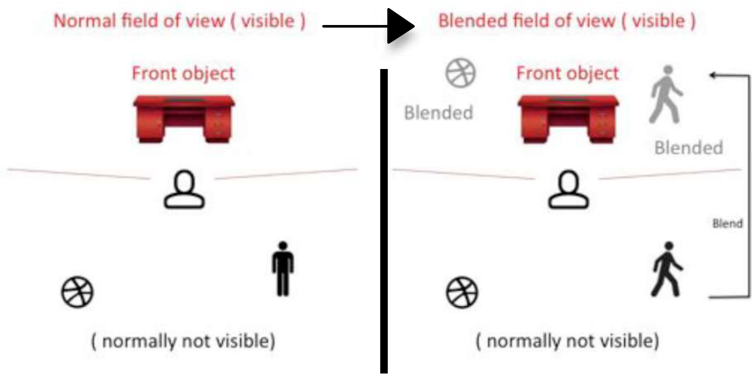


Figure 2.2: Spidervision sight extension diagram [13]

In a similar project undertaken by Mateevitsi et al. [16] the user would only see the front view but would be notified of objects outside the normal field of view approaching. The possible uses of the device included compensating for damaged or missing senses or to extend existing senses such as assisting the user in navigating while avoiding obstacles or communicating information from one sense which is overloaded via another, less occupied sense.

However the transfer of information from one sense to another poses difficulties as to how information from one sense can be converted into a form that another sense can detect. In their paper Novich and Eagleman [17] investigated the use of vibration as a potential way of communicating information with the brain. They aimed to use this idea to convert sound into vibrotactile messages to enable those with impaired hearing to identify different sounds [18]. Their hope was to find a non-invasive and low cost alternative to the cochlear implant [19].

The use of vibratory motors as a form of tactile communication has also been used in an attempt to provide geographical orientation information in a project by Nagel et Al [20]. The prototype used a ring of vibratory motors around the waist to give the wearer information from a magnetic compass, giving the wearer information regarding which direction they are facing with regards to magnetic north.

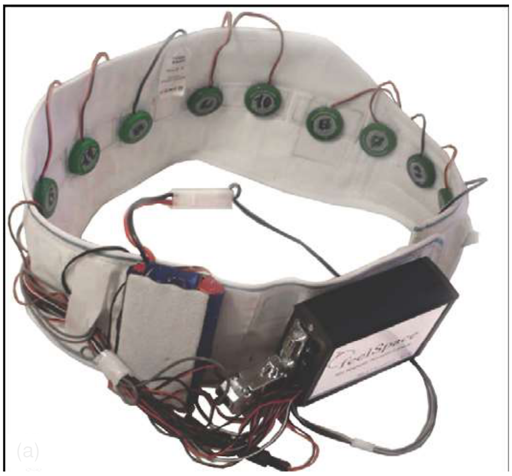


Figure 2.3: The orientation sense design by Nagel et Al [20]

The ability of the brain to interpret new signals provides the opportunity to extend our perception of the world around us through the use of additional sensors. This allows potential beyond extending existing senses to create entirely new senses, collecting information about our environment using electronics and communicating these new signals to our brain via our natural senses.

3. Concept

The purpose of the project was to create a system capable of conveying a new sense to the user using vibrations. In order to create a sixth sense, the project needs two distinct parts: a system able to collect the information for the new sense and a device to communicate this information to the user. The device is a piece of wearable technology that can relay a sense to the user. This device is most practical if it can be application independent so it may be used for other senses, rather than only for the sense created in this project. The device is controlled by an application on a smart phone which will accumulate the data from the sensor and analyse it to determine how the device should impart the information.

3.1 Device

The original description of the project conveyed the idea of extending human perception through the wearing of vibrating transducers. After testing a number of piezoelectric transducers and vibratory motors, it was decided that small vibratory motors, of the type found in cell phones, were the most suitable, being effective for vibrotactile communication as well as cheap, easily obtainable and relatively low power. The use of vibratory motors also allows the vibration amplitude to be altered, either by altering circuit resistance or by using pulse width modulation (PWM), which allows the vibrations to be optimised for the wearer of the device to be comfortable but still allow the wearer to detect the information. These motors could be arranged in an array to create spatiotemporal patterns in order to communicate the sense information.

All of the electronics will be attached to a garment to create a wearable device that can be easily put on and taken off, rather than directly to the skin which would require reapplication for every use. This will also avoid the use of adhesives or other methods of attaching electronics directly to the skin which could cause discomfort or injury including allergies or skin abrasions.

Figure 3.1: Vibratory Motor

Avoiding attaching the motors directly to the skin also makes this solution less invasive or obtrusive [21].

The vibratory motors will be directly in contact with the skin. The best areas of the body to use for skin interfaces are large areas of skin that are of a similar size across all adults and that experience little movement when the body is in motion [22], such as the back, the back of the hand or the neck.

Communication

Wearable technology allows us to use the skin as a technology-brain interface. As wearable technology becomes more mainstream, investigation into the sensitivity of our natural senses has become increasingly important.

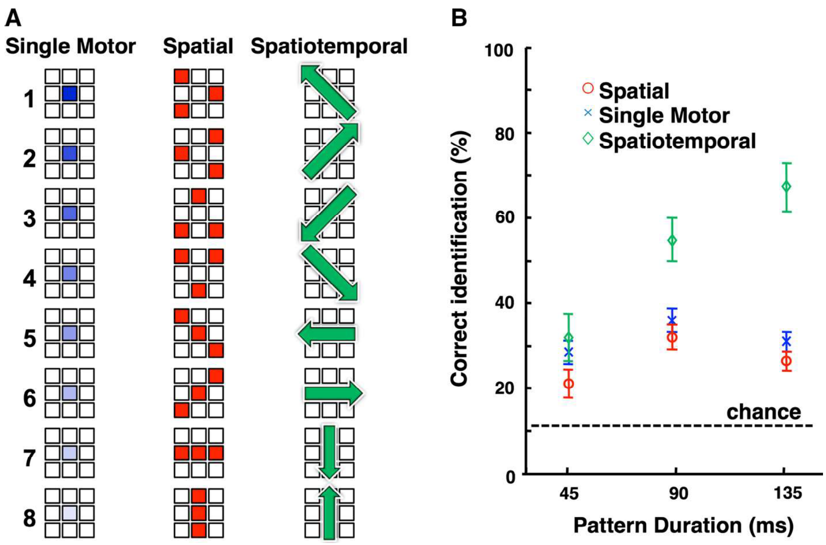


Figure 3.2: Correctness with which subjects identified spatiotemporal vibration patterns in Novich and Eagleman's experimentation into the suitability of the skin for sensory substitution [17]

In Novich and Eagleman's paper "Using space and time to encode vibrotactile information: toward an estimate of the skin's achievable throughput" [17] it was investigated how touch receptors can be used to communicate information to the wearer and whether they could be used for sensory substitution. The skin has already been investigated for communication of information, for example vibrotactile aids have been shown to be a suitable way of communicating speech or sound in adults with impaired hearing [23]. Novich and Eagleman's paper focused on testing how effective the skin of the lower back [24] is in relaying information and investigating how the use of temporally and spatially encoded vibration patterns can effect how easily the information is understood. The experiments found that the resolution of the lower back was low, needing vibration transducers to be placed at least 6cm apart.

The results of the experiments conducted by Novich and Eagleman [17] show that spatiotemporally encoded patterns were more successfully identified than vibration amplitude or spatial patterns (see figure 3.2) with spatiotemporal patterns being preferred (see figure 3.3). In showing that different vibration patterns can be identified, this indicates that if a single piece of information for a sense could be communicated by a single pattern, there is the potential to convey enough information to form another sense, given enough unique patterns. Therefore the wearer needs to be able to interpret the meaning of each vibration pattern, either through training or intuitive understanding. The experiment explained in Part I investigates whether patterns can be used to give intuitive directional instructions.

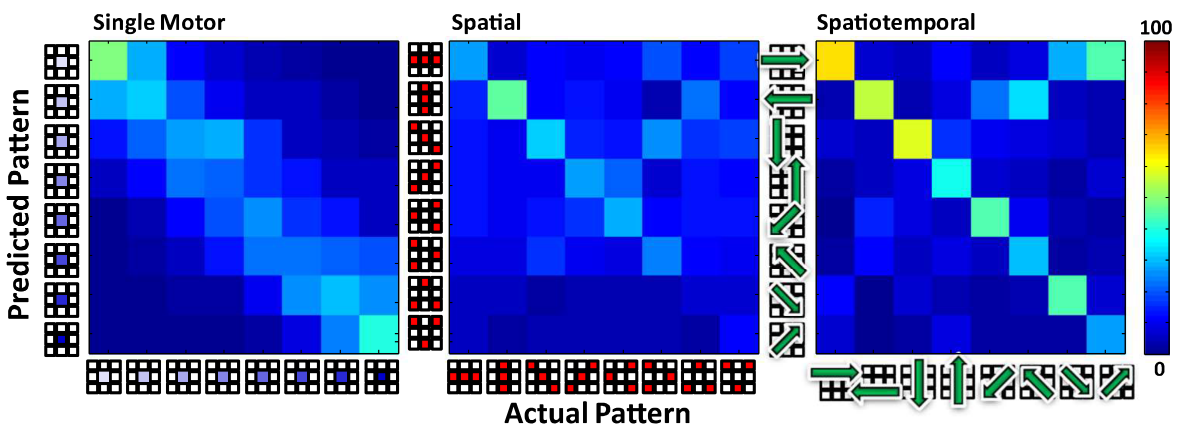


Figure 3.3: Confusion matrices for spatiotemportal vibration patterns from Novich and Eagleman's experimentation into the suitability of the skin for sensory substitution [17]

3.2 System

Electronic sensors can be used to collect a wide variety of information that could be communicated to the brain as a new sense. The important consideration to be made regarding a suitable new sense is how much information needs to be communicated with the user. The use of vibrotactile communication would not be suitable in the case of a sense where a large amount of information is required in a short space of time as it has a very limited bandwidth. Similarly a sense that has a large number of different pieces of information is also unsuitable as each would need to have its own unique vibration pattern. Following discussion on different ideas for suitable senses it was decided that an idea included in the original description of the project, a sense of direction through GPS navigation, would be the most suitable, only requiring different vibration patterns for each direction and GPS sensors being widely available. As GPS sensor are incorporated into most smart phones along with Bluetooth wireless technology [25], this makes an application running on a smart phone the most suitable way to control the wearable device.

The application was built on the Android platform due to its ease of use and the relatively low cost of smart phones running Android compared with other platforms. In order to implement Bluetooth Low Energy [26] the smart phone requires Android 4.3+.

System Overview

The vibrations patterns representing instructions are run on an array of motors embedded in the wearable device. The motors are controlled by a smart phone application via Bluetooth and each vibration pattern represents a different direction.

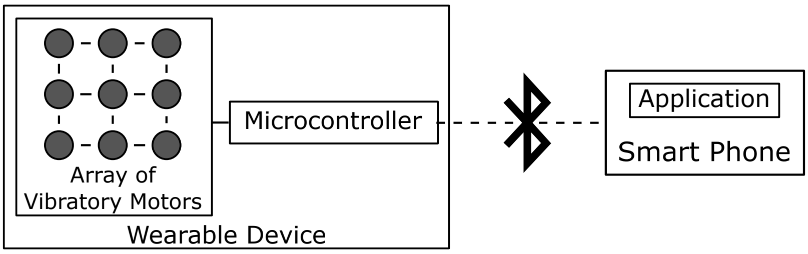


Figure 3.4: System Overview [27]

Collection of Information

Maps and GPS navigation are widely available as applications on smart phones, however they only communicate this information visually. Many of these applications have publically available Application Programming Interfaces, APIs, which can be used to request the navigation instructions for a route which can be converted into a suitable form for vibrotactile communication.

The GPS sensor on the smart phone can be accessed in the application and the data collected from the GPS sensor is used to determine the location of the user with respect to the navigational instruction.

Control

The application sends commands to the microcontroller, controlling an array of motors, via Bluetooth Low Energy. Bluetooth capability is built in to most smart phone and supported by more up-to-date smart phone operating systems, alleviating the need for any extra hardware. The commands sent represent different vibration patterns which could consist of numbers or names using the Universal Asynchronous Receiver and Transmitter (UART) interface.

4. Part I - Vibrotactile Communication

An experiment is required in order to investigate the use of spatiotemporally encoded vibration patterns as a method of communicating directions. The results were used to discover whether any vibration patterns have some intuitive directional meaning and will inform the decisions of which vibrational patterns are used in the device presented in Part II of this paper and whether any training is required prior to use.

4.1 Experiment Design

The aim of the experiment was to identify vibration patterns that can be use to give an intuitive directional instruction. The experiment undertaken investigated vibrational patterns for 8 different directions; up, down, left, right, diagonally up and right, diagonally up and left, diagonally down and right and diagonally down and left. In the work of Novich and Eagleman [17] it was found that sweeps of vibration, for example a sweep from left to right, was considerably more effective than simply vibrating a motor in a relative location, see figure 3.2. The eight directions can be split into 2 groups of orthogonal directions: cardinal (up, right, down, left) and ordinal (diagonal directions). For both direction groups, 4 different types of sweeps were identified that could be used to communicate directional information, Example pattern types are given below, for a full list of patterns see Appendix A. As well as investigating the understandability of different types of patterns, the period of time between changes in the vibrations, interlude time (T), throughout the pattern was alternated between 200ms and 400ms to investigate how the length of time over which the pattern ran affected the understanding of the pattern.

Cardinal direction pattern, upwards sweep example, T = 200ms:

- Pattern A

  1. Turn on the bottom row of motors
  2. After 200ms, turn on the middle row of motors
  3. After 200ms, turn on the top row of motors
  4. After 200ms, turn off the bottom row of motors
  5. After 200ms, turn off the middle row of motors
  6. After 200ms, turn off the top row of motors

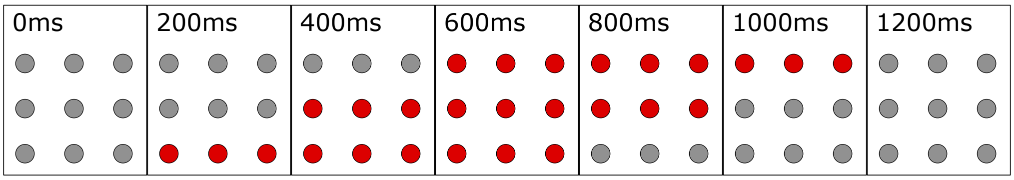


Figure 4.1: Pattern A

- Pattern B

  1. Turn on the bottom row of motors
  2. After 200ms, turn off the bottom row of motors and turn on the middle row of motors
  3. After 200ms, turn off the middle row of motors and turn on the top row of motors
  4. After 200ms, turn off the top row of motors

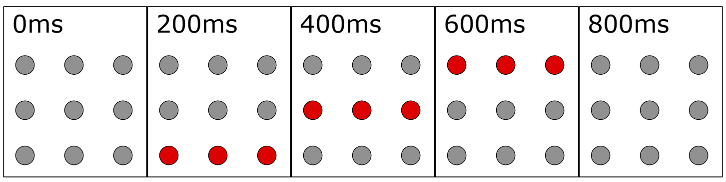


Figure 4.2: Pattern B

- Pattern C

  1. Turn on the central motor in the bottom row of motors
  2. After 200ms, turn on the central motor in the middle row of motors
  3. After 200ms, turn on the central motor in the top row of motors
  4. After 200ms, turn off the central motor in the bottom row of motors

5. After 200ms, turn off the central motor in the middle row of motors
6. After 200ms, turn off the central motor in the top row of motors

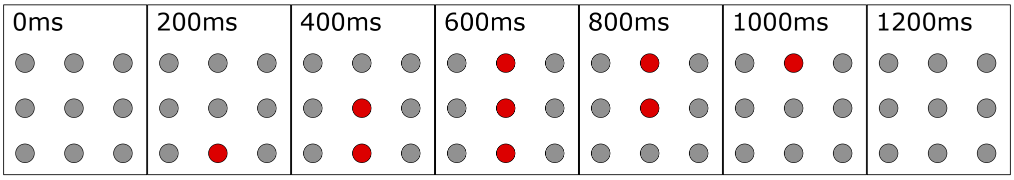


Figure 4.3: Pattern C

- Pattern D

1. Turn on the central motor in the bottom row of motors
2. After 200ms, turn off the central motor in the bottom row of motors and turn on the central motor in the middle row of motors
3. After 200ms, turn off the central motor in the middle row of motors and turn on the central motor in the top row of motors
4. After 200ms, turn off the central motor in the top row of motors

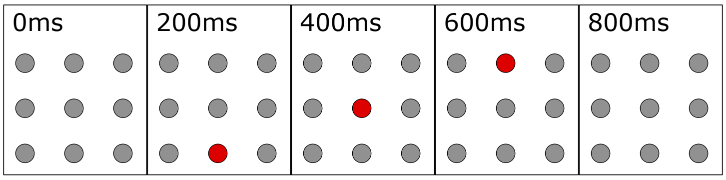


Figure 4.4: Pattern D

Ordinal direction patterns, diagonally upwards and right example, T = 200ms:

- Diagonal Pattern A

1. Turn on the bottom left motor
2. After 200ms, turn on the middle left and the bottom centre motors
3. After 200ms, turn on the top left, the middle centre and the bottom right motors
4. After 200ms, turn on the top centre and the middle right motors
5. After 200ms, turn on the top right motor
6. After 200ms, turn off the bottom left motor
7. After 200ms, turn off the middle left and the bottom centre motors
8. After 200ms, turn off the top left, the middle centre and the bottom right motors

9. After 200ms, turn off the top centre and the middle right motors
10. After 200ms, turn off the top right motor

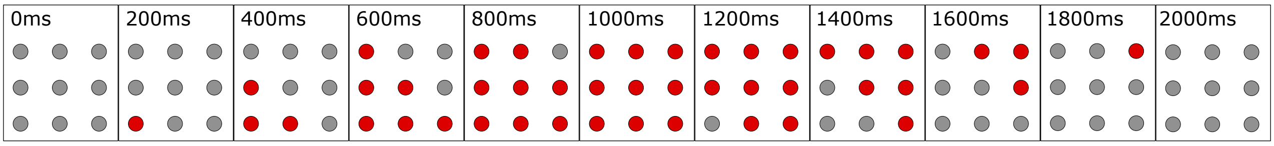


Figure 4.5: Pattern A

- Diagonal Pattern B

1. Turn on the bottom left motor
2. After 200ms, turn off the bottom left motor and turn on the middle left and the bottom centre motors
3. After 200ms, turn off the middle left and the bottom centre motors and turn on the top left, the middle centre and the bottom right motors
4. After 200ms, turn off the top left, the middle centre and the bottom right motors and turn on the top centre and the middle right motors
5. After 200ms, turn off the top centre and the middle right motors and turn on the top right motor
6. After 200ms, turn off the top right motor

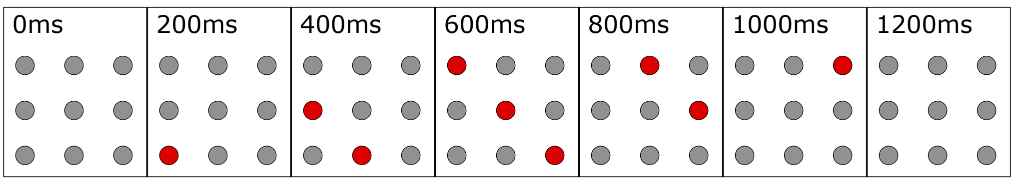


Figure 4.6: Pattern B

- Diagonal Pattern C

1. Turn on the bottom left motor
2. After 200ms, turn on the middle centre motor
3. After 200ms, turn on the top right motor
4. After 200ms, turn off the bottom left motor
5. After 200ms, turn off the middle centre motor
6. After 200ms, turn off the top right motor

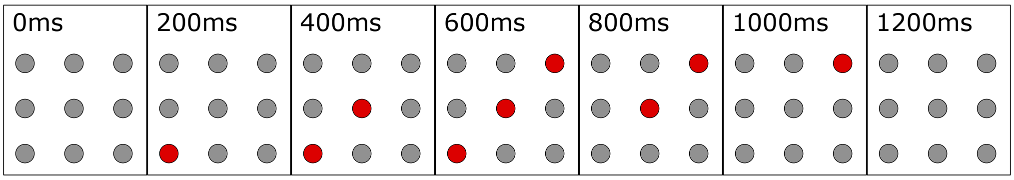


Figure 4.7: Pattern C

- Diagonal Pattern D

  1. Turn on the bottom left motor
  2. After 200ms, turn off the bottom left motor and turn on the middle centre motor
  3. After 200ms, turn off the middle centre motor and turn on the top right motor
  4. After 200ms, turn off the top right motor

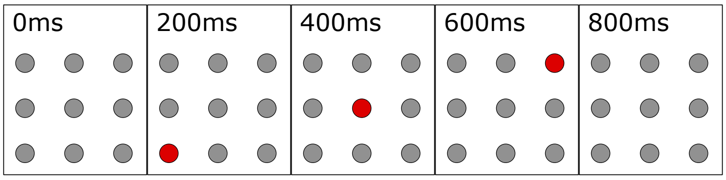


Figure 4.8: Pattern D

4.2 Device

The wearable device for this experiment needs to be easily attached and detached from the test subjects, as well as fit a variety of different people. In this case the back of the hand is the most suitable location as it is easy to access and reduces the complexity of the experiment by guiding the hand rather than the whole body, for this reason a glove was built.

The 3x3 array of vibratory motor and LED pairs embedded in the glove are controlled by a microcontroller which receives commands from the smart phone via Bluetooth. The controller used in the glove is an Arduino UNO which is capable of controlling all 9 motors using digital input/output pins, the enable pins to run the LEDs as well as a breakout board for the Bluetooth communication, in the case of the glove an Adafruit nRF8001 Bluefruit LE Breakout. The Bluefruit breakout board supports Bluetooth Low Energy communications which is more power-efficient than conventional Bluetooth, important in this case as the device will be running for prolonged periods of time. It simulates a UART device, sending ASCII encoded data which enables the different pattern commands to be represented by an alpha-numerical string.

The Arduino was to advertise it's presence as a UART device and wait for a request to connect. Once connected it listened to the serial port for incoming messages and on receipt it compared the message to a list representing the different vibration patterns. If the message matched a pattern representation the Arduino runs the vibration pattern on the array of motors. If the message commands enabling or disabling the LEDs the enable pin is set appropriately.

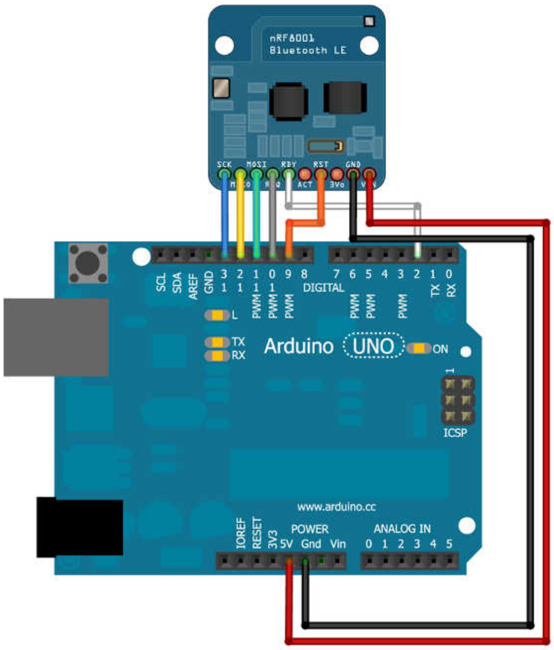


Figure 4.9: Arduino UNO connection to Adafruit nRF8001 Bluefruit LE Breakout[28]

The attachment of the Bluefruit breakout board requires 6 of the 14 digital output pins available on the Arduino UNO, additionally the Bluetooth communication uses the serial communication on the board making pins 0 and 1 (RX and TX) not usable. This leaves a remaining 6 digital I/O pins and therefore 3 of the Analog input pins, which can also be used for digital output, to be used in order to control all 9 motors.

Although the pin output current is enough to run a single motor, the board cannot drive multiple motors concurrently. Therefore the simplest solution was to use the Arduino pins to control MOSFETs which will drive the motors from a 5V USB power back or laptop USB port. The LEDs will be controlled by their respective motor pins as well as a pin used to enable and disable the LEDs, the command for the motor and the enable will be ANDed to give the input for the LED.

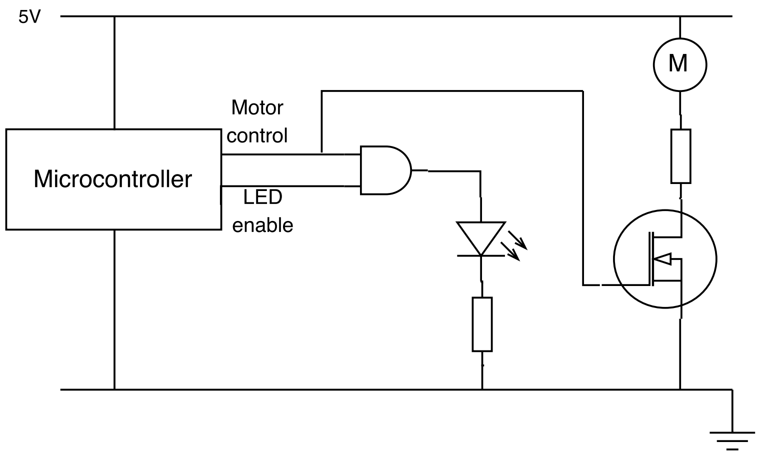
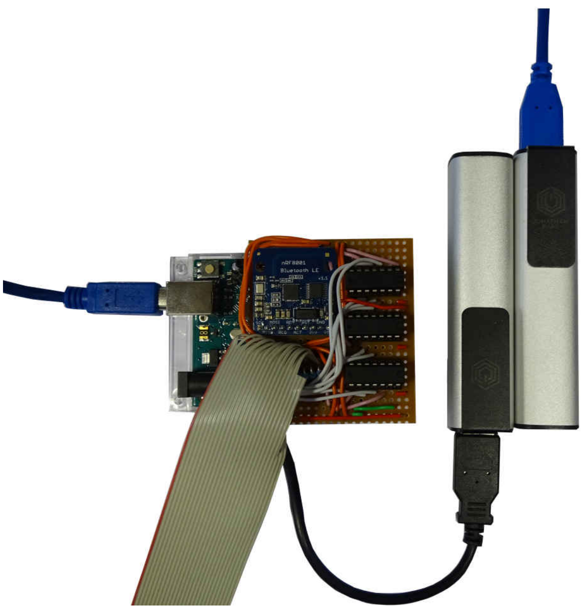


Figure 4.10: Circuit for control of 1 of the 9 glove motor and LED pairs



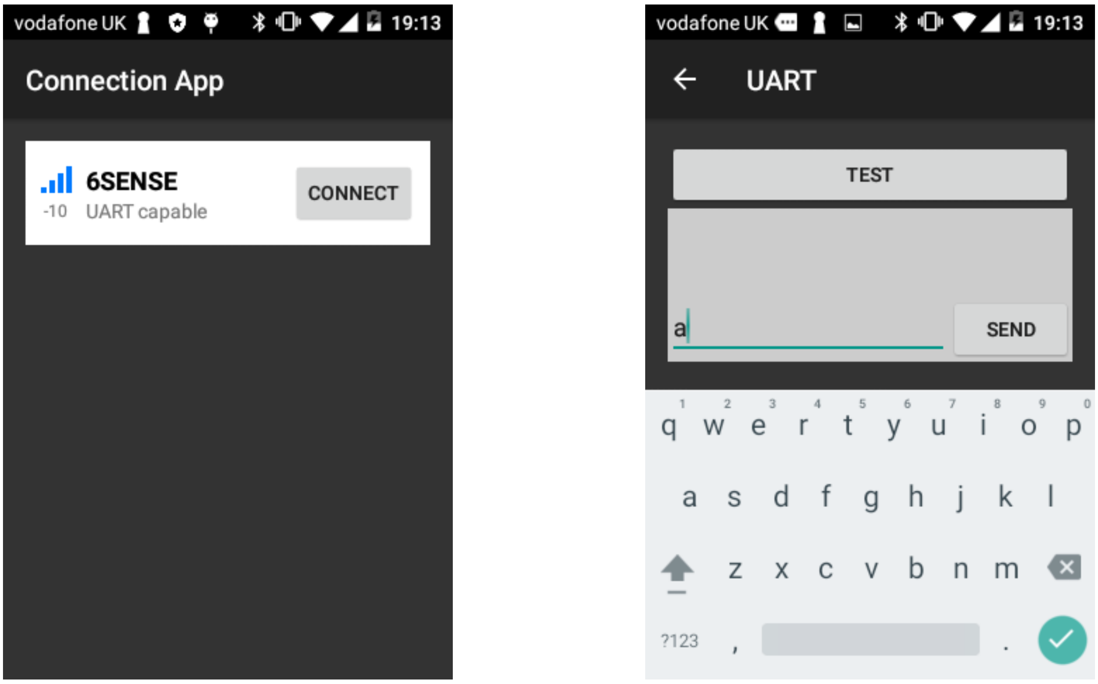
(a) Glove control - Arduino UNO, Bluetooth breakout board and LED logic

(b) Glove - 9 motor and LED pairs, MOSFETs

Figure 4.11: Glove used for the experiment at Imperial Festival

4.3 Application

The application was adapted from the Bluefruit LE Connect application [29] provided by Adafruit. This application has a number of features including the simulation of a UART interface. For the experiment application, the Adafruit example application was simplified to only contain the relevant UART functionality, allowing messages sent as ASCII strings which represented vibration patterns to be run or to enable and disable the LEDs. The application scans for Bluetooth devices and filters them by name and UART service availability and displays those devices to the user, who is then able to connect to one of them. On connecting, the user is taken to a further screen where they are able, via the smart phone keyboard, to input a string and then send it to the connected device.



(a) Start Screen: displays available devices (b) Message Screen: sends a string via Bluetooth

Figure 4.12: Application for the Festival Experiment

4.4 Method

For the Imperial Festival, two gloves were created, one large glove for older children and adults and one small glove for young children. Each volunteer was asked to wear the glove and then to place their hand in the centre of a ring of eight coloured targets, each representing one of the eight testable directions. Initially the LEDs were turned on and a vibration pattern was demonstrated, allowing the wearer to see the pattern as well as feel it, to help explain what a vibration pattern is. The LEDs were then disabled so that the participant could only feel the pattern, not see it. They were then given a number of vibration patterns and for each were asked to identify which direction they believed the pattern to be indicating by pointing to the relevant coloured circle, see figure 4.13.

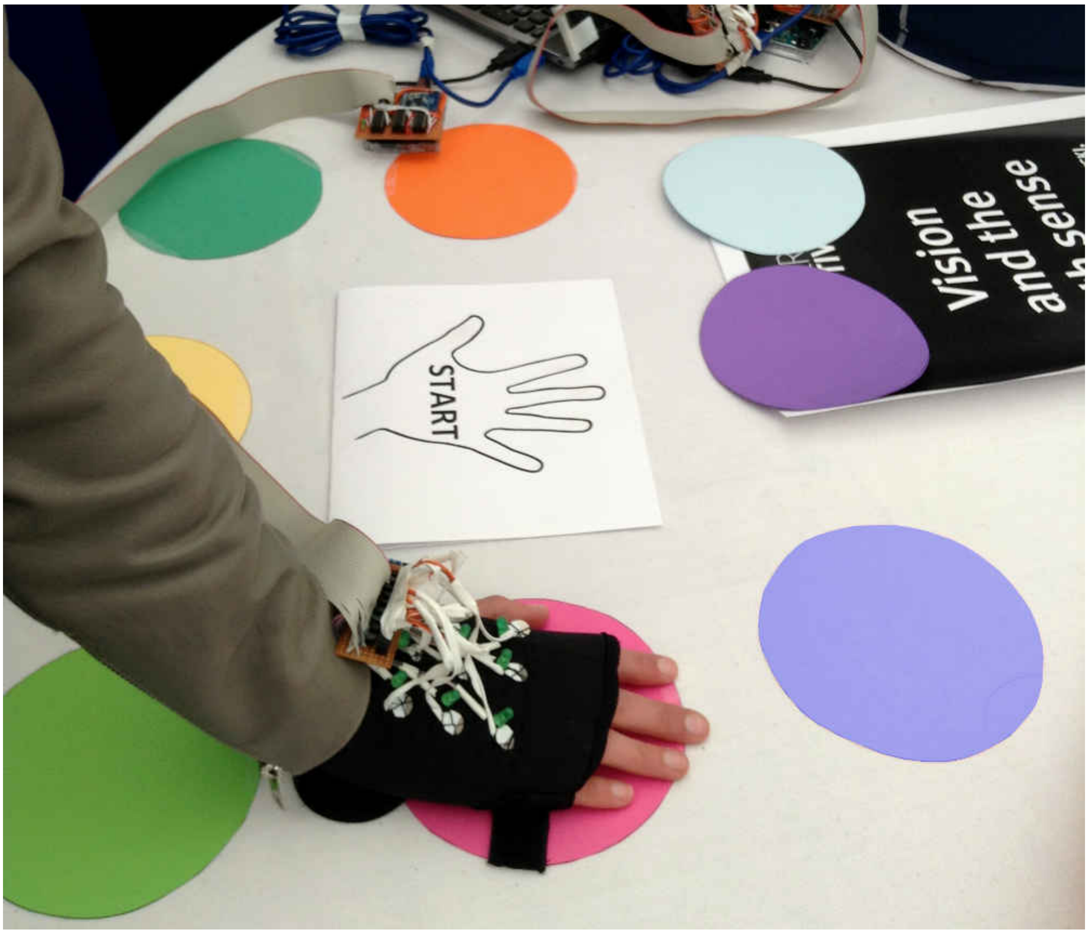


Figure 4.13: Experiment setup at Imperial Festival

4.5 Results

Over the course of the Festival, the experiment was conducted on 122 volunteers. 21 people wore the small glove and 101 people wore the large glove. The data collected was analysed in a confusion matrix, a form which made it easier to visualise how successfully the vibration patterns were identified as directions. A confusion matrix displays the direction of the test pattern down the left hand side and the answer given along the top. The number of answers correctly identifying the direction fall into the relevant cell along the diagonal of the matrix. A confusion matrix with a well defined diagonal shows that a high proportion of answers identified the pattern correctly and few answers were incorrect. Cells adjoining those of the diagonal contain the answers as the adjacent direction, for example the test pattern given was "up" but the wearer gave the answer "diagonally up and right". These cells indicate the number of answers that are close to being correct.

When using confusion matrices, the most common measure of the overall correctness is the classification rate. The classification rate is the proportion of correctly identified directions for the entire experiment, with a value of 0 indicating that none were answered correctly and a value of 1 indicating that all were answered correctly. The classification rate should be above the guess rate to show that directions are understood, the guess rate in this case is 0.125.

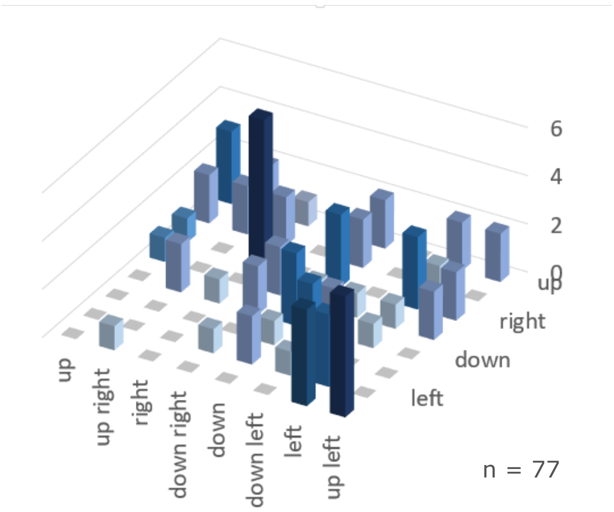
$$ClassificationRate = \frac{n_{(answer=correct)}}{n_{all}} \tag{4.1}$$

Another measure commonly used to identify the correctness for each input, i.e. the direction of the tested pattern, is the recall. The recall is the ratio of correct answers for a given input i.e. the proportion of answers given as "up" when the given pattern was "up". A high recall indicates that the pattern is often correctly recognised, i.e. a recall of 1 indicates that all examples were correctly identified.

$$Recall = \frac{n_{answer=up}}{n_{all}} \tag{4.2}$$

4.5.1 Small Glove

Those wearing the small glove were asked the identify and average of 4 patterns each. The overall results for the small glove are shown in figure 4.14. The figures should show a defined diagonal ridge, showing high proportions of correctly identified directions for the input pattern. The other values should be low, showing few incorrect answers. Figure 4.14a clearly displays a defined ridge along the diagonal and relatively low bars on either side of this ridge, showing reasonably high levels of accuracy. Likewise the confusion matrix, figure 4.14b, shows a diagonal line of higher values, shown in darker shades, and lower values either side of the diagonal, shown in paler shades. It can also be noted that close either side of the diagonal are some higher values, this indicates that those answers, although incorrect, are the neighbouring directions, for example "up" and "up right", and therefore are less extreme mistakes than those further from the diagonal. Note however that the top right and bottom left cells represent neighbouring direction to those in the bottom right and the top left respectively, i.e "up left" (bottom left cell) is an adjacent direction to "up" (top left cell).



(a)

	↑	↗	→	↘	↓	↙	←	↖
↑	3	2	1	1	0	0	0	0
↗	2	2	0	0	2	0	0	1
→	1	2	6	0	1	0	0	0
↘	0	0	0	2	2	0	1	0
↓	2	2	3	1	3	1	2	0
↙	0	0	0	1	2	3	1	0
←	2	1	3	1	1	0	3	4
↖	2	0	2	2	0	0	0	5

(b)

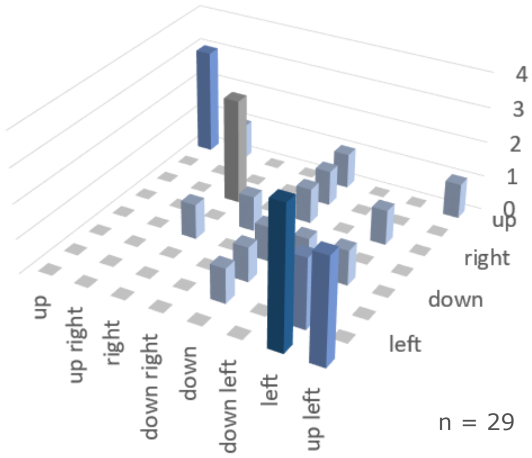
Figure 4.14: Confusion Matrix for the overall results of the small glove

The classification rate overall for the small glove is 0.35 which is significantly greater than the guess rate which would be 0.125.

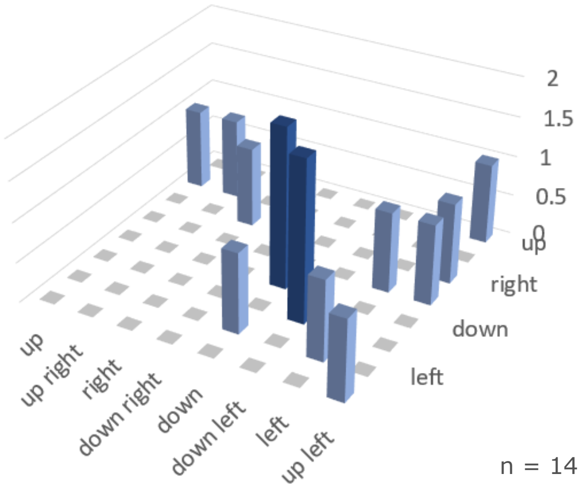
Of those who wore the small glove, 1 was left handed, 1 was ambidextrous and 19 were right handed. Those who were right handed or ambidextrous performed similarly and the subject who was left handed worse, however with only 1 subject it may not be representative. In order to come to a conclusion as to whether dominant hand affected how well the vibration patterns were understood, the results of the large glove must be taken into account.

Of the patterns tested with the small glove, 39 were conducted with the longer interlude time of 400ms and 39 with the short interlude time of 200ms. Results showed little difference between the different interlude times: when the interlude time was 400ms the classification rate was 0.33 and when the interlude time was 200ms the classification rate was 0.36.

For tests using the small glove, the 4 different types of pattern produced some interesting results. For both pattern A and pattern C the classification rates were only marginally above the guess rate (0.125) at 0.167 and 0.172 respectively. Patterns B and D yielded significantly better results with pattern B delivering a classification rate of 0.464 and pattern D achieving a classification rate of 0.571, a more that 57% success rate. The proportion of answers correct to within one direction, i.e. including the adjacent direction, gives classification rates of 0.724 for pattern B and 0.714 for pattern D. The confusion matrices for these two pattern types are shown in figures 4.15 and 4.16. As can be seen in the figures, particularly figures 4.15a and 4.15b, as well as having a better classification rate, pattern D has a more clearly defined diagonal than that of pattern B, meaning that there was less confusion in the meaning of the patterns. The recall for each direction also shows that pattern D performed slightly better with more consistently high proportions of correct answers.



(a) Pattern B



(b) Pattern D

Figure 4.15: 3D representation of the confusion matrices for pattern B and pattern D for tests run with the small glove (both interlude times included)

	↑	↗	→	↘	↓	↙	←	↖
↑	3	0	0	0	0	0	0	0
↗	1	0	0	0	0	0	0	0
→	0	0	3	0	1	0	0	0
↘	0	0	0	1	0	0	0	0
↓	1	1	1	0	1	1	1	0
↙	0	0	0	0	1	0	0	0
←	0	0	1	0	1	0	2	4
↖	1	0	0	0	0	0	0	3

(a) Pattern B

	↑	↗	→	↘	↓	↙	←	↖
↑	0	1	0	0	0	0	0	0
↗	0	1	0	0	0	0	0	0
→	0	0	1	0	0	0	0	0
↘	0	0	0	0	0	0	0	0
↓	0	0	0	0	2	0	1	0
↙	0	0	0	0	0	2	0	0
←	0	0	0	1	0	0	1	0
↖	1	0	1	1	0	0	0	1

(b) Pattern D

Figure 4.16: Confusion matrices for pattern B and pattern D for tests run with the small glove (both interlude times included)

Recall							
↑	↗	→	↘	↓	↙	←	↖
1	0	0.75	1	0.14	0	0.25	0.75

Table 4.1: Pattern B

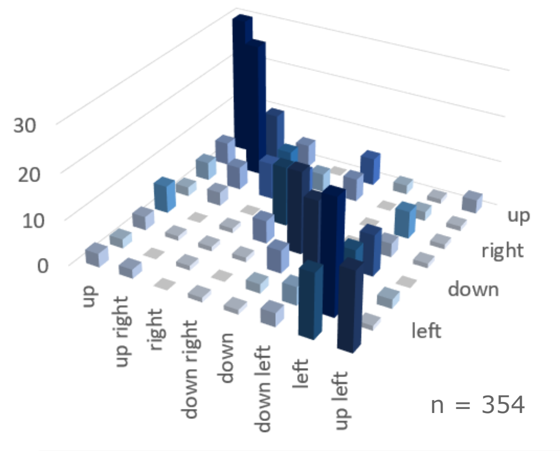
Recall							
↑	↗	→	↘	↓	↙	←	↖
0	1	1	0	0.67	1	0.5	0.25

Table 4.2: Pattern D

4.5.2 Large Glove

Of those 101 wearing the large glove 16 were noted as having relatively small hands, i.e. their hands were slightly too large for the small glove to fit adequately but were small in the large glove. In this case there was a difference in results with those who had hands too small for the glove having a classification rate of 0.35 whereas those who the glove fitted properly had a classification rate of 0.45. This can be explained by the motors probably not making the necessary contact with the skin and as a result there was more confusion in the answers given, therefore these 16 sets of data will be excluded from the analysis of the data acquired from the large glove.

The overall results for the large glove are shown in figure 4.17, with a total of 354 patterns tested. Similarly to the small glove results, a defined ridge can be seen across the diagonal, indicating a high proportion of correctly identified directions. The overall classification rate for the large glove is 0.446, well above the guess rate of 0.125.



(a)

	↑	↗	→	↘	↓	↙	←	↖
↑	30	5	4	2	6	3	2	3
↗	10	29	5	3	0	1	0	2
→	5	7	8	0	1	1	1	0
↘	0	4	8	13	5	1	0	1
↓	6	5	5	7	18	5	2	1
↙	2	0	0	0	4	18	4	3
←	1	2	6	3	9	10	25	14
↖	3	1	1	1	0	2	1	17

(b)

Figure 4.17: Confusion Matrix for the overall results of the large glove

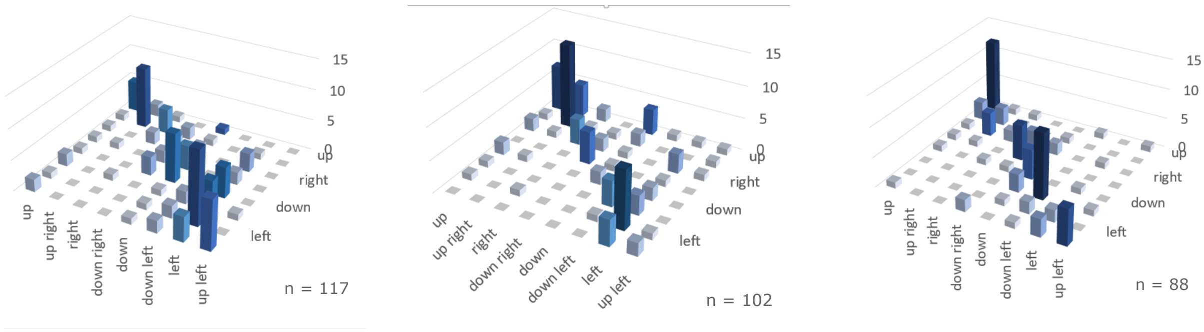
Of those who wore the large glove, 1 was ambidextrous, 9 were left-handed and 75 were right-handed. The results showed little difference between the different groups with right-handed and left-handed receiving classification rates of 0.44 and 0.39 respectively, ambidextrous had a classification rate of 0.5 but given that this is the result from only one subject it may not be representative. From these results, in combination with the results of the small glove, in can be concluded that dominant hand of the test subjects did not influence their ability to understand the vibration patterns.

For the large glove the interlude time proved much more influential than the small glove. For the interlude time of 200ms the classification rate was 0.371, however for a interlude time of 400ms the classification rate was 0.5, significantly better.

For the subjects who tested the large glove, the results for the different patterns were significantly different, as can be seen in table 4.3. Patterns B, C and D showed reasonably high classification rates with performance well above the guess rate, 0.125, when including adjacent directions. There were a small number of occasions when the test subjects were not able to identify the direction of the vibration pattern, as shown in the bottom row of the table, which showed pattern D performing better than pattern C and much better than pattern A and B. These conclusions that are also reflected in the classification rates. Patterns B, C and D all perform well, the confusion matrices for these are shown in figures 4.18 and 4.19, from these it can be seen that pattern D, as well as measuring the best performance, shows the most defined diagonal with a large proportion of correctly identified directions. The recall for pattern D is also more consistently high across all direction than either pattern B and C.

Table 4.3: Classification rates and number of indeterminate answers given for all pattern types

	Pattern A	Pattern B	Pattern C	Pattern D
Classification Rate	0.333	0.419	0.451	0.534
Including adjacent directions	0.622	0.684	0.686	0.795
Total number of tests	45	117	102	88
No. of test answers “no direction”	6	6	4	1



(a) Pattern B (b) Pattern C (c) Pattern D

Figure 4.18: 3D representation of the confusion matrices for patterns B, c and D for tests run with the large glove (both interlude times included)

	↑	↗	→	↘	↓	↙	←	↖
↑	5	1	1	1	1	2	1	2
↗	2	10	0	1	0	0	0	0
→	1	4	2	0	0	1	0	0
↘	0	2	2	2	3	0	0	0
↓	1	1	2	4	8	1	1	1
↙	0	0	0	0	1	2	2	2
←	0	1	3	2	5	5	12	4
↖	0	0	0	0	0	1	0	8

(a) Pattern B

	↑	↗	→	↘	↓	↙	←	↖
↑	7	1	2	0	2	1	1	0
↗	5	13	1	0	1	0	0	0
→	2	1	4	0	0	0	1	0
↘	0	1	2	5	0	0	0	0
↓	4	2	1	1	2	0	0	0
↙	1	0	0	0	3	4	1	0
←	1	0	3	1	2	3	9	4
↖	1	1	1	0	0	0	1	2

(b) Pattern C

	↑	↗	→	↘	↓	↙	←	↖
↑	12	3	1	1	1	0	0	1
↗	1	3	4	1	0	0	0	0
→	1	1	2	0	1	0	0	0
↘	0	0	3	6	1	0	0	2
↓	0	1	2	0	5	3	1	0
↙	1	0	0	0	0	11	2	1
←	0	0	1	0	1	0	2	3
↖	1	0	0	0	0	1	0	6

(c) Pattern D

Figure 4.19: Confusion matrices for tests run with the large glove (both interlude times included)

Recall							
↑	↗	→	↘	↓	↙	←	↖
0.36	0.77	0.22	0.2	0.4	0.29	0.36	0.73

Table 4.4: Pattern B

Recall							
↑	↗	→	↘	↓	↙	←	↖
0.5	0.65	0.5	0.56	0.18	0.4	0.39	0.29

Table 4.5: Pattern C

Recall							
↑	↗	→	↘	↓	↙	←	↖
0.63	0.33	0.4	0.5	0.42	0.73	0.29	0.67

Table 4.6: Pattern D

4.6 Discussion

The results collected for both sizes of glove have classification rates significantly higher than the guess classification rate, 0.125, with 0.350 overall for the small glove and 0.446 overall for the large glove. These results show that direction instructions can, to some degree, be understood from patterns of vibrations. The discrepancy between the results for the small glove and the large glove could be explained by the vibratory motors being placed significantly closer together and therefore having less definition between adjacent motors.

The different pattern types tested also showed greater refinement, with pattern D proving the most effective for both gloves, for both cardinal and ordinal directions. The test results of the large glove also highlighted that patterns that were tested with an interlude time of 400ms were more successfully identified than those with a interlude time of 200ms. This can be seen for the large glove, with 51 tests conducted with pattern D and interlude time of 400ms achieving a classification rate of 0.608, including adjacent directions gives a classification rate of 0.863, an 86.3% success rate. Therefore this pattern type and time period is the best to use in the prototype described in Part II.

5. Part II - The Sixth Sense

The aim of the final experiment was to test whether the sense of touch can be used as a channel to communicate a completely new sense to the brain. This experiment saw the creation of a practical, application independent wearable device and a smart phone application designed to give the user a sense of direction.

5.1 Experiment Design

The aim of the experiment was to discover how successfully a sense of direction can be given to a person, through the use of a wearable device embedded with vibratory motors. Each test subject should be given a number of navigation tasks and the accuracy with which they followed the route was to be measured.

5.2 Device

There are multiple different aspects that need to be considered in the design of a wearable device, such as practical considerations of location of electronics and maintainability of the device as well as the way in which they will be attached [30]. Among the most important aspects of wearable design is the placement of the vibratory motors and the way in which they communicate information [31] [32].

Location

As described in Part I, the most suitable area of the body for vibrotactile communication are the back of the hands, the neck and the back. These areas of skin are relatively large and consistent across different people as well as being less prone to wrinkles and folds in the skin which could change the effectiveness of the interaction.

An experiment was undertaken in order to determine the best location for the vibratory motors to be placed from the suitable sites identified in the paper "Assessing the Wearability of Wearable Computers" [22]. This test was carried out on 5 volunteers who had a 2x2 array of vibratory motors spaced 4cm apart applied to the skin of the lower back, back of the neck and the back of the right hand in turn. For each location the subjects were asked to identify which motors were vibrating, first for a single motor and then for two motors being driven at the same time. Each subject was also asked to answer a short questionnaire for each location rating the comfort and the understandability of the vibrations and whether they thought that the device in that location could cause annoyance or get in the way of everyday activities. The questionnaire can be found in Appendix B.

Figure 5.1: Experiment setup for the back of the hand

The results of the experiment showed that for identification of a single motor vibrating the lower back was the best location of the three, with only one of the five test subject identifying the motor incorrectly compared with two incorrect identifications for both the back of the neck and the back of the hand. For the identification of two vibrating motors the results were reversed with both the back of the neck and the back of the hand having one incorrect identification out of the five subject, where one motor was identified correctly and the other incorrectly. Whereas the lower back had three incorrect identifications, in all three, one motor of the two was correctly identified and one mistaken. These results show that all locations performed similarly well, with the back of the neck and the back of the hand getting 80% correct classifications and the lower back getting 73% correct classifications, see Appendix C for full results. The tests may have proved slightly disadvantageous to the results for the lower back due to the relative spacing of the motors. For consistency the motors were arranged in the 2x2 array spaced 4cm apart as this was the largest size that would fit comfortably on the back of the hand, however this spacing is relatively large compared to the skin area on the back of the hand and the back of the neck whereas it is relatively small compared with the area of skin on the lower back. In fact Novich and Eagleman found in their experiment that the optimum spacing of vibratory motors on the lower back was 6cm [17] and this could explain the difference between the performance of the lower back and the other areas.

The test subjects' answers to the questionnaires did identify some differences between the 3 areas. All locations scored similarly for understandability with averages of 6.4, 6.8 and 6 out of 10 for the lower back, back of the neck and the back of the hand respectively. However, when rating the comfort of the vibrations for each location the test subjects identified the lower back as being the most comfortable location with an average score of 9 out of 10 compared with 7.4 for the back of the neck and 7.8 for the back of the hand. Other answers and comments relating to the practicality of the device indicated that a device on the back of the hand could get in the way of everyday activities or be annoying and that a device of the back of the neck could be restricting depending on how it was attached, and some had concerns that the device would be visible. However all test subjects agreed that a device located on the lower back was least likely to be an annoyance and would not interfere with everyday activities.

Taking into account the results of the experiment and the answers to the questionnaires, the lower back appeared to be the most suitable location. This choice is also supported by previous research, in the work of Novich and Eagleman [17] the lower back was investigated as a suitable area for vibrotactile communication. Another advantage is the added weight of the device should be placed as close to the centre of gravity as possible to make it more comfortable and unobtrusive to wear [22], making the lower back the most suitable option over the other areas investigated. Bach-y-Rita also identified tactile effects on the lower back as a suitable sensory substitution touch location [6].

The array of motors must be spaced far apart, preferably about 6cm, as discovered by Novich and Eagleman [17], but there must also be enough motors so as to create a large number of unique vibration patterns. Ideally there should be an odd number of rows and columns so that there is a centralised row or column. However due to the spine running down the centre of the back, forming an indent down the centre of the area, the vibrational motors may not be able to make effective contact with the skin, therefore there will need to be an even number of columns. The most suitable arrangement of the motors is therefore a 3 row, 4 column array.

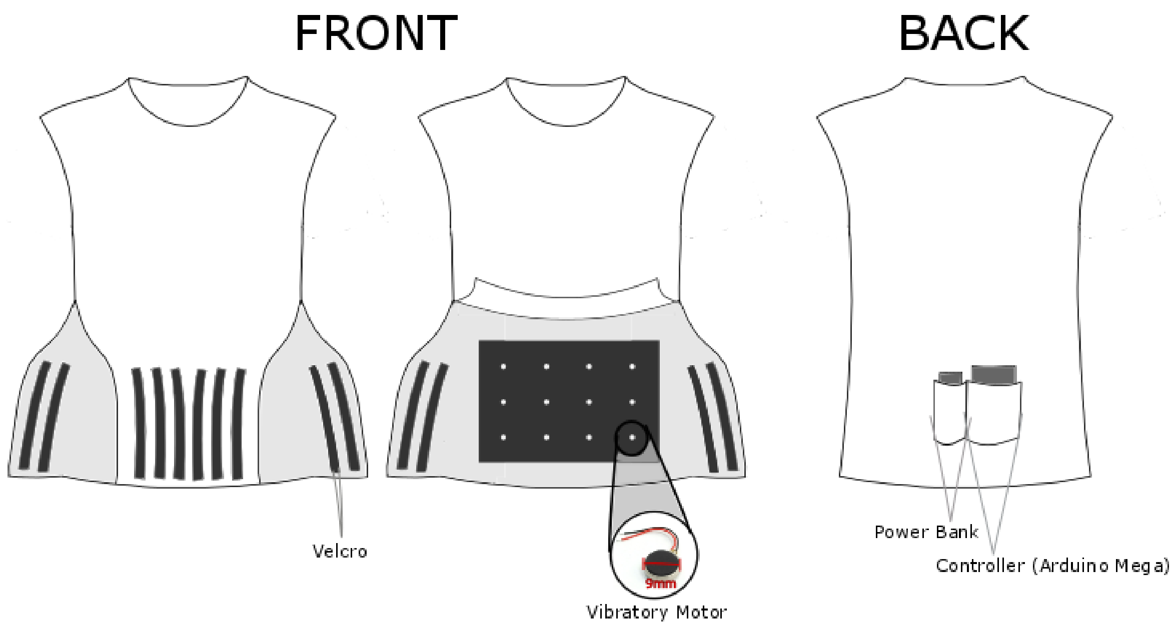


Figure 5.2: Wearable device design

Interaction

Following the experiments carried out at Imperial Festival, described in Part I of this report, it was identified that the most intuitively understandable pattern type was the pattern D, for example for indicating right for a 3x4 array:

1. Turn on the left-hand motor in the middle row of motors
2. After 400ms, turn off the left-hand motor in the middle row of motors and turn on the left of centre motor in the middle row of motors
3. After 400ms, turn off the left of centre motor in the middle row of motors and turn on the right of centre motor in the middle row of motors
4. After 400ms, turn off the right of centre motor in the middle row of motors and turn on the right-hand motor in the middle row of motors
5. After 400ms, turn off the right-hand motor in the middle row of motors

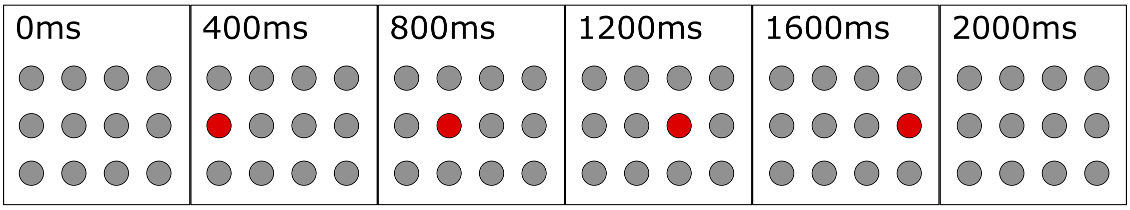


Figure 5.3: Example pattern indicating “right”

The full list of vibration patterns for the device is shown in Appendix F.

Practicality

The garment will need to be washable, therefore the electronic components of the wearable must be easily removed to allow this. However, when making the electronics removable it must not be easy for the electronics to move or fall off when they are attached to the garment and the electronics themselves should be reasonably robust and durable to ensure that they are not damaged in removal and reapplication.

The vibratory motors will not be in direct contact with the skin but encased in a very thin skin-friendly fabric that will insulate the wearer from any small thermal changes and also protect the electronics from moisture. However the encased electronics must be relatively accessible in the case that a component requires replacing. It is important to consider the mobility and flexibility of the device. The device must not restrict movement or cause any discomfort to the wearer when they are conducting normal movements, and therefore must be flexible. However, as the wearer moves the vibratory motors must remain in place relative to the skin.

Implementation

The device was implemented in a similar way to the gloves except for the larger array and the LEDs not required. Due to the number of motors in the array, the Arduino Uno had to be replaced with an Arduino Mega which has more digital I/O pins and is therefore capable of driving all motors in the array and the Bluefruit LE Breakout board. As no LEDs were required the circuit itself was simplified, shown in figure 5.4.

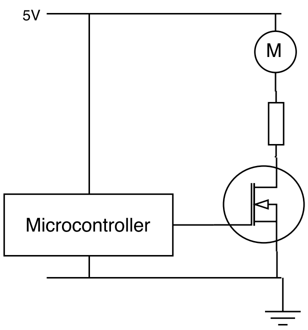


Figure 5.4: Wearable device motor circuit

The array of motors was embedded in a piece of neoprene material in order to cushion and support the motors and make them more comfortable for the wearer in the case that there is pressure on the back, for example when sitting on a chair.

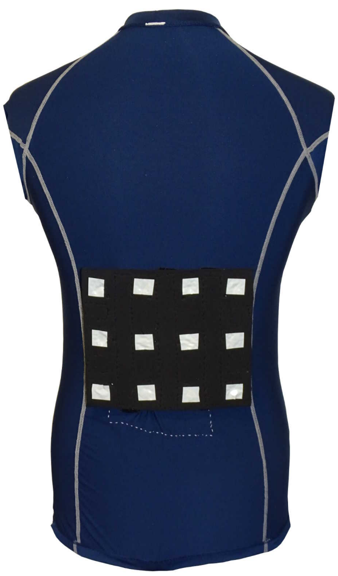


Figure 5.5: The wearable device shown inside out so as to display the array of motors on the lower back

5.3 Application

The sense application is to run on a smart phone, functioning as a GPS navigational aid to communicate with the wearer of the device a subconscious knowledge of directions. The application uses Google Maps Directions API via the Google Maps Java Client to retrieve navigation information. Other practical concerns include ensuring that application does not save large amounts of data as this is a limited resource on the phone and make the application less energy intensive so as not to drain the battery.

Graphical User Interface

A well-designed graphical user interface (GUI) should be intuitive to use and require few steps to complete the navigational setup, as well as providing suitable feedback to the user such as displaying an overview of the directions before commencing with the instructions using the wearable.

GPS Navigation

The GPS navigation part of the application requires the use of an existing and publicly available API which can be used to retrieve turn-by-turn directions along with the associated GPS locations. A number of existing APIs are capable of this: Google Maps APIs, which support a number of different functionalities, as well as with HERE maps, which provides both JavaScript [33] and REST [34] APIs which allow for pedestrian routing, and the Scout API [35], which allows for routing and turn-by-turn navigation.

The most suitable API is the Google Maps Directions API [36] which is a web service allowing requests to be made with a origin and destination as well as being able to specify the mode of travel, i.e. driving, walking or cycling. The responses include the turn-by-turn instructions along with the start and end GPS location for each instruction, which can be saved and each instruction accessed in turn on arriving at the end location of that instruction. The web service can be used by the application through the Java client library for Google Maps API Web Services [37] which simplifies the integration into the application given that Android applications are written mostly in Java.

Communication

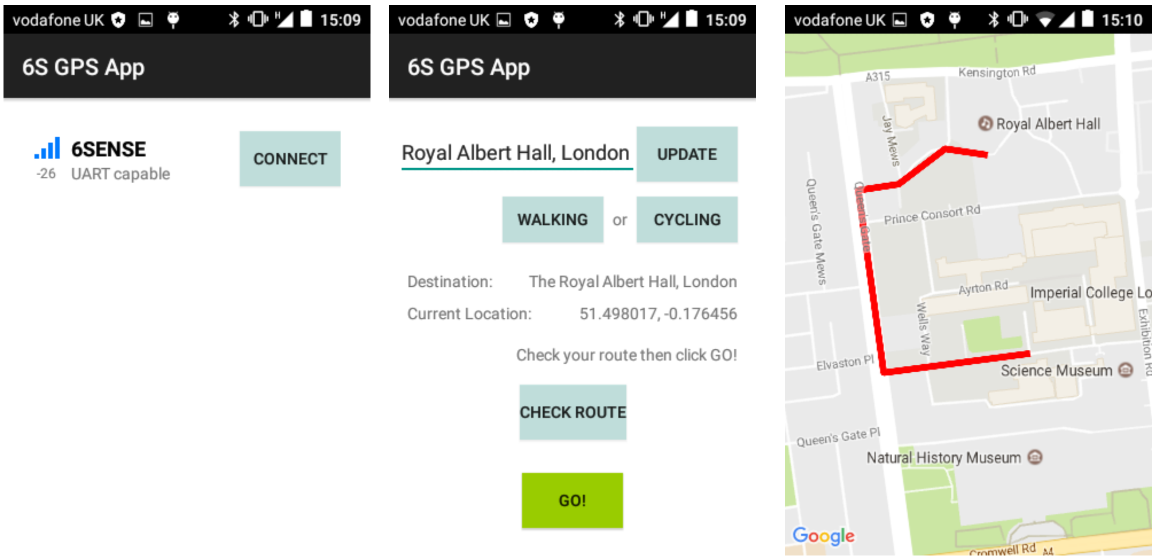
As well as the the vibration patterns, the application allows users to adjust the amplitude of the vibrations to ensure comfort and understandability.

The application will require an Internet connection in order to retrieve the navigational data via the API. However, as the purpose of the application is to assist the user to navigate open areas, requiring an Internet connection to be maintained throughout use may not be feasible, therefore the application should download the route when connected to the Internet and then save it for offline use.

Implementation

The application from Part I provided all the Bluetooth functionality required and was therefore extended to incorporate the fetching of directions and the GPS location. After connecting to the UART device, the user inputs the destination name, for example "The Albert Memorial, London, UK", the application then requests the directions via the Google Maps Directions API using the Google Maps Java Client. The request returns a list of directions with their associated start and end GPS locations. The directions are saved and the user is then able to check the route displayed on a map before starting the navigation, initiating the 1st instruction, sent to the device via Bluetooth. On reaching the end GPS location for the 1st instruction the application will initiate the 2nd instruction. This continues until the user reaches the destination.

The application screens are shown in figure 5.6. The user starts on the Home Screen, figure 5.6a, which displays the wearable device's Bluetooth broadcast. On connecting with the device



(a) Home Screen (b) Navigation Setup Screen (c) Map Screen

Figure 5.6: Application Screens

the Navigation Setup Screen is displayed, the user enters their destination, whether they are walking or cycling and can then check their route. The Map Screen is displayed, showing the user the planned route. The user then returns to the Navigation Setup Screen and presses Go to start the navigation.

5.4 Method

The tests were conducted with a variety of volunteers who were set a number of navigation tasks to unknown locations. The correctness of their route was recorded along with any misunderstandings or hesitations. On completion of the experiment the test subjects were also requested to fill in a questionnaire concerning the comfort of the device, the effort required to understand the information relayed to them and whether this decreased with use and whether they felt more aware of their surroundings compared with using a conventional GPS navigation mobile phone application.

Example routes are shown in Appendix D and the questionnaire for subjects to complete after the experiments is shown in Appendix E.

5.5 Results

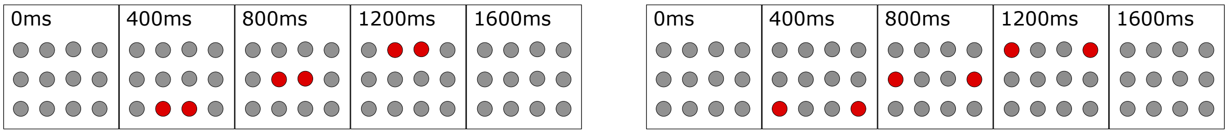
Over the course of the testing three volunteers undertook a number of navigation challenges in the area surrounding Imperial College. Experiments have ranged from navigations involving 6 directions given over the distance of 0.4 miles to 10 directions over 0.7 miles. All map images shown are courtesy of Google Maps.

5.5.1 Test Subject 1

Test Subject 1 completed 3 navigation tests in total. The first route was between Imperial College London to Holy Trinity Brompton, the map is shown in figure 5.7. The correct route is shown in black with each box and its associated arrow indicating a direction instruction. The outline of the box indicates whether the direction was correctly identified (green) or incorrectly identified (red). As the figure shows, the wearer headed in the correct direction at the start but misinterpreted the second direction, where the test subject should have gone straight on they in fact turned left, describing that they felt the device indicated to go forward and to the right. Thereafter the user continued along the red route, following the directions indicate correctly, before rejoining the original route and continued to follow the route correctly to the destination.

Figure 5.7: Test Subject 1 - 1st Navigation Test

Throughout this first test,“left” and “right” directions were easily identified, however the “straight on” direction was incorrectly identified. This direction instruction is harder to communicate as the array of motors in the device are orthogonal to the direction of movement. The “straight on” pattern used in this test was a rolling progression upwards along the two central columns of motors, see figure 5.8a, however the user felt that the pattern moved from bottom right to top left. This is likely due to small variations in the motors resulting in some having a slightly stronger vibration than others, in this case the bottom motor in the right-of-centre column and the middle and top motors of the left-of-centre column felt slightly stronger. To remedy this problem adjustments were made to the arrangement of the motors in an attempt to balance the level of vibrations. The pattern was also changed to a rolling progression upwards along the outer two columns of motors, see figure 5.8b, in order to make the distance between the rows larger to prevent the feeling of progression from one column to another. All other tests were undertaken with this new pattern indicating forwards.



(a) Original forwards pattern (b) Updated forwards pattern

Figure 5.8: Forwards pattern

The second route was from Imperial College Road to the Serpentine Gallery, the route is shown in figure 5.9. In this task the test subject correctly followed all 9 direction instructions with no hesitations.

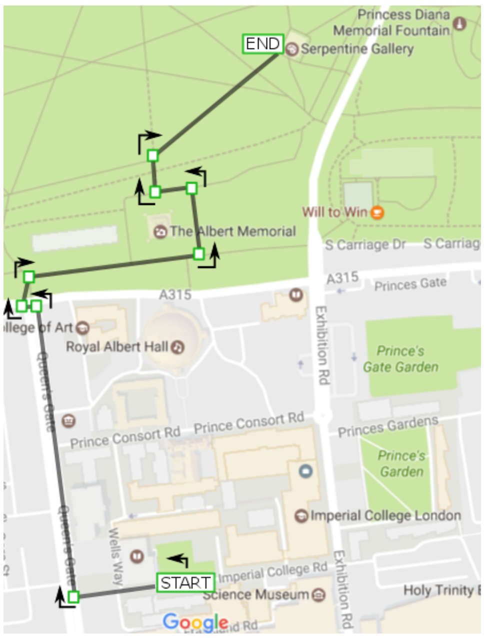


Figure 5.9: Test Subject 1 - 2nd Navigation Test

The third route ran from Imperial College London to the Russian Orthodox Church, figure 5.10 shows the route taken. Once again the user completed the navigation exercise correctly without any hesitations. This route gave the opportunity to test the new "forward" vibration pattern, as the second test had not included a "forward" instruction, which proved significantly more understandable than the previous version.

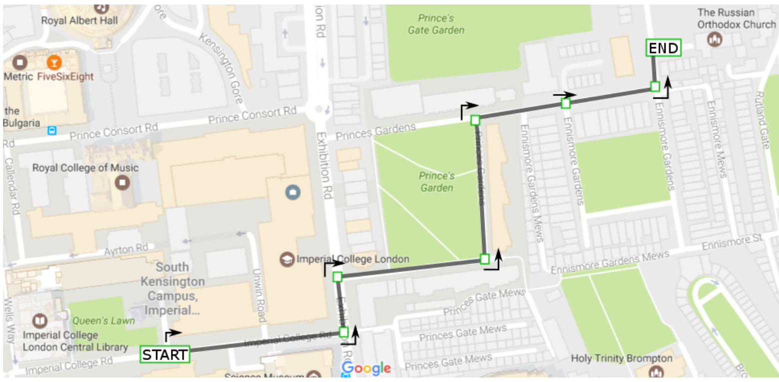


Figure 5.10: Test Subject 1 - 3rd Navigation Test

The answers given to the questionnaire is shown in table 5.1. The test subject commented that the device was less comfortable than it could have been due to it being warm to wear, with the t-shirt being thermal material. They also commented that the second "forward" vibration pattern, as seen in the third navigation task, was much clearer than the first iteration of the pattern, as seen in the first navigation task.

Table 5.1: Test Subject 1 - Questionnaire Answers

Comfort	7/10
Understandability	8/10
Gained better understandability as tests went on?	yes
Felt the device gives you a "sense of direction"	yes
Felt aware of surroundings?	yes
Choose to wear device for everyday activities	yes

5.5.2 Test Subject 2

Test subject 2 completed 1 navigation task form Imperial College Road to The Albert Memorial, the route taken is shown below in figure 5.11. This user correctly followed the directions although were hesitant for the second instruction, shown in yellow. However they commented that after a couple of instructions they found the device easier to understand.

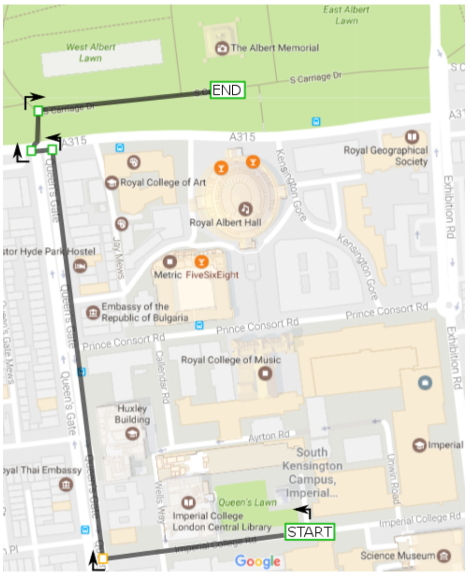


Figure 5.11: Test Subject 2 - 1st Navigation Test

Test subject 2's questionnaire answers are shown below in table 5.2. Similarly to test subject 1 they found the device reasonably comfortable and understandable but commented that the device could improve from a larger area used for the array of vibration motors.

Table 5.2: Test Subject 2 - Questionnaire Answers

Comfort	7/10
Understandability	6/10
Gained better understandability as tests went on?	yes
Felt the device gives you a “sense of direction”	yes
Felt aware of surroundings?	yes
Choose to wear device for everyday activities	yes

5.5.3 Test Subject 3

Test subject 3 first completed a navigation test from Imperial College Road to the Princess Diana Memorial Fountain in Hyde Park, the route is shown below in figure 5.12. This user correctly identified all direction instructions and reached the destination without any hesitations. However the 3rd instruction required the user to cross the road in order to follow the direction, however there was no crossing point at that part of the road but there had been a number of crossing points on the road that could have been taken before reaching this location. Ideally the mapping API would have detected this and added an instruction to cross the road at a crossing point. The Google Maps API has previously given directions to cross the road in the navigation to the Serpentine Gallery (see figure 5.9) and so is capable of doing so, but this could be an important feature to examine in the future and possibly require a change in GPS navigation API.

Figure 5.12: Test Subject 3 - 1st Navigation Test

The second route ran from Imperial College Road to Kensington Palace. All 7 directions were interpreted correctly, the route is shown in figure 5.13. There was only one hesitation, at the fifth instruction, due to the direction being given to turn left, however there were two paths to the left and some confusion to which should be taken. This imprecision is due to the lack of definition in the directions provided by Google Maps. Similarly to the problem of road crossings in the 1st navigation test this could be solved with the use of another GPS navigation API.

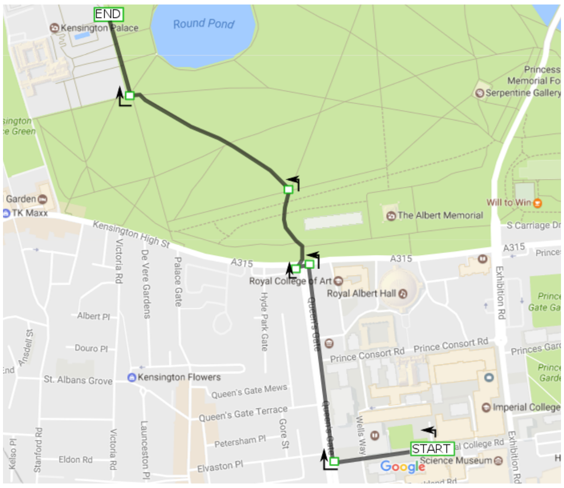


Figure 5.13: Test Subject 3 - 2nd Navigation Test

The third set of directions were between Kensington Palace and the Royal Albert Hall, shown in figure 5.14, all 3 directions were correctly identified without any hesitations.

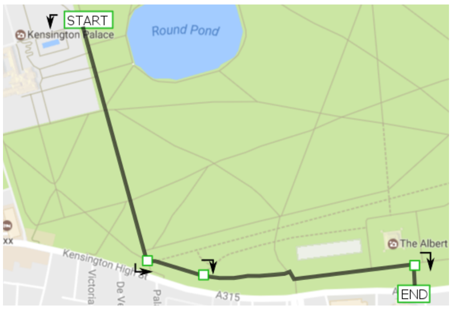


Figure 5.14: Test Subject 3 - 3rd Navigation Test

Answers given to the questionnaire are shown in the table below. Similarly to test subject 1 they commented that the neoprene surrounding the motors was not breathable and therefore resulted in the user becoming hot.

Table 5.3: Test Subject 3 - Questionnaire Answers

Comfort	7/10
Understandability	7/10
Gained better understandability as tests went on?	yes
Felt the device gives you a “sense of direction”	yes
Felt aware of surroundings?	yes
Choose to wear device for everyday activities	yes

5.6 Discussion

The tests have shown that wearers of the device can accurately and easily complete navigation tasks with a 98% success rate in identifying directions correctly and 96% of instructions correctly identified without hesitation.

Answers given in the questionnaires show that users found the device reasonably comfortable and the vibration patterns understandable. All test subjects marked that the device gave them a sense of direction and that they felt more aware of their surrounds.

These results show that an entirely new sense can be created, through the use of electronic sensors, and imparted to the user via vibrotactile communication. The prototype device did indeed give the users a sense of direction, enabling them to navigate to unknown destinations with very high accuracy.

6. Conclusion

The project saw the design, implementation and testing of a prototype device to give the user a sense of direction. This report details the experiment conducted at Imperial Festival in order to investigate how vibration patterns could be used to communicate directions, see Part I, and the design and implementation of a wearable device and smart phone application to assist users in navigation tasks, see Part II. The Imperial Festival experiment tested different vibration patterns on over 120 people and showed that directions could be communicated effectively through the use of spacio-temporally encoded vibration patterns without any training required. The results from this experiment informed the design of vibration patterns for use in the wearable device created for the communication of the sixth sense. The results of the final experiment showed that the prototype device enabled users to navigate to unknown destinations with very high accuracy.

6.1 Future Work

A possible use of the device could be assisting those who are visually impaired to navigate, for example those who use guide dogs are assisted in avoiding obstacles but are restricted to routes where they are able to direct the guide dog, requiring them to learn and remember routes. With the help of the proposed device, a visually impaired person could navigate new areas while still using their guide dog for safety, helping them to be more independent. The current prototype could be adapted to make it more suitable for the users such as the application being voice operated and other vibration patterns to warn the user of junctions and indicate safe places to cross roads.

A number of suggestions were made by people who visited the stall at Imperial Festival, mostly discussing the embedding of the motors into a car seat for drivers or the handlebars of cyclists. A further idea discussed was the potential to use the gloves as indicators for surgeons in robotic assisted surgery. For example, vibrations could be used to warn the surgeon that they are approaching the edge of the operating area.

Overall the prototype device achieved its aims, it did indeed give the users a sense of direction with an accuracy that exceeded expectations. Moving forward, the prototype device can be improved by condensing the control electronics to make it smaller and more comfortable. The application can be adapted for different user's needs and new applications can be built to create other new senses.

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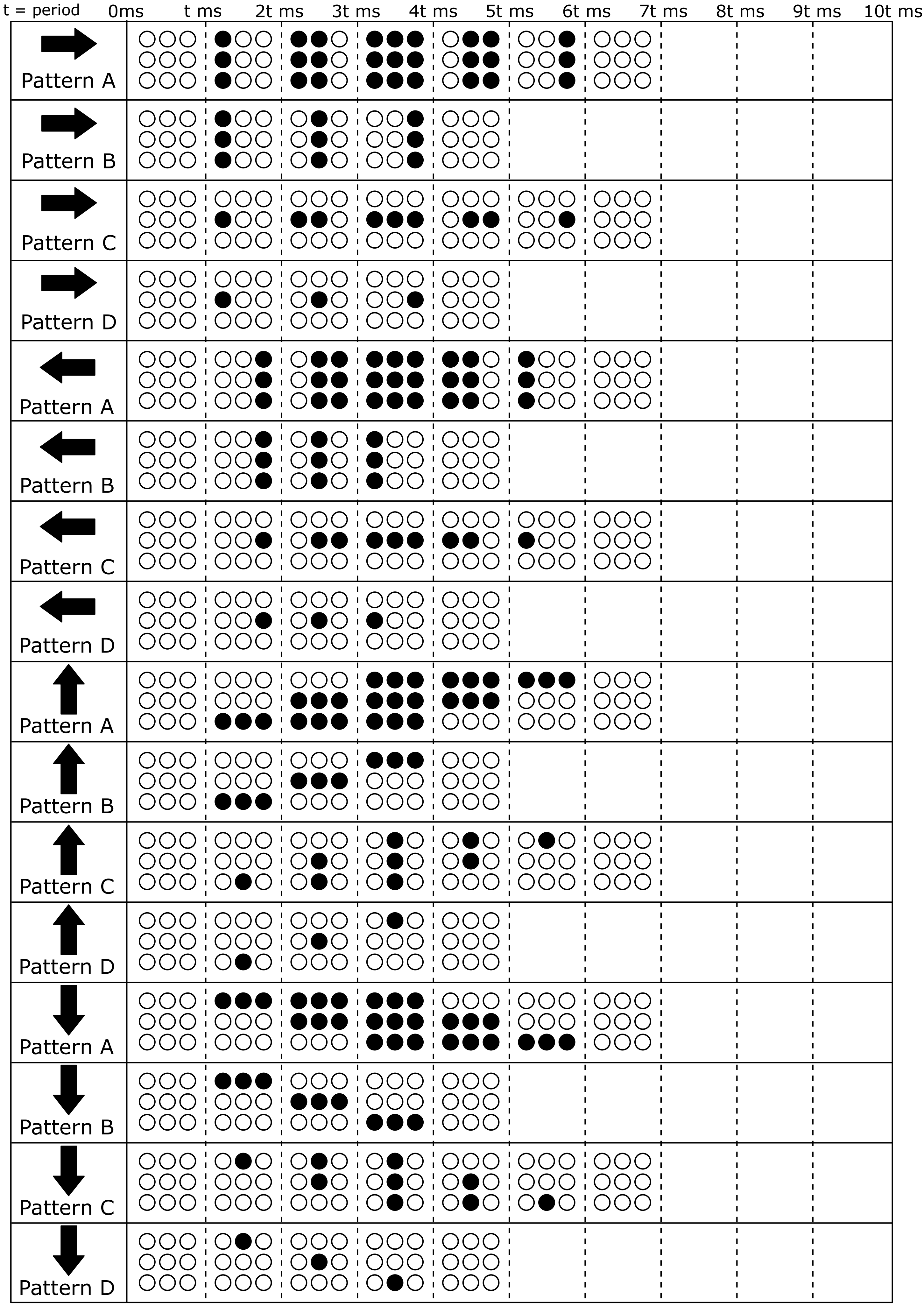
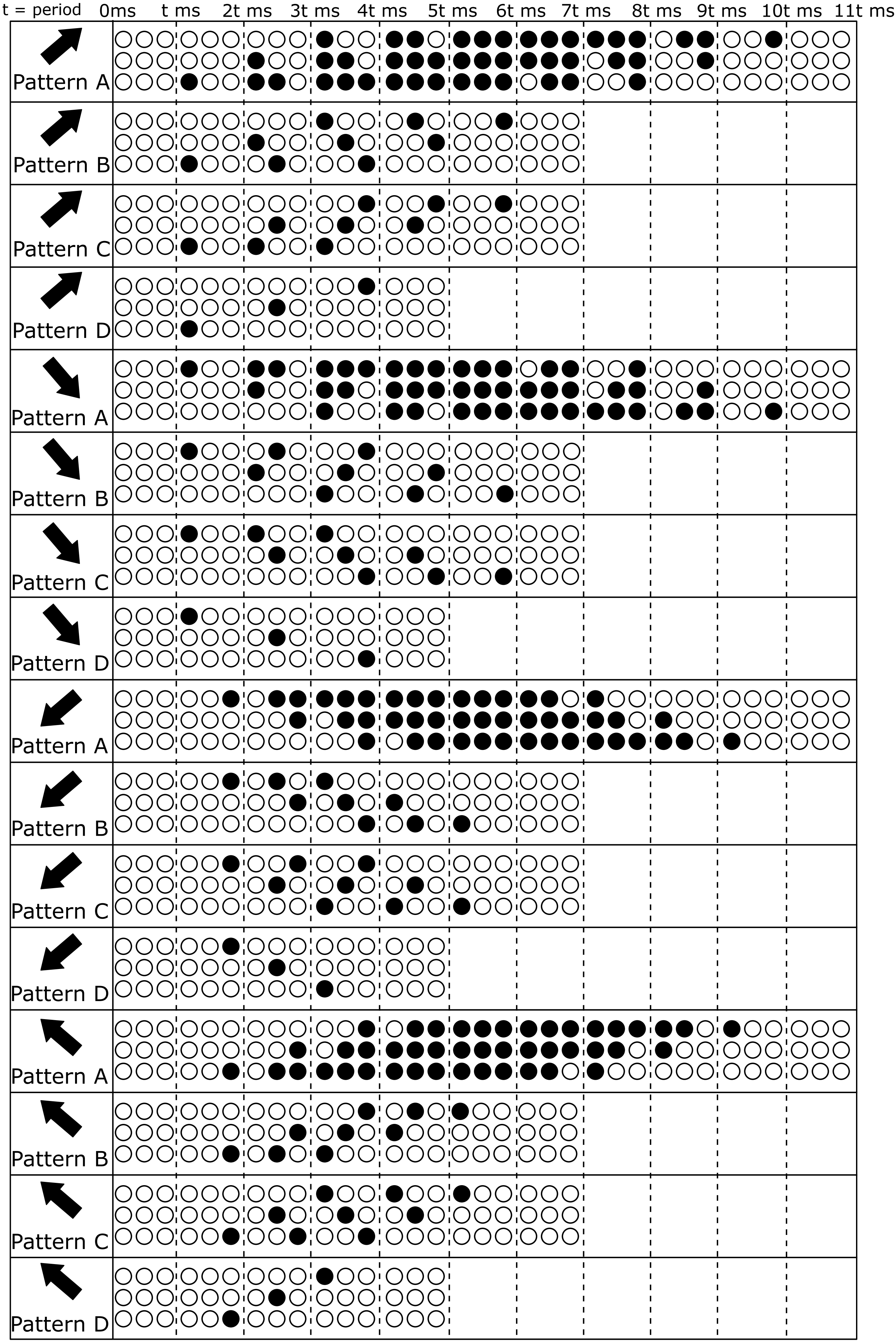
Appendix A - Imperial Festival experiment patterns



t = period
0ms
t ms
2t ms
3t ms
4t ms
5t ms
6t ms
7t ms
8t ms
9t ms
10t ms
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D


t = period
0ms
t ms
2t ms
3t ms
4t ms
5t ms
6t ms
7t ms
8t ms
9t ms
10t ms
11t ms
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D
Pattern A
Pattern B
Pattern C
Pattern D

Appendix B - Location Sensitivity Test Questionnaire

Questionnaire

Details

male / female Age:

Lower Back

1. How comfortable were the vibration patterns in this area?

   uncomfortable **1 2 3 4 5 6 7 8 9 10** *comfortable*

2. How understandable were the vibration patterns in this area?

   incomprehensible **1 2 3 4 5 6 7 8 9 10** *understandable*

3. Where the vibrations in this area annoying?

   yes no

4. Would having the motors in this area get in the way of everyday activities?

   yes no

Neck

1. How comfortable were the vibration patterns in this area?

   uncomfortable **1 2 3 4 5 6 7 8 9 10** *comfortable*

2. How understandable were the vibration patterns in this area?

   incomprehensible **1 2 3 4 5 6 7 8 9 10** *understandable*

3. Where the vibrations in this area annoying?

   yes no

4. Would having the motors in this area get in the way of everyday activities?

   yes no

Back of Hand

1. How comfortable were the vibration patterns in this area?

   uncomfortable **1** **2** **3** **4** **5** **6** **7** **8** **9** **10** *comfortable*

2. How understandable were the vibration patterns in this area?

   incomprehensible **1** **2** **3** **4** **5** **6** **7** **8** **9** **10** *understandable*

3. Where the vibrations in this area annoying?

   yes no

4. Would having the motors in this area get in the way of everyday activities?

   yes no

Appendix C - Location Sensitivity Test Results

Lower Back	● ○ ○ ○	○ ● ○ ○	○ ○ ○ ●	○ ○ ● ○
● ○ ○ ○	2	0	0	0
○ ● ○ ○	0	1	0	0
○ ○ ○ ●	0	1	1	0
○ ○ ● ○	0	0	0	0

Back of Neck	● ○ ○ ○	○ ● ○ ○	○ ○ ○ ●	○ ○ ● ○
● ○ ○ ○	0	0	0	0
○ ● ○ ○	0	2	1	0
○ ○ ○ ●	0	0	1	0
○ ○ ● ○	0	0	1	0

Back of Hand	● ○ ○ ○	○ ● ○ ○	○ ○ ○ ●	○ ○ ● ○
● ○ ○ ○	1	0	0	1
○ ● ○ ○	0	1	0	0
○ ○ ○ ●	0	0	1	0
○ ○ ● ○	1	0	0	0

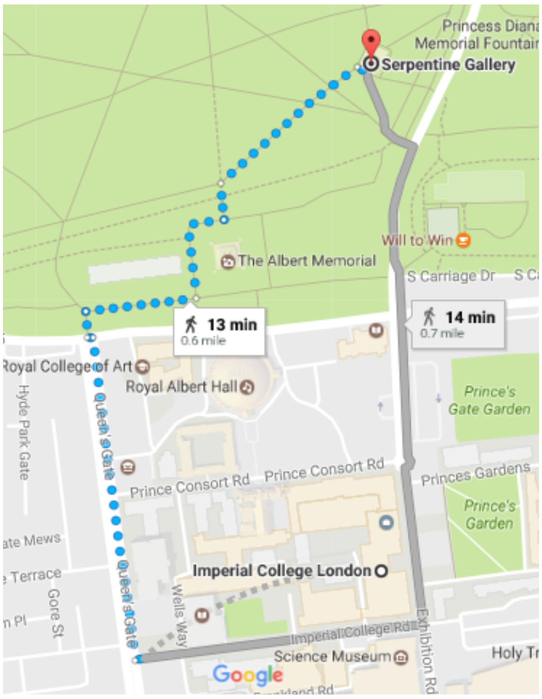
Lower Back	●● ○○	○● ○●	○○ ●●	●○ ●○	●○ ○●	○● ●○
●● ○○	0	1	0	0	0	0
○● ○●	1	0	0	0	0	1
○○ ●●	0	0	1	0	0	0
●○ ●○	0	0	0	0	0	0
●○ ○●	0	0	0	0	1	0
○● ●○	0	0	0	0	0	0

Back of Neck	●● ○○	○● ○●	○○ ●●	●○ ●○	●○ ○●	○● ●○
●● ○○	1	0	0	0	0	0
○● ○●	0	2	0	0	0	0
○○ ●●	0	0	0	1	0	0
●○ ●○	0	0	0	1	0	0
●○ ○●	0	0	0	0	0	0
○● ●○	0	0	0	0	0	0

Back of Hand	●● ○○	○● ○●	○○ ●●	●○ ●○	●○ ○●	○● ●○
●● ○○	0	0	0	0	0	0
○● ○●	0	0	0	0	0	1
○○ ●●	0	0	1	0	0	0
●○ ●○	0	0	0	1	0	0
●○ ○●	0	0	0	0	1	0
○● ●○	0	0	0	0	0	1

Appendix D - Example Navigation Test Routes

Test 10 - Serpentine Gallery



13 min (0.6 mile)

via Queen's Gate

Imperial College London

Kensington, London SW7 2AZ

- Walk west on Imperial College Rd towards Queen's Gate
  36 ft
- Turn right onto Queen's Gate
  0.3 mi
- Turn left onto Kensington Rd/A315
  23 ft
- Turn right onto S Carriage Dr
  112 ft
- Turn right to stay on S Carriage Dr
  469 ft
- Turn left
  453 ft
- Turn left
  151 ft
- Turn right
  0.1 mi
- Turn right
  49 ft

Serpentine Gallery

Appendix E - Example Navigation Test User Questionnaire

Questionnaire

Number of tests participated in:

1. How comfortable was the device?

   uncomfortable **1 2 3 4 5 6 7 8 9 10** *comfortable*

2. How understandable were the vibration patterns?

   incomprehensible **1 2 3 4 5 6 7 8 9 10** *understandable*

3. Did you feel that you gained a better understanding of the instructions (vibrations) with more tests?

   yes no

4. Do you feel that the device gives you a ”sense of direction”?

   yes no

5. Did you feel aware of your surroundings? (i.e. more aware than if you had been using a navigation/map app on your phone)

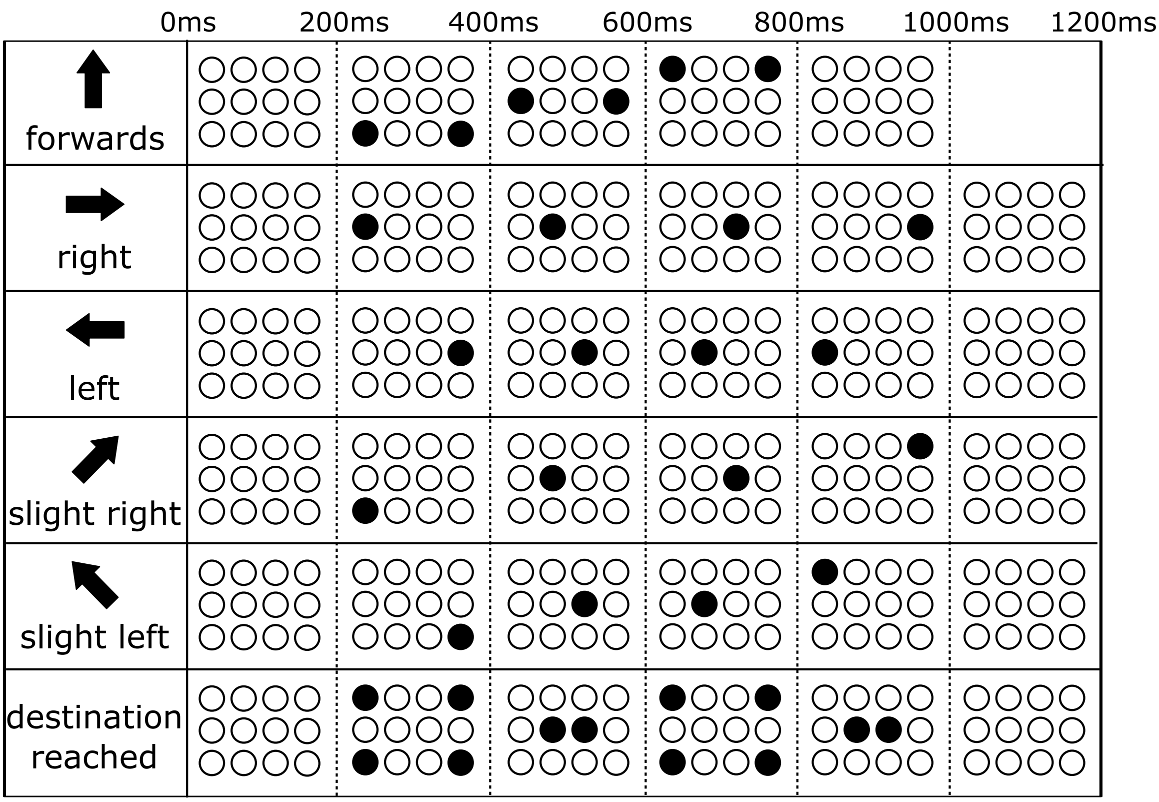
   yes no

6. Would you choose to use the device for everyday activities?

   yes no

7. Comments:

Appendix F - Navigation Device Vibration Patterns


0ms
200ms
400ms
600ms
800ms
1000ms
1200ms
forwards
right
left
slight right
slight left
destination reached

Appendix G

Please find the full listing of code for this project at:

`https://github.com/jubooth/sixth_sense`