Creation of Low-Cost Haptics

Third Year Individual Project – Final Report

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Contents

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Abstract

While complex audiovisual feedback is commonplace in many devices and almost ubiquitously used, haptic feedback (feedback using the sensation of touch) lags behind, seeing use as simple notifiers in phones and only presenting more complex feedback in expensive and uncommon devices. However haptic feedback has potential to enrich already complex feedback in many areas such as medicine, robotic, and entertainment. This report details a promising avenue of haptic feedback research: vibrotactile illusions. These illusions have been implemented successfully using sparse actuator arrays making them an obvious choice for attempts at implementing low-cost haptic devices. This report also designs, carries out, and discusses the results of tests for two vibrotactile illusions: phantom sensation and apparent tactile motion. The results from this show that, while the hardware tested is incapable of reliably producing vibrotactile illusions, some can be produced and that the confounding factors preventing their inducement are known and may be resolved.

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1 Introduction

1.1 Background and motivation

In an overwhelmingly technology-oriented world, it is becoming increasingly important that we have a diverse array of ways in which we can interact with the systems around us. Conventionally, visual and audio feedback have dominated in this regard; with most if not all people now owning a device which can produce complex audio-visual feedback. This is understandable as these methods of interaction are generally the easiest to produce, store, and transmit. However, this leaves a gap in the expressiveness of our technology, a gap which is rapidly being filled using the sensation of touch.

Haptic feedback, in the broadest sense, can be considered any feedback from a system which uses the sensation of touch. Haptic technology then, is any device or system that can output this haptic feedback. Generally, haptic technologies are broken down into these sub-categories[1] :

- Kinaesthetic haptics – forces are directly applied to resist motion or displace user.
- Skin deformation – skin is stretched or otherwise manipulated to create feedback.
- Vibrational haptics – sources of vibration are used to deliver feedback.
- Haptic surfaces – a surface moves outside of a user to deliver feedback.

There is a myriad of uses for each of these different kinds of feedback including but not limited to:

- Feedback for teleoperation or cooperation [2], where feedback is given to the operator of a device, usually a robot, even when the operator is not physically interacting with the device in question.
- Medical Rehabilitation [3] where the focus is on giving haptic feedback to support people with disabilities or injuries.

- Augmenting Virtual reality and augmented reality experiences where haptic feedback is used to simulate objects with no real-world physical equivalent [4].

1.2 Motivation

With most of these implementations there is either a high cost – with most haptic devices being either custom made or costing multiple hundreds, if not thousands of pounds. To compound on this issue, the hardware used in high-resolution haptics tends to be either expensive or inaccessible to most.

Thus, there exists a space for low-cost high-resolution haptics which can be produced using commonly accessible components.

1.3 Aim of the project.

The main aim of this project, and by extension this report, is to detail the implementation and testing of low-cost haptic feedback method which can competently mimic the sensations and phenomena given by higher-end devices.

2 Literature review

2.1 Introduction

Haptics technology (haptics) is a rapidly growing field of inquiry which brings together disciplines of medicine, psychology, and many types of engineering. With so many differing implementations, it is critical that an appropriate form of haptic feedback is chosen to minimise cost and improve accessibility.

To this end, vibrational haptics was chosen as an area of interest as the implementations of vibrational devices tend to be cheaper and easier to come by. Coincidentally they are also safer to implement than their equivalents as they apply no potentially harmful forces to the body.

2.2 Tactile Illusions

According to a review article on haptic feedback by Culbertson *et al* [1], one of the most promising approaches to vibrational haptics is that of tactile illusions. In particular, those implemented by A.

Israr and I. Poupyrev in [5] and further developed in [6] detail three of the most useful tactile illusions:

- Phantom sensation (AKA the funnelling illusion [7], AKA Haptic Intensity Order Illusion [8])
- Apparent tactile motion (AKA vibrotactile flow [9])
- Sensory saltation (aka cutaneous rabbit)

All three of these effects require at least two vibrational motors positioned in a line and controlled separately. Phantom vibration is created by varying the amplitude of one or both motors and presents as a third "phantom" vibration taking the place of each separate motor. Apparent tactile motion is generated by causing a delay between the onset in vibration between the two motors. It presents, in the best circumstances, as a continuous smooth brush-like feeling. Sensory saltation is caused by pulsing the delayed vibrations mentioned in the above section. This final illusion presents a small "hopping" object crossing the area. All the above effects are illustrated in [6] which is shown in fig 1 for convenience.

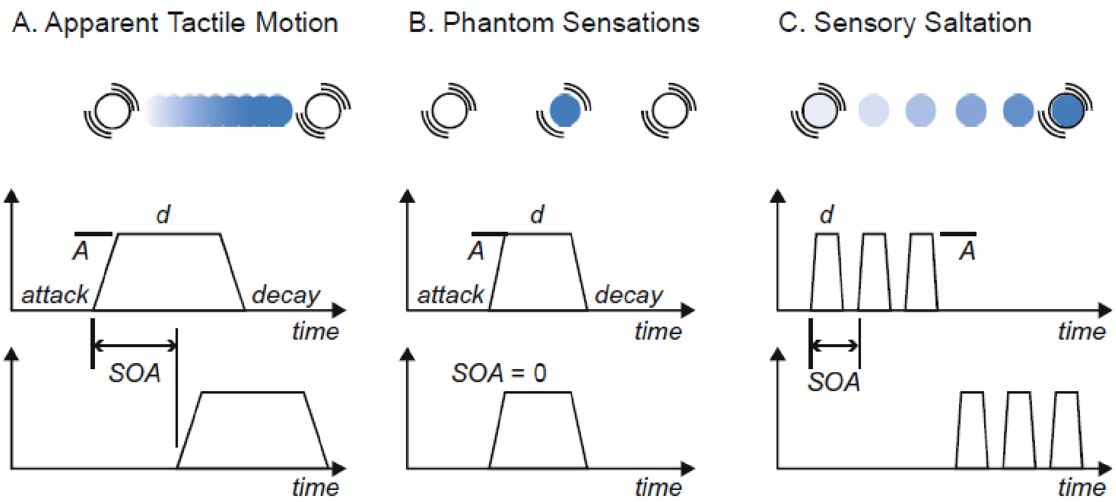

Figure 1: the different tactile illusions based on motor playback. A. shows apparent tactile motion produced by single pulse with SOA. B. shows phantom sensation produced by single pulse with no SOA. C. shows sensory saltation produced by multiple pulses with SOA. Copy of [6, fig 2]

2.3 Multidimensional tactile illusions

The illusions shown in section 2.2 can be extended and combined to produce simple two-dimensional strokes and more complex planar motion. If, instead of using two actuators, a grid of

4 or more are used, multidimensional “strokes” can be expressed on the surface these actuators are attached to. This

is more clearly illustrated in [5] which is shown below.

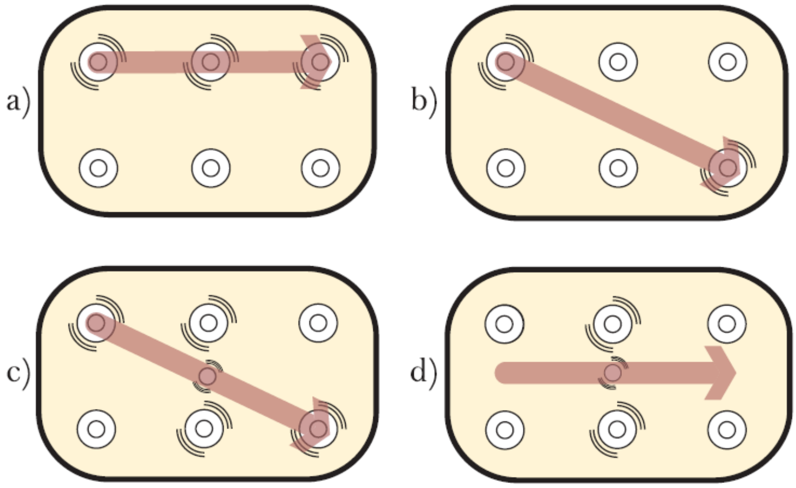

Figure 2: 2D renderings of apparent tactile motion. a) and b) apparent tactile motion using physical actuators while c) and d) use phantom tactors. Reproduced from [5]

A set of equations were also developed which allow for the calculation of the delay between vibrations also known as the inter-stimulus onset asynchrony (SOA) as well as the amplitude of vibrations which are required for any arbitrary tactile stroke [5]. Equation 1 shows the linear equation to determine SOA where d is the duration of the effect and both d and SOA are measured in milli seconds.

$$SOA = 0.32d + 47.3$$

Equation 1: Linear SOA equation

This is further extended by using the phantom sensations to create the feeling of virtual tactors. These tactors can then be used as starting and stopping points for the apparent tactile motion. The implication of this being that a sparse array of tactors can create high resolution effects thus reducing cost, lowering power consumption, and freeing space on part of the body to which this has been applied.

This is typically done with a rectangular grid as shown in Figure 2 (d) and equations were developed by [5] to modulate the amplitude of these phantom tactors. Equation 2 shows the calculation of the amplitude of real motors A1 and A2 to reach desired amplitude of phantom tactor Av based on the ratio of the distances between tactor A1 and A1 represented as β.

$$A_1 = \sqrt{1-\beta} * A_v \,, A_2 = \sqrt{\beta} * A_v$$

Equation 2: Amplitude of tactors A2 and A1 to reach desired phantom tactor amplitude.

However, this is not the only approach and others have reported success in implementing apparent tactile motion with as few as 3 motors by use of a triangular formation of tactors [10]. This formation is shown in Figure 3.

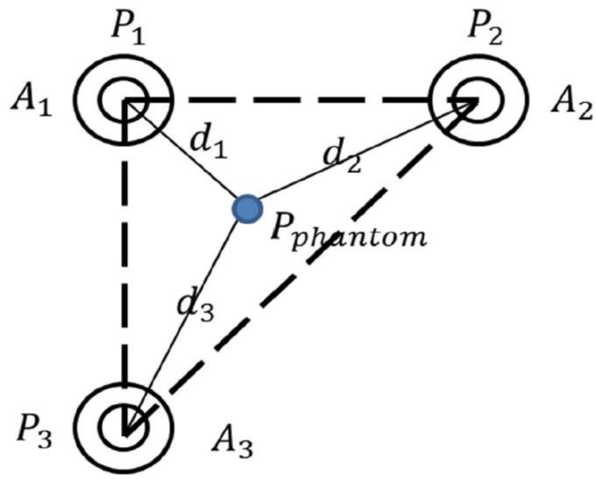

Figure 3: Triangular layout of physical tactors to create phantom tactors with sparse array. Copy of [8, fig3]

This has even been extended to incorporate hand posture with the current state of the art in rendering tactile illusions [11] where an algorithm has been developed to accommodate the position of the hand and fingers even when adapting already available vibrotactile hardware.

These algorithms have been developed to be independent of hardware, as a result they are excellent candidates for the implementation of haptics in which low-cost actuators are used. Therefore, it is proposed that a such illusions could be implemented, using non-specialised off the shelf hardware, for the purpose of presenting haptic feedback.

2.4 Psychophysical testing

In order to test the hardware used, psychophysical testing is required. This section explores previously conducted tests in this field and concludes on the specific aspects of tests which were useful in later investigation. Psychophysical testing can be defined as 'presentation of a sensory stimulus to a subject, who is scored based on a particular aspect of their perception of that stimulus' [12]. They are broadly split into two categories, threshold and suprathreshold. Threshold involves testing for the minimum amount of a certain stimuli which can be perceived by a subject. In contrast a suprathreshold test would test for qualitative aspects of a stimuli [12]. For example, a threshold test of light perception might reveal the minimum light intensity perceptible by a subject whereas a suprathreshold test may categorise the colour of differing wavelengths of light.

Many different psychophysical tests have been conducted around phantom sensation with one of the most influential being the report by D. Alles in 1970 [13]. In this work many aspects of the inducement of tactile illusions were tested and quantified including the effects of amplitude variation, temporal characteristics of vibration, and training.

In the development of the previously mentioned tactile brush, a threshold test for the apparent tactile motion effect was conducted [5]. This test involved modulating the SOA of a vibrotactile stimuli until the upper and lower threshold of apparent tactile motion could be determined. Other suprathreshold tests have quantified the relationship between the perception threshold of these illusions and factors such as gender [14] by use of the same vibrotactile stimulus across a wide array of participants.

To accurately determine whether the hardware in this report is viable for the implementation of low-cost haptic feedback, both threshold and suprathreshold tests are useful in determining if and to what extent these illusions present respectively.

2.5 Project objectives.

The literature shows that vibrotactile illusions can be elicited and tested for using various psychophysical tests. From this we can elaborate on the aims of the project, the following set of objectives will be used to measure its success:

- Find low-cost hardware which could be used to implement the various tactile illusions.
- Design and implement a test to determine if such hardware can achieve the phantom sensation and apparent tactile motion described in section 2.
- Design and implement hardware which can be used to carry out such a test.
- Provide both quantitative and qualitative analysis of the effectiveness of hardware at producing such effects.

3 Methods

3.1 Introduction

The main problem of the project can be summarized as follows:

It is unknown whether unspecialised inexpensive hardware can be made to produce tactile illusions to the degree necessary in order to convey relevant information.

This problem hides a series of sub problems:

- A series of inputs need to be created to act as a baseline measure of success; if the haptic feedback system can accurately display these inputs, then the hardware can be considered fit for use.
- The components selected may not be able to produce the required effect.
- There are factors outside of component selection which may prevent the tactile illusions from presenting [5] including:
    - Distance between and arrangement of actuators.
    - Actuator placement.
    - Actuators contact point i.e. if the actuator is in direct contact with the skin and what padding is provided.
    - Padding in between the actuators.

    - Duration of effect.
    - SOA.
- Different people may have different sensitivity to said illusions [14] This needs to be resolved if the results of haptic feedback implementations using low-cost hardware are to be universally accessible.

The rest of this section will be a detailed breakdown of each problem including:

- how it was initially tackled.
- how the solution developed over time.
- what the final approach was and why it was chosen.

3.2 A detailed breakdown of each problem

3.2.1 The components selected may not be able to produce the required effect.

The first attempt to solve this problem was to use the most commonly available haptic vibrating ERM motors (Seeed Studio 316040001 Mini Vibration Motor). This motor was largely selected for its low cost and accessibility, being sold for less than £2 (excluding VAT) by RS.

However, this motor caused several problems.

1. The motor supplied had leads which were so short as to prevent any reasonable integration with other hardware. The shortness of leads also made it almost impossible to repair motors when breakage occurred during testing.
2. The motor, while powerful, tended to heat up when run for extended periods, making it more difficult to test for tactile illusions.
3. The resonant frequency was not supplied with the motor meaning that choosing an appropriate SOA was made more difficult.

Another motor tested was the Model No. 310-003 10mm vibration motor – 3mm Type from Precision Microdrives. This was also an ERM vibration motor, and it had some major advantages over its previously used counterpart:

1. The motor has guaranteed lead lengths as the motor is ordered straight from the manufacturer.
2. The motor runs at 1.5V instead of 3V meaning less losses due to heat.

3. The resonant frequency is supplied, and relatively close to that used in [5] for maximum SOA margin.

However, an oversight in selection meant that the amplitude of the motor was about half of what was standard in similar studies (0.9 G versus the standard 1.4 G) [15]. Model No.310-122 10mm vibration motor – 3mm Type also from Precision Microdrives was chosen to resolve this problem as it has a maximum amplitude of 1.9 G which was the highest that could be found for pancake or button type motors.

Other hardware was then chosen to enable the use of these motors.

A microcontroller (Arduino Nano) was selected as a baseline to allow for the implementation of any algorithms on similar hardware. This was chosen due to the open-source nature of Arduino software architecture making it present on many other microcontrollers, allowing for flexibility if needed later in the project.

The motor driver board (drv2605) was chosen because if its inbuilt PID controller and other features including[16]:

- Automatic overdrive / breaking.
- I2C communications
- Fast start up time
- Automatic actuator diagnostic.

A I2C Multiplexer (TCA9548A) was also used to facilitate the communications with multiple boards. This hardware was tested using the procedure laid out in the sections below.

3.2.2 There are factors outside of component selection which may prevent tactile illusions from presenting.

These factors needed to be controlled using a suitably designed test rig. It was deemed best to design this rig with geometrically simple anatomy in mind. As such the idea of a hand-held device, such as those put forward in [17], was disregarded as the variation in hand sizes and shapes between potential users was too great. Instead, the anterior forearm was chosen for its sensitivity [15] and simple geometry.

Initial designs of the rig involved motors embedded in a thin sheet of rubber in a square grid of 4 physical tactors. With wiring also embedded to prevent mechanical wear. The processor and drivers were to be kept separate from this sheet. The sheet would then be laid over the forearm and fixed in place with small amounts of medical tape. A rendering of this rig is shown in Figure 4.

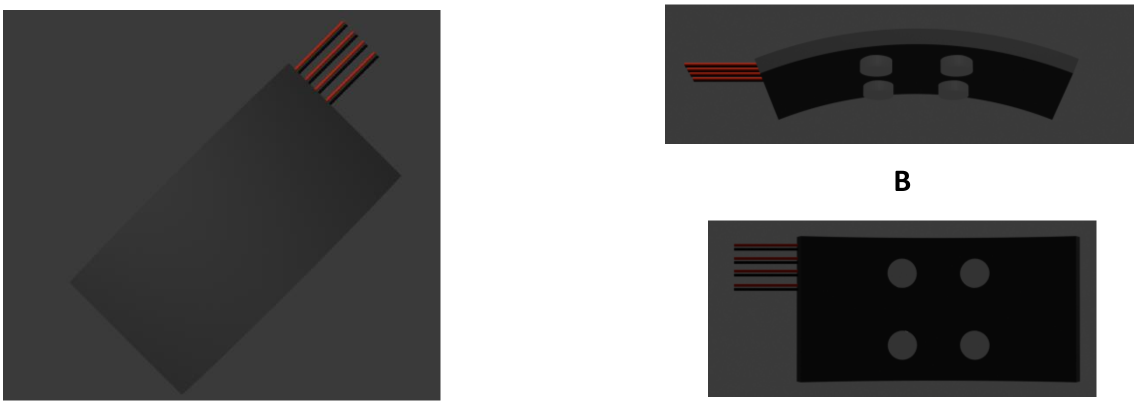

Figure 4: Rendering of initial test rig design.

However, in the implementation of this rig, several key issues were discovered:

1. The rubber sheets transmitted vibration across the surface of the skin which is detrimental to the implementation of tactile illusions [13].
2. Large but thin sheets or rubber were not available to be cut to length for a cost lower than the remaining budget.
3. Embedding into the material risked damage to the motors.

An alternative test apparatus was developed by further looking at the methodologies of the studies by D.S. Alles [13] and V.A Shah *et al* [15]. From this the following changes were made:

- The rubber material was replaced with a pad of memory foam cut into a (4 x 5 x 1) inch cuboid. This is for both padding and measurement as the study by D.S. Alles [13] recommends 5 inches as the optimum distance for this display on the forearm.
- The actuators were attached directly to the skin on either side of the foam with sports tape.

- The arm with the motors would be placed face down on the foam and the test would begin.

The final version of the test rig is shown in Figure 5 below.

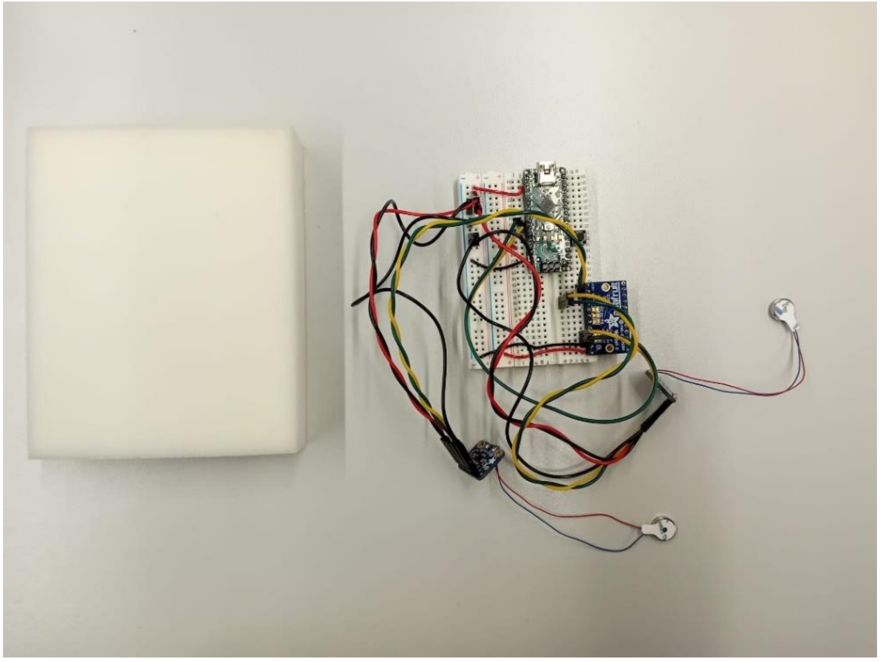

Figure 5: Final created test rig.

This controls several of the previously mentioned variables.

- Actuator arrangement and placement can be kept consistent over many tests due to the motors always being placed either end of the foam.
- Contact points remain discrete with the memory foam in-between damping vibration which would otherwise radiate outwards from the point of contact.

This allows for the isolation of hardware as the primary factor in the production of tactile illusions.

3.2.3 Different people may have different sensitivity to said illusions.

To properly account for variations in the sensitivity of individuals to phantom sensation and apparent tactile motion, two tests were designed and carried out with the goal of quantifying this difference. This controlled both hardware and external factors by using the test rig outlined in section 3.2.2. The Test script used for both tests can be found in the report appendices.

Before any of the following tests, participants were given a brief which included:

- A step by step of what will happen during the test.

- Opportunities for participant to ask questions.
- A collection of some non-identifying information.
- An encouragement for the participant to act on instinct and not dwell on answers for too long.

Participants were also given headphones which played white noise for the duration of the test to prevent auditory identification of motor activation. Training to identify the effect was avoided and only enough information to complete the test was given verbally. The justification for this was a comparison to audio-visual feedback for which no training is required e.g. no training is required to interpret an image shown on a screen or sound played from speakers. During testing participants were asked to use their dominant arm to mimic setup present in [15]. The test script used can be found in appendix E.

For phantom sensation

31 people were tested with 7 females and 24 males with ages ranging from 19 to 65 (Mean 24.68 and standard deviation 10.52) who all self-reported normal sense of touch in arms and hands. The test devised was roughly based on the two-point discrimination test commonly used in neurological examinations[18]. Whereas in the original two sharp points are applied in close proximity on the skin to test whether a participant can tell between them, in this test, a randomised sequence of motor activations was played over the motors with the participant being prompted to identify where they felt vibration from a set of options after each activation. These answers would then be compared to the actual vibration given and the total number of successes for each option recorded. The options given to participants were upper forearm (closest to the upper arm), lower forearm (closest to the wrist), middle (in between the two motors), and both. An additional option was given as “I don’t know” or “I’m not sure” to prevent participants from choosing an option they did not strongly identify with. The resulting test is 5 alternative forced choice. The time it took to set up this test and brief the participant allowed the temperature of the apparatus to match body temperature mitigating this as a disrupting factor. During initial testing it was found that the time to answer and record answers gave sufficient time between activations to avoid accidental inducement of apparent tactile motion. The activations take place in a random order which is stored by the testing program and is unseen by either the participant or the person responsible for administering the test. The activation types were:

- Both motors activate at the same amplitude.
- Upper most motor activated.
- Lower most motor activated.

Each of these different activations will occur fifteen times per participant. This test only assesses the specific middle position case of Equation 2 and does not test for 2 dimensional tactile effects. This was done as it was reasoned that if the tactile illusion could not be produced in one dimension, it would also not be produced in multiple dimensions. The phantom sensation tests were kept double blind in terms of the order of the effects generated as to prevent other senses from influencing results on the part of the participants and to prevent the reaction of the test administrator to answers doing the same

For apparent tactile motion.

10 people were tested with 2 females and 8 males with ages ranging from 21 to 22 (Mean 21.10 and SD 0.30) who all self-reported normal sense of touch in arms and hands.

For apparent tactile motion a test was created based of the test present in [5] where the SOA of two motors being played is increased from a point where it is clear that the motors are active discretely to a point where they appear to be activated simultaneously. The same test rig and setup as the phantom sensation test was used. The SOA was raised from 0 ms to 200 ms in 25 increments of 8 ms each. A stimulus duration of 160 ms was chosen to further mimic the test by A. Israr et al. The smaller number of tests was determined to not warrant any pauses. Participants were asked at each point to identify if the effect was discrete, simultaneous, or continuous along the arm with the resulting test being 3 alternative forced choice. The answers were recorded for each increment.

3.2.4 Software implementation of testing.

Both of the tests listed in section 3.2.3 were implemented in firmware-based C++ using the visual micro extension for the visual studio IDE. Arduino compatible Adafruit libraries were used to control hardware.

The phantom sensation test had to be kept double blind in terms of the order of the effects generated. To do this a shuffling algorithm [19] randomised the order of a preset array of tests. Basic GPIO functions were used to read the input from a pushbutton which would start the next vibration. The program was made to print the order of the test to the serial monitor only after all 45 vibrations had been played. These were then copied into a spreadsheet where they could be compared to the given answers and the number of successes for each type of vibration recorded. The SOA timings for apparent tactile motion were created by use of the on-board clock of the Arduino nano which at a speed of 16 MHz provided sufficient accuracy [20].

3.2.5 Completed Testing apparatus.

A system diagram of the final test apparatus is shown in Figure 6 below along with a photograph of it in use shown in Figure 7.

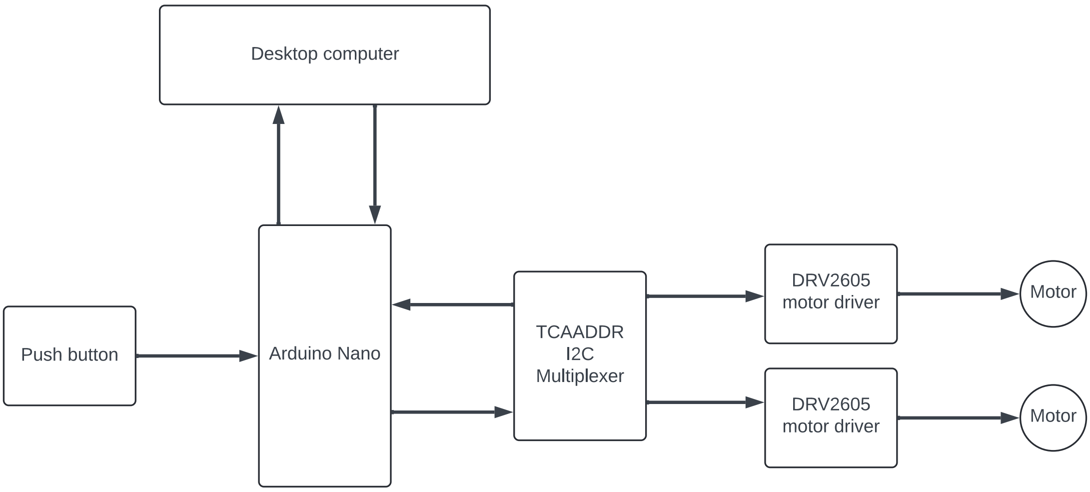

Figure 6: System diagram of final test apparatus.

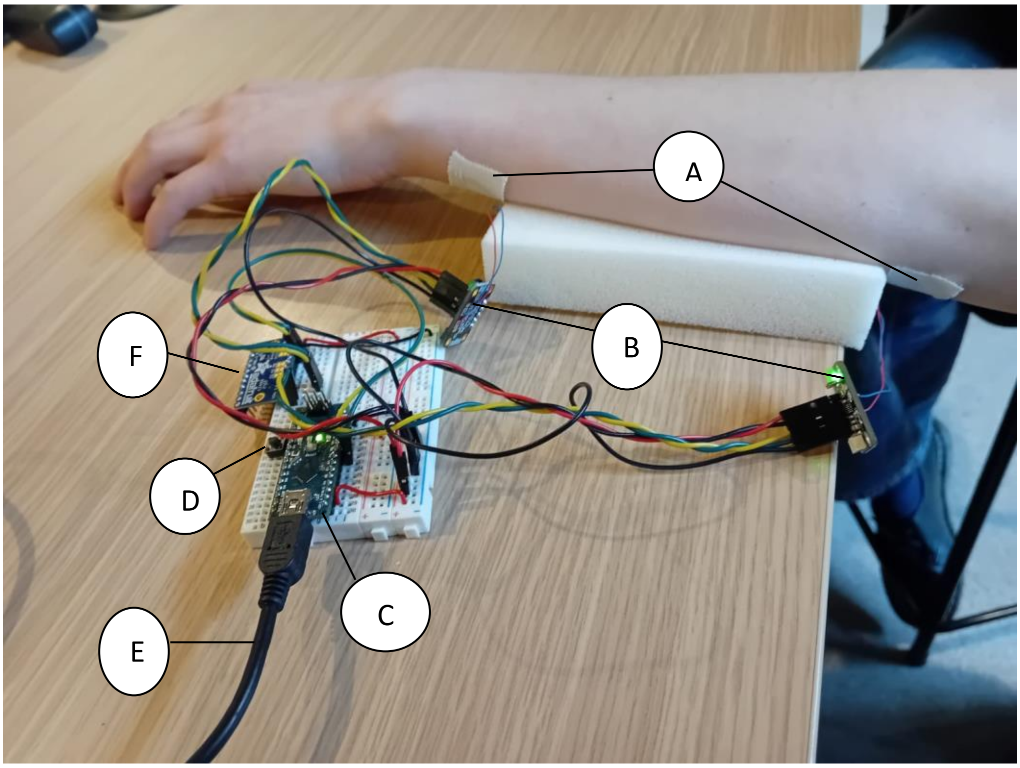

Figure 7: Test rig in use. A: Motors attached with tape. B: DRV2605 motor driver. C: Arduino Nano. D: Push button. E: USB connection to desktop computer. F TCA9548A I2C multiplexer

4 Results and discussion

4.1 Introduction

The results of the test can largely be split into two sections:

- Phantom sensation
- Apparent tactile motion.

However, both tests conducted showed results which suggests that the hardware tested is incapable of presenting tactile illusions with many participants not experiencing either illusion. This section will discuss the details of these results along with an analysis of the possible confounding factors which led to this outcome.

4.2 Results of the Apparent tactile motion and phantom sensation tests.

4.2.1 Phantom sensation

The phantom sensation test results show that, while it was possible to induce the illusion on multiple occasions, it was not possible to consistently produce the illusion even when keeping hardware, environment, and motor actuation consistent. Figure 8 below shows the results of the test conducted.

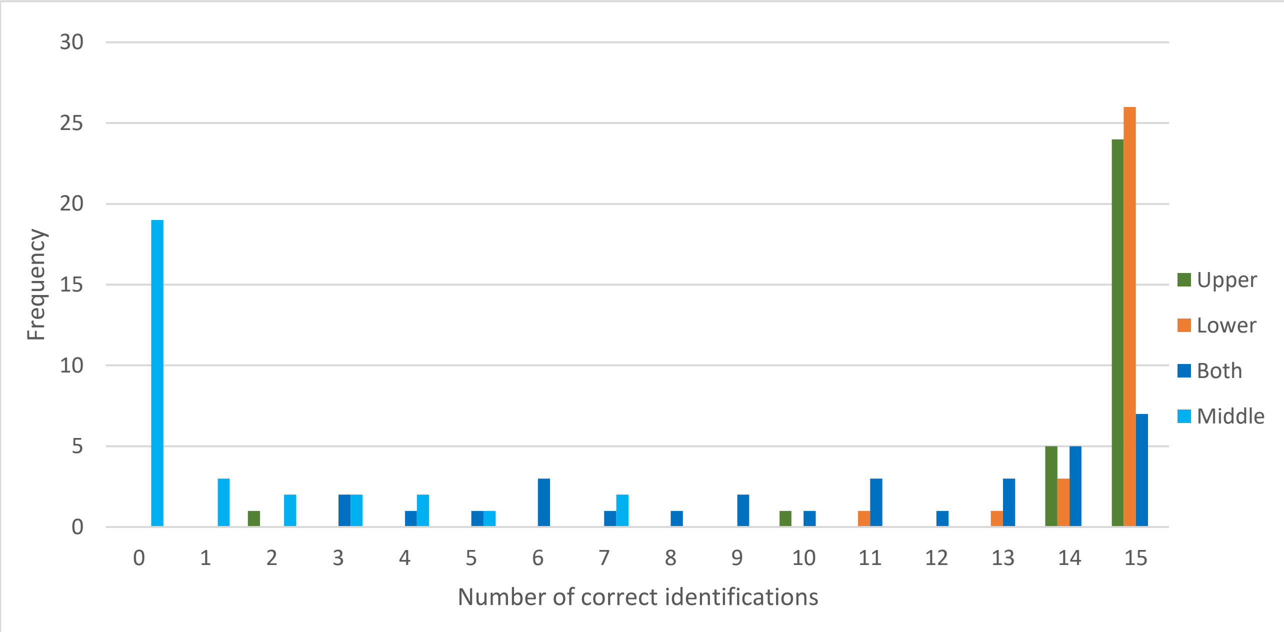

Figure 8: Frequency of the Number of correct identifications for each activation type.

Both upper and lower activations serve as the control and show how participants reacted to a real (rather than phantom) sensation. Almost all (~83.87% for Lower and 80% for upper) were able to identify which motor had been activated with 100% accuracy when no attempt at illusory haptic feedback was attempted. Even considering those who did not correctly identify all activations of upper and lower motors the minimum number of correct identifications were still high with results only dropping to 10 correct identifications for upper and 11 for higher (giving ranges of 5 and 4 respectively). The only exception to this is a single result in the upper forearm playback. This result was found to be anomalous as it was recorded when a participant was resting the upper forearm on a hard table beyond the foam. This overloaded the motor and prevented it from reaching the required vibrational amplitude. As such it is anomalous and can be ignored.

A basic measure of confidence in answers can be attained via inspection of the quantity of “I don’t know” responses. Even when given an option to express that they did not know what they were experiencing most participants chose not to use those options. Figure 9 shows the number of “I don’t know” responses per participant. From this it can be inferred that respondents were highly confident in their answers for both control tests with 100% of responds never giving “I don’t know” responses for upper motor activation and ~96.67% of participants never giving “I don’t know” responses.

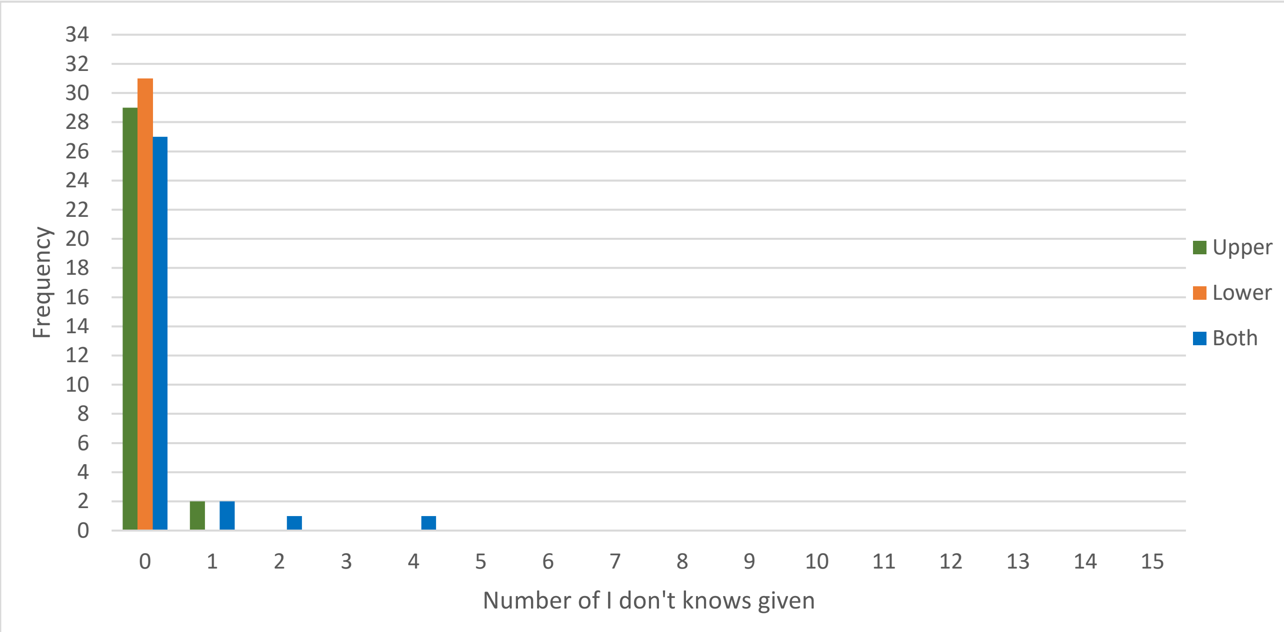

Figure 9: Frequency of Number of “I don’t know” given per activation type.

The upper results were found to be significantly associated with the binomial distribution given by B(15, 0.98) ($\chi^2 = 1.10$, d.f = 1, $p < 0.05$) while lower results were found to be significantly associated with the binomial distribution given by B(15, 0.98) ($\chi^2 = 3.43$, d.f = 1, $p < 0.05$). In both of these cases probability of successes was estimated from the respective samples.

Results show a much worse consistency in identification when both motors are activated at once. With participants exclusively identifying both motors in only ~22.58% of cases with the other ~77.42% spread across a range of 11 different values.

Participants identifying middle were experiencing the phantom sensation illusion and, while some were able to experience it on as many as half of all activations, the majority of participants

(~61.29%) were unable to feel the illusion at all. Even in those who could, no participant reported phantom sensations in more than half of motor activations.

Confidence when both motors were activated also dropped with ~87.10% percent of participants showing 100% confidence (no “I don’t know” answers). However, it can still be inferred that, despite having the “I don’t know” option, most participants were confident in their answers even if those answers were incorrect or illusory.

The “both” results were not found to significantly fit with the binomial distribution given by B(15, 0.72) (χ^2 = 32.17, d.f. = 3, $p < 0.05$). Likewise, “middle” results were not found to significantly fit with the binomial distribution given by B(15, 0.09) (χ^2 = 27.10, d.f. =2, $p < 0.05$).

4.2.2 Apparent tactile motion

The apparent tactile motion test shows results which are contrary to those presented in [5]. The results for this test are shown in Figure 10. Each SOA segment contains the response of all ten participants for that SOA value and the grey shaded region represents the range of SOA values for which A. Israr et al reported to induce apparent tactile motion (50 ms to 150 ms).

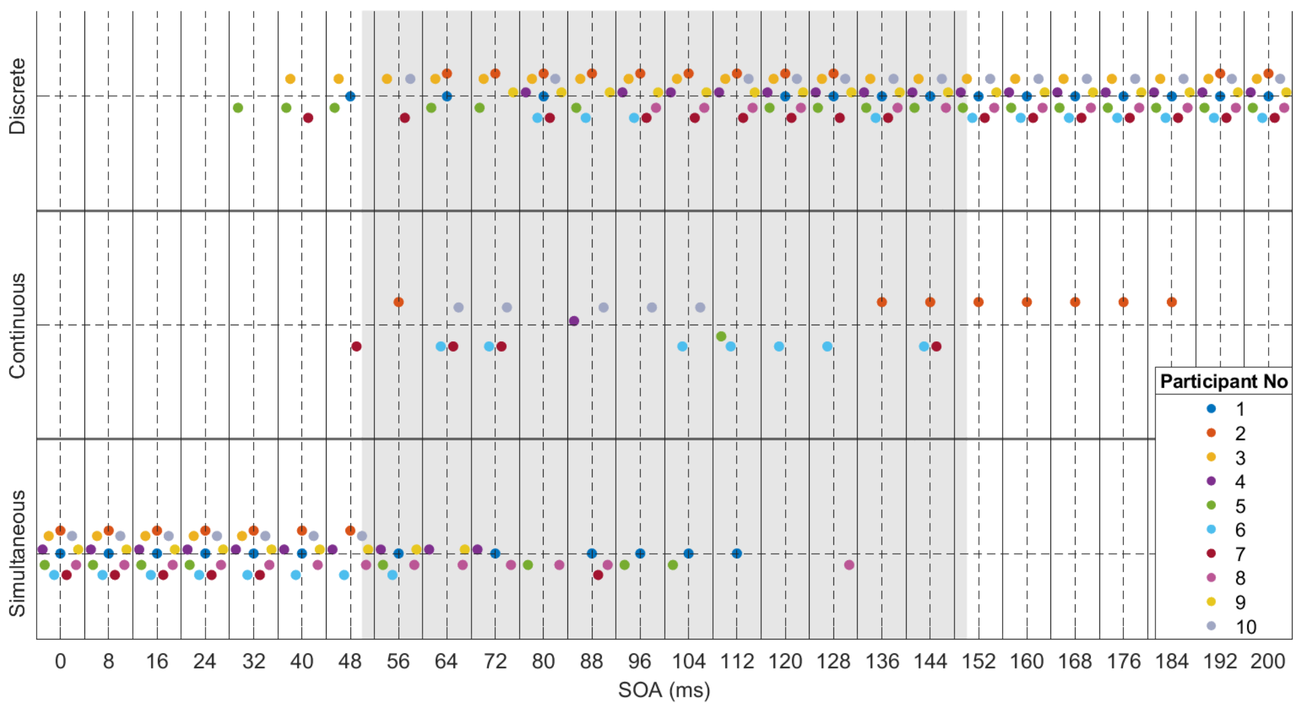

Figure 10: Results from apparent tactile motion test. Grey area shows acceptable SOA region as proposed by [5]

While in the paper a broad range of SOA values presented with an apparent tactile motion effect, the test carried out here shows gaps within that range. This included 40% of participants (Numbers 1, 3, 8, and 9) who did not experience the illusion at all. The results also show instances where apparent tactile motion was induced well outside of the averaged SOA range (participants 2 and 7) with participant 2 experiencing the effect up to 34 ms higher than the proposed maximum useable SOA and participant 7 experiencing the effect 8 ms below the minimum threshold.

Overall, the apparent tactile motion illusion presented in a low number of total observations (10.4%) and only a slightly higher number within the region described in literature (16.67%)

4.3 Discussion of results and confounding factors

Little if any of the literature discussed surrounding the implementations of haptic illusions report negative results of their work; because of this it is critical that the results here are thoroughly discussed.

4.3.1 Discussion of phantom sensations results

The results from section 4.2.1 heavily suggest that the hardware present in this experiment should not be used to induce the phantom sensation tactile illusion. This is because compared with the control, identifying when both motors were active and identifying the phantom sensation was unreliable especially since the majority of participants were not able to experience the illusion at all.

While it could be argued that this hardware could instead be used solely for non-illusory haptic feedback, these mixed results indicate that the effectiveness of said feedback could be hampered by the phantom sensation illusion. It is conceivable that confusion could occur where the discussed hardware is used to make a non-illusory haptic feedback system and yet phantom effects are still felt by users. This is especially true for situations where the actuators are not directly visible as the user would have no non-illusory visual feedback to aid in the distinction. In practice the consequences for such confusion could be dire as, in use cases such as that presented in [21], delays of even a few seconds can be the difference between life and death. Steps would need to be taken to mitigate the effects of these illusions. To this end the recommendations laid out by [13] could be taken in reverse with examples including non-simultaneous activation, non-optimum distances between motors, and removal of skin stabilisation. This matter is made far worse by the measure of participant confidence. Confidence measured was high even for activations with low identification accuracy. Users, if not given proper instruction or made aware of these illusions, will invariably identify strongly with even incorrect perceptions of stimuli.

For non-illusory vibrational haptic feedback, the chi-squared goodness of fit test suggests that participant accuracy can be modelled as binomially distributed with probabilities of successes around 98%. This can serve as a benchmark for further attempts to implement illusory haptic feedback and is also an important statistic to monitor when designing non-illusory systems for information critical environments. This analysis is useful because having a prediction for the probability of correct identification allows for redundancy to be built into any display non-illusory vibrational feedback to avoid situations of misinterpretation.

However, the same test finds that the same distribution cannot be applied to instances where both motors are activated simultaneously. This implies that either identifications of simultaneous activations are dependent on those which came previously, a change in probability of the success of identification occurs between observations, or a combination of both. Whether this difference in probability distribution is caused by a factor controllable but not accounted for in this experiment or is due entirely to human psychophysiology is unknown.

The study by A. Barghout et al [22] found similar results when testing in the same place with a similar actuator arrangement with only 10% correct identifications for a central phantom sensation compared to the 8.60% correct identifications present here. However, in its conclusions, this report did not consider this as a failure to produce tactile illusions, instead choosing to focus on the accuracy of participants in identifying non-illusory haptic feedback. If the goal of such studies is to develop illusion based vibrotactile displays, then it is essential to discuss the effectiveness of hardware to produce such illusions.

4.3.2 Discussion of apparent tactile motion.

The results of section 4.2.2 heavily suggest that this hardware should also not be used to induce apparent tactile motion due to this inconsistency in of illusions both between and in participant observations.

Once again, the fact that the illusions present in only some cases poses a risk to any implementation of a haptic feedback system which does not intend to use tactile illusions. The confusion which could be caused by this may be especially pernicious as, while meanings associated with singular phantom sensations can convey only intensity, the moving nature of the stimulus can erroneously convey both direction and magnitude. To make matters worse, perceived motion can even alter the perception of the last location of a stimulus (an effect known as representational momentum [23]).

Closer inspection of the replicated test [5] shows that, while participants did experience apparent tactile motion outside of the averaged values they were still within the maximum and minimum SOA values recorded for that duration suggesting that the apparent tactile motion was the effect induced (as opposed to implied motion [24]). However multiple participants experienced no illusions within this range suggesting that the average regions present are not appropriate as upper and lower bounds for guaranteed inducement for this hardware. That some experience apparent tactile motion while others do not imply factors beyond those controlled affecting the inducement of the illusion.

4.3.3 Potential confounding factors

This section discusses and assess the many factors which may have prevented the consistent rendering of tactile illusions.

Motors

Several elements of a motor's construction and performance could affect the chosen motor's ability to induce the required illusion however the most important factors can be found by a comparison to literature. When developing the tactile brush, A. Israr et al used specialised haptic vibrational tactor [5] which was designed to resonate within the frequencies that the skin is the most sensitive to (200-300Hz) [25]. However, the motors used in this report had linear frequency characteristics meaning that only when operating around the maximum rated voltage did these motors achieve frequencies in that range [26]. This has the effect of further reducing the impact of lower amplitude vibrations on illusions which is especially destructive to effects such as apparent tactile motion which are most easily evoked at lower frequencies [5].In contrast to this, there were many instances where non-speciality hardware was able to induce the desired effects. The differentiating factor is instead in the particular kind of low-cost motor, with many choosing to use linear resonance actuators (LRA) instead of eccentric rotating mass (ERM) motors[17, 27]. Analysis of this factor is further frustrated by some literature describing motor form-factor instead of motor type [22, 28] suggesting that type can be disregarded, while others emphasise the importance of motor type and discuss it at great length [9]. As a result, it is likely that the motors are at least in part responsible for the lack of effectiveness, however it is unlikely that the difference lies solely on this factor.

Motor drivers

The motor driver board used (DRV2605) used automatic overdrive and breaking as well as closed loop control to decrease the overall startup latency of the actuators attached to it [16]. This is especially useful to timing critical illusions such as the apparent tactile motion. Other studies have used audio equipment to interface with their hardware [5, 6, 8] especially when interfacing with motors with independent frequency and amplitude. Others still use direct pulse width modulation to control amplitude [27, 28]. The novel use of these motor drivers makes them suitable candidates for investigation as a confounding factor.

Padding

The tests carried out in this report deviated heavily from others in terms of whether padding was used. As recommended in the study by D. Alles [13] an attempt was made to reduce surface vibrations along the skin of the arm. Other studies investigating tactile illusions made no such effort [14, 22] while some have test apparatus which appears to contain padding and yet makes no mention of padding as a factor [28]. The previously discussed failure of [22] to elicit the phantom sensation illusion in a meaningful number of cases suggests that their lack of padding is a contributing factor. However, the tests detailed in section 3.2.2 considers padding as a factor while demonstrating the same results. Therefore, while isolating each vibration is important (as shown in the design of the C2 tactor discussed before) it may not, by itself, be entirely detrimental to the presentation of these illusions.

Visual cues.

While the orientation of the forearm in the test detailed in 3.2.2. attempts to control for visual cues by positioning the actuators out of view. Knowledge of position and number of actuators was unavoidable due to the setup methods and design of the test apparatus. This was deemed acceptable due to the tests being emulated, also not attempting to keep this information from participants [5, 22]. However, other studies have reported variation in the quality of presented illusions when inconsistent visual stimuli were applied [29]. While the disguising of actuator position and number could pose a significant challenge for skin attached haptic feedback systems, it may be necessary to improve the rendering of the discussed illusions. This is the most likely cause of the failure to induce apparent tactile motion as the lack of moving visual cues contradicts the stationary apparatus.

Training

Here, training refers to a period of time given to users to acclimatise to tactile illusions without recording of results. A participant is not considered trained if only verbal instruction is given. Those not given an official training period instead acclimatised during testing giving an overall larger error during initial rounds of testing, in which, said error decreased to a constant value [13]. This provides a reasonable explanation for the results presented in section 4.2.1. More specifically, it is a possible reason as to why the probability of success changes or why the observations made are dependent on each other; the probability changes as participants improve their ability to distinguish stimuli and the tests are dependent on each other as a subject's probability of success depends on the number of observations previously completed. This heavily suggests that training is the main confounding factor in the attempt to induce phantom sensation and that it is inappropriate to try and reduce levels of training in haptic feedback to those found in the use of audiovisual feedback methods. Literature is inconclusive on the effect of training on the performance of apparent tactile motion.

4.4 Summary

This report finds that the hardware used is incapable of consistently inducing the illusions required for rich haptic feedback using current methods.

Phantom sensation could not be reliably induced in any participant with only around 8% simultaneous activations identified as inducing the tactile illusion as opposed to an overall 98% accuracy in identifying a non-illusory control activation. These Non-illusory vibrotactile stimuli were able to be modelled using the binomial distribution B(15, 0.98) however simultaneously activated motor feedback could not be accurately represented using a binomially distributed model regardless of whether it was illusory. Many factors which may have influenced this outcome were discussed with the most likely cause being a lack of time given to training participants as well as visual cues inconsistent with provided stimuli.

While apparent tactile motion could be induced in some participants (6 of 10), it too could not be produced reliably suggesting that the ideal SOA region put forward in [5] may not be applicable to all hardware and environments. The fact that this particular illusion was induced in some but not in others adds weight to the idea of an extra confounding factor outside of those controlled in this report. The major factors contributing to this were also discussed with the most likely factor being solely inconsistent visual cues with further testing required to more thoroughly measure the impact of training.

Results were discussed in the larger scope of haptic feedback systems including the detrimental impact of accidentally induced tactile illusions in non-illusory vibrotactile systems. Such impacts largely involve the worsening of display quality and the exclusion of this display type from the consideration of information critical environments. Results were also compared to others produced by similar studies and comments were made on the conclusions drawn by said studies. Many other factors were considered as potential causes of the failure of this system including motors and padding.

5 Conclusions and future work

5.1 Conclusions

Tactile illusions are capable of providing a rich tactile interface with very few actuators even in sparse arrangements. There are diverse range of tactile illusions which can provide both stationary and moving sensation on many parts of the body. They can be used in multiple arrangements forming both one-dimensional and two-dimensional tactile displays when fixed to the body, attached to clothing and worn, or embedded in external devices. They can be combined to form high resolution tactile displays even when using only a small number of actuators. In previous literature their use has been described and modelled extensively using both threshold and suprathreshold psychophysical testing methods. In this report suitable tests were designed for both phantom sensation and apparent tactile motion. A test apparatus was created which controlled for:

- Skin stabilisation (padding)
- Amplitude of vibration
- Actuator placement and separation
- Actuator contract point
- Duration of activation
- SOA

Suitable off the shelf hardware was selected for the test and it's use justified.

The hardware was unable to produce results comparable with those shown by more specialized and, importantly, more expensive hardware. For phantom sensation, results showed that the effect could not be produced consistently enough to be useful in a full tactile display such as those shown in section 2.3. Results also indicate that the hardware used cannot produce apparent tactile motion as this effect could not be produced in every participant as was done in literature.

Factors effecting the hardware (including padding, motor selection, and how the motor was driven) were discussed, as well as factors that could affect the participants including training and visual cues. Training was also identified as a potential cause for the inability of the distribution of successes for simultaneous activation to be modelled binomially. For the phantom sensation test, a confidence in answer was also measured and discussed. As such both quantitative and qualitative analysis has been performed.

This hardware in its current state should not be used to elicit either phantom sensation or apparent tactile motion. This report explicitly controlled and accounted for a set of factors recommended by [13]. Analysis of the effectiveness of the hardware was performed instead of linking performance to factors outside of hardware. It also attempted to replicate the results present in [5] using off the shelf hardware. No other such work can be identified in literature, as such the work in this report can be considered novel.

5.2 Future work

The report tests the viability of vibrotactile illusions on inexpensive off the shelf hardware, however there are still many factors left unaccounted for. In future work tests should repeated with allotted time for training and chi-squared goodness of fit analysis reattempted to verify whether training is responsible poor fit. Further investigations could also test multiple different kinds of low-cost actuator under the same conditions to account for different motor characteristics.

Further statistical investigations of the distribution of error within participant identification of activation could also help to provide a measure of success when characterising potential hardware. I.e. if the error can be attributed to a certain distribution, then this could provide a way of comparing different devices by allowing comparisons of the different success rates that users experience when identifying stimuli.

Beyond user testing, if tactile illusions can be replicated, a universal benchmark needs to be created to test the accuracy and resolution of developed tactile displays as most literature currently lacks such a metric. This report proposes the use of input algorithms which replicated simple physics objects such as a ball on a slope.

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Appendices

A Project outline.

"Haptic" as a term refers to the sensation of touch, haptic technology (abbreviated to haptics hereafter) then is the use of technology to influence the sensation of touch. There have been many different approaches to implement haptics, including but not limited to:

- Kinaesthetic haptics.
- Skin deformation.
- Vibrational haptics.
- Haptic surfaces.

These implementations have seen a wide range of applications in various fields:

- Teleoperation – both in surgical and hazardous environments settings.
- Augmenting virtual reality (VR) environments.
- Medical rehabilitation

This project would attempt to create a low-cost version of a vibrational haptic interface in the form of a device which sits in the palm and vibrates to relay information.

Motivation

The goal for the project is a demonstration of high-resolution haptic interface for as low a cost as possible, both in development and construction. Many haptic devices such as the ones shown in and can cost hundreds, if not thousands of pounds per individual device.

Our main objective then, is to create a competent implementation of haptics which, due to it it's low development cost (under £175) will be accessible to a broader range of people and applications.

Overall aim and associated objectives

The overall aim of the project is to implement a hand-held device capable of generating high resolution vibrational haptic feedback while also staying as far under the proposed budget as possible.

The specific implementation of haptic feedback which will be used in this project leverages two psychophysiological phenomena: apparent tactile motion and phantom sensation. it will largely be based on the findings of the research done by A. Israr and I. Poupyrev in their paper on the "tactile brush" [5].

Due to the psychophysiological nature of this haptics implementation, it is also important to thoroughly test this device on multiple users during development to ensure that it works for the highest number of people possible.

Specific objectives of the project

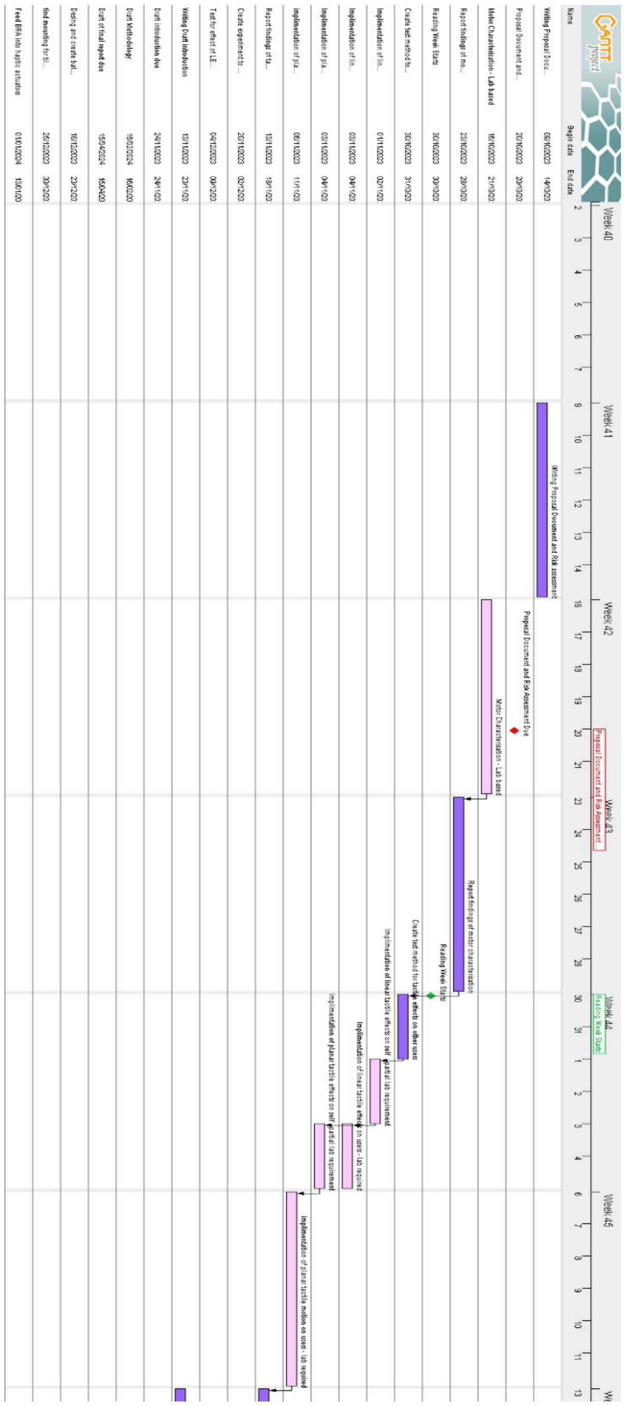
Below are the main actionable objectives of the project.

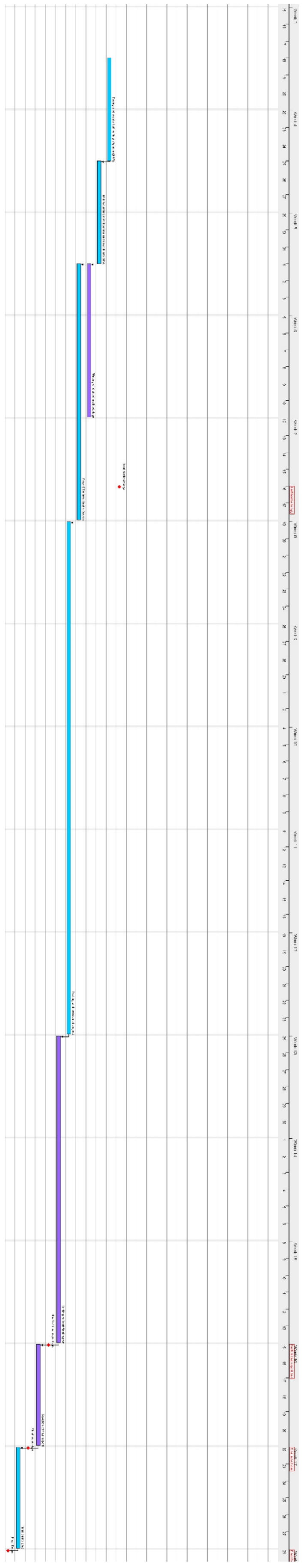
- Testing and implementation of low-cost vibrational motors in achieving the phantom sensation and apparent tactile motion.
- Testing and implementation of LEDs to reinforce haptic feedback with visual feedback.

- Development of the hardware capable of keeping said actuators in place while also carrying other components.
- Development of a simple ball-on-a-slope model which will give input to the haptic feedback.
- Application of tilt sensor as an input to ball on a slope model.
- Connection of programmed model to haptic device.

These will inform the proposed project plan listed below.

Project plan:





B Risk assessment

Risk assessment is a required appendix. Put here.

Laboratory Risk assessment form.

Date:	Assessed by:	Checked / Validated* by:	Location:	Assessment ref no	Review date:
19/10	Elliot Winterbottom		Labs.	001	

Task / premises:
Use of lab spaces in MECD and elsewhere.

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Using electrical equipment	Electrical shock	Users, others in vicinity.	- User must ensure that equipment has been PAT tested within the last twelve months (check PAT label). All equipment is inspected, and PAT tested annually. Any maintenance is to be carried out by trained staff only. (REF 1). - Before each use carry out visual inspection of electrical equipment and cable for any signs of wear, corrosion or damage before use. If faulty report item to the ALPI and remove from use. - Carry out all necessary precautions to ensure all cables; junction boxes; sockets and fittings are not damaged in any way and are safe to use. - Only use in suitable location i.e. flat, dry bench area away from combustible materials/substances. Ensure equipment is not at risk of damage by lab activities.	LOW	T
Use of vibrational motors for haptic feedback	White finger syndrome	Users of the vibrational haptic feedback.	- Must ensure that the amplitude of the vibrations remain small enough not to induce the syndrome. - Users must take regular breaks between tests. - Tests must be kept brief no more than 10 mins of actual stimulus applied.	Low	T
Use of vibrational motors for haptic feedback	Burns from vibrational motors or other parts of device in contact with skin.	Any user or test subject who will have motors fixed to them.	- Must ensure that motors used are small enough that they cannot generate enough heat to cause harm. - Must ensure current through any part of any device is too low to cause burns	Low	T

Risk Assessment Form of use of computer clusters study, areas, common rooms and multi occupancy offices.

Date:	Assessed by:	Checked / Validated* by: (3)	Location:	Assessment ref no	Review date:
Task / premises: The use of PC clusters, study areas, common rooms and multi occupancy offices. CAMPUS EMERGENCY CONTACT DETAILS: Security internal extension 69966 or external 0161-306-9966 users of FSE buildings are encouraged to store this contact number in their telephones. EMERGENCY SERVICES: If an incident requires ambulance, police or fire service dial 999 (9-999 internal) and follow up by calling Security as above.					

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Use of display screen equipment (DSE)	Repeated / Prolonged or incorrect use	All users working with computer workstations. Repetitive strain injuries, neck and back pain, eye strain and/or fatigue	Provision of an adjustable chair, adjustable screen height, suitable and sufficient lighting is maintained in each area. DSE signage detailing advice for correct use of the chair, screen and seating position are posted in each PC cluster and on Staffnet. There is on-line DSE user set up information signposted during the induction process. Staff complete this as part of department safety induction. Staffnet provides Wellbeing advice regarding staying healthy and comfortable when using PCs and laptops. Various external web sites provide advice e.g. www.posturite.co.uk/mobile-device-accessories	Low	A

Computer Use	Electricity: Electric shock, burns, fires, electrocution	All users working with computer workstations and electrically powered office equipment Personal injury – electric shock, electrocution and/or burns. Secondary injuries which may ensue	Electrical equipment is PAT tested regularly on a schedule. Tested items are labelled "Pass" and the expiry dated. Estates are responsible for PAT testing PC equipment in Estates managed PC Clusters. All users are advised not to interfere with plugs, cables or any device, especially when any equipment is connected to the power supply at induction. They are advised to report defective items to their manager/supervisor in the first instance. In PC clusters eating or drinking is not allowed to minimise the risk of spillage onto electrical equipment. Bottles of water should be kept closed when not in use and should be stored beneath desks to avoid spillage onto the equipment. All users receive, during the induction process, fire and evacuation awareness safety training and are asked to make themselves familiar with emergency procedures for the areas they visit.	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
			Personal emergency evacuation plans are in place as necessary for those requiring assistance.		
Moving around in, and to and from the PC clusters / study areas / offices	Trips, slips and falls any other injury which may occur in these locations	All users (normal working hours). Personal injury e.g. bruises, sprains and strains, slips, trips and falls (stairs, or tripping over objects), manual handling (e.g. PCs, desks, printer paper boxes)	Areas around computers must be kept free of trailing cables, floor areas are kept free from obstruction, adequate lighting is provided, and waste bins are supplied for rubbish. PC clusters, study areas and offices are inspected regularly. Stairwells and corridors are well lit.	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Lone working during normal working hours	Lack of or reduced access to first aid	Users of PC clusters, study areas or offices during low occupancy Personal injury and delayed medical attention	Avoid lone working and only use areas where there are other people within shouting distance. First aid support may be delayed if a person is lone working. Security can provide 1st aid and their contact number is on the rear of all University ID swipe cards and on the signage posted on doors to each PC cluster. Phone number is 0161 306 9966 Office users are made aware of this during safety induction sessions. For users with medical conditions that could be exacerbated by the delay of access to first aid the supervisor must seek the opinion of the person and if necessary the University Occupational Health service. A separate personal risk assessment may be needed.	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Lone working during normal working hours	Intruders	All users of computer clusters or offices who are lone working. Becoming the subject of violence or aggression – stress, panic and injury	Avoid lone working and only use areas where there are other people within shouting distance. Users should have phone access to Security staff and should save this number in their mobile phones. During incidents of unease or suspicious activities, users should immediately go to a safe location and report to Security staff on 0161 306 9966. Details should later be shared with the Education Support Office/Safety Office.	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Lone working during normal working hours	Lack of support in the event of a fire Fire, smoke inhalation, burns	Users of PC clusters and offices who are lone working. Confusion, becoming lost, delay in exiting in an emergency situation – smoke inhalation, burns, unconsciousness and death	The evacuation procedure for the buildings is part of induction; this includes fire action notices, evacuation notices, and routes out of building, types of exit mechanism, fire alarms (audible and visual) and assembly points. All users receive an induction at the start of their programme. The contact number for Security is on the rear of the swipe card, this information is highlighted in the building inductions and on signage placed on the door to the clusters. Phone number is 0161 306 9966 All occupants must leave the building as soon as they hear the fire alarm by their most direct fire exit to the assembly point, quickly and calmly and proceed to the nearest assembly point and telephone Security. During an evacuation, face coverings should be worn while transiting but distancing may be temporarily ignored, as the duration is very short. Once outside the building social distancing should be resumed.	Low	A

Date:	Assessed by:	Checked / Validated* by:	Location:	Assessment ref no	Review date:
			Working from home		

Task / premises: working from home.

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Working from home	Lone working	Home working staff Isolated	1. Please refer to the University Lone Working policy and guidance for more information 2. Please refer to the new University Working at Home guidance 3. Please refer to the new University Wellbeing Support website 4. Staff to remain in regular direct contact with line manager and colleagues via phone, Skype, Zoom, Slack or email	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Working from home	Poor posture, repetitive movements, long periods looking at DSE (display screen equipment)	Staff, students, visitors Back strain (due to poor posture). Repetitive Strain Injury (RSI) to upper limbs. Eye strain.	1. Please refer to the DSE policy, guidance and poster for more information on how to set up your workstation properly 2. Complete DSE self-assessment for guidance on how to set up workstation properly 3. Set up workstation to a comfortable position with good lighting and natural light where possible 4. Take regular breaks away from the screen 5. Regularly stretch your arms, back, neck, wrists and hands to avoid repetitive strain injuries. Refer to workstation exercises here 6. Set up a desktop working space where possible and try to avoid working on a laptop without a docking station	Low	A
Working from home	Stress / Wellbeing	Home working staff Psychosocial effects, Work / Life imbalance, Anxiety	1. Please refer to Stress Prevention and Management toolkit for policies and guidance 2. Please refer to new University guidance for Managing teams working from home 3. Please refer to Seven rules of home working published by AMBS 4. Regular contact meetings with manager and peers, Skype, Zoom, Phone 5. Define working hours, set a start & close daily routine, get dressed and prioritise your tasks. 6. Manager / Employee consultation, wellbeing focused.	Low	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Use of electrical appliances	Misuse of electrical appliance, faulted electrical appliance.	Home working staff Electric shock, burns and fire	1. All office equipment used in accordance with the manufacturer's instructions 2. Visual checks before use to make sure equipment, cables and free from defects 3. Avoid daisy chaining and do not overload extension leads 4. University IT equipment brought home should already be PAT tested 5. The domestic electrical supply and equipment owned by the employee is the responsibility of the employee to maintain 6. Liquid spills cleaned up immediately 7. Defective plugs, cables and equipment should be taken out of use	Med	A
Moving around the home office	Obstructions and trip hazards	Home working staff Slips, trips and falls causing physical injury	1. Floors and walkways kept clear of items, e.g. boxes, packaging, equipment etc 2. Furniture is arranged such that movement of people and equipment are not restricted 3. Make sure all areas have good level of lighting 4. Reasonable standards of housekeeping maintained 5. Trailing cables positioned neatly away from walkways 6. Cabinet drawers and doors kept closed when not in use	Med	A
Working from home	Fire	Staff Home Working Risk of burns, smoke inhalation, asphyxiation	1. In the event of a fire evacuate out of the building and call the fire brigade 2. All waste, including combustible waste, removed regularly. 3. Heaters located away from combustible materials and switched off when office is left unattended 4. Avoid daisy chaining and do not overload extension leads 5. Test smoke alarm routinely and replace batteries every 6-12 months 6. Please refer to fire brigade Home Fire Safety and Smoke Alarms	Med	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Working from home	High risk activities	Staff Home Working Personal injuries / accidents	1. Home working is restricted to the use of laptops, computers and low-power equipment which complies to < 42 Volts operation & < 3 Amps total current consumption and which cannot exceed > 40degC operational temperature 2. No practical hardware work must be undertaken which requires tools, power-tools, soldering or any other sources of physical or chemical hazard	Low	A
Working from home	Manual handling of items delivered to a home address Interaction with the delivery driver	Staff Home Working Personal injuries / accidents / infection	1. When ordering goods the intended recipient must first check the weight and dimension of the delivery. Only items below 25kg will be allowed to be delivered to a home address. If the goods is deemed suitable to be received at home please move onto step 2. 2. Ensure there is an ability for the delivered item/s to be left on the door step to prevent the need to engage with the delivery driver to maintain 2m social distancing. 3. Follow government's advice on general hygiene to protect against Covid-19 4. Use kinetic lifting techniques e.g. feet apart, load held close and in front of the body. If lifting off the floor, bend knees and keep the spine neutral. 5. Ensure there is a firm grip on the item whilst moving 6. Ensure trip hazards are removed on route from the front door to where the item is to be located. 7. Do not store large, heavy, fragile or cumbersome items at height (eg on high shelves or on top of cabinets/bookcases etc)	Low	A
Working from home	Illness related to Coronavirus	Staff Home Working Infected Self-isolation	1. For the latest advice please visit the National Health Service, Public Health England and the University coronavirus website. 2. All staff to declare sickness absence by completing the form available here. Emily Crawford will then inform your line manager that you are absent due to sickness 3. All staff to keep in touch and inform EEE of your expected return to work date (working from home) 4. If you do not have access to VPN or networked laptop, please contact Emily Crawford via email to add your absence manually	Med	A

Activity	Hazard	Who might be harmed and how	Existing measures to control risk	Risk rating	Result
Working from home	Accident / Incidents	Staff Home working Injuries from home working activities	1. If you suffer an accident / incident whilst working at home in relation to your workstation, please report the event to your line manager and the School Safety Advisor to complete an accident / incident form	Low	A

MANCHESTER
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C Risk register

Project Title:	Creation of low-cost haptics		Submission Date:	26/04/2024	
Student Name:	Elliot Winterbottom				

Project Risk	Severity			Potential			Score (Severity x Potential)	Mitigation Measures
	L	M	H	L	M	H	L=1, M=2, H=3	
Component delays		X				X	4	Oder components well in advance, try to order components from companies with low shipping times I.e. UK bases companies.
Phantom effects do not present			X			X	9	Plan alternative outcomes of project which allow for null results.
Component breaks / damage			X	X			3	Backup any software-based work and allow enough budget to reorder broken components.
Delays caused by inconsistent lab access	X					X	3	Plan weekly activities around allotted lab times and prep work in labs which can be done outside of it
Fall ill			X	X			3	Work given margins to account for time which may be needed to taken off.

Ethics approval required for user testing			X		X		6	Record no personalised data. Complete university provided checks to predict whether ethical approval will be required.

D. Code listing and results.

Both are included in the GitHub link below:

https://github.com/ElliotWinterbottom/Testing_Rig

E. Test script

Begin the test by informing the participant of the events of the test, tell them:

Test setup:

- I'm first going to outline the test procedure, if you have any issues or questions about what's going on or what something is doing, please ask me immediately.
- We are going to test the human perceptions of vibration.
- To do this I'm going to get you to put your arm face down on some foam before attaching motors at either end of said foam.
- I'll be attaching them with medical tape.
    - Please do not quickly move your arm once attached as the apparatus is delicate.
- To prevent your other senses from playing a part I'll ask you to wear some headphones which play white noise.
- As a participant I will need to record your age and your gender.
- Once this is concluded we'll begin the test

During the test:

TEST 1 – PHANTOM SENSATION

- Every time I press this (gesture) button a vibration will be "played" through the motors.
- Each vibration should last no longer than 3 seconds.
- After each vibration I need you to tell me where you felt the vibration. Please pick from these options:
    - Upper arm (the motor further up your arm)
    - Lower arm (the motor closer to your wrist)
    - Middle (you may feel the sensation in-between where the two motors have been placed)
    - Both (you may feel the sensation on both motors at the same time)
    - You're not sure (you can't pin down where you felt that sensation)
- Please give your immediate thought, do not deliberate on your answer.
- After each vibration I will record your answer.
- There is no "correct answer" to each part, I am interested in what you feel each time.
- There are 45 vibrations in total.
- We'll take about 1 minutes break every 15 or so vibrations.
- The test will take about **20** minutes.

TEST 2 – APPARENT TACTILE MOTION

- Every time I press this (gesture) button a vibration will be "played" through the motors.
- The vibrations should be very short, if they last for longer than about 3 seconds let me know.
- After each vibration I need you to tell me what you feel
    - Simultaneous - Both vibration motors activated at the same time.
    - Discrete - One vibration motor activated and then the other.
    - Continuous - a continuous stroking motion from one motor to the other.
-

Are you ok with the test procedure as it has been laid out?

Although this will not be recorded, is there anything that may affect the feeling in your arms or hands?

Are you ok with the data being gathered? (even though it is non identifiable I still think this is good to ask)