Developing A Grid Based Vibrotactile Device Producing Smooth Funneling on the Forearm

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Chapter 1

Introduction

Apparent motion is a phenomenon that is experienced when multiple distinct vibrations are applied in a sequential order onto the skin via actuators placed near each other. When done correctly the vibrations are perceived as one signal moving along the path formed by the actuators. Using these vibrotactile actuators in certain configurations on the body we can create complex vibrotactile motion paths on the skin using the apparent motion illusion. For example, in [7] a method was developed to allow for arbitrary paths to be generated on a person's back. This work was intended to enhance the experience of people watching films by matching certain patterns to visual cues. The vibrotactile actuators generally used for creating apparent motion are relatively cheap, do not consume much power, are easily replaceable and they are small. As such the actuators can be easily fitted on the forearm without greatly encumbering a person in their daily routine. The forearm is a prime location for an apparent motion capable device as the prominence of the forearm in our visual field lets us easily combine visuals with motion happening on the forearm while allowing more skin surface area to work with than the hands. In this work we will concentrate on smooth continuous apparent motion as many forms of motion are indeed perceived as a continuous experience. The motion remains constant in velocity during its duration. The motion will travel in straight lines in between actuators. We could use such motion in virtual reality (VR) or augmented reality (AR) to simulate an insect walking along the arm. It could also be used to convey direction information in navigation without even having to look at the forearm. As such we endeavor to create a three by three actuator grid device composed of three lines of actuators placed next to each other on the top, left and right side of the forearm. We choose these sides of the forearm as this is where traditionally people expect device interfaces such as a watch on the wrist area or a band to hold various devices. Smooth continuous apparent motion would allow us to feel motion between actuators despite the low resolution of only using nine actuators. To develop such a vibrotactile device for use in such situations as VR or AR and to prove its effectiveness we need to apply methodologies from the cognitive sciences to verify with experimentation.

To build a device capable of smooth apparent motion that can be placed on the forearm we must first ascertain that perceiving smooth apparent motion on the forearm is even achievable. The first issue is if the small subcutaneous differences in tissue and bone at certain areas of the forearm influence perception. We can divide the forearm's skin in roughly four parts (top, left, right, bottom). Each part of this skin is slightly different in sensitivity due to relative bone and muscle placement in the forearm. Consider a simple case of a motion that travels in a straight line with constant velocity over three actuators from elbow to wrist on one of these sides. It could be that the difference in sensitivity due to muscle and bone placement may lead to a difference in perception of how smooth the motion is depending on what part of the skin it travels over (see Figure 1.1).

A second issue is if the forearm's skin curvature might have influence on the perception of smooth continuous apparent motion. The forearm's skin curvature differs from area to area. At different locations travelling over the skin across the arm leads to different angles of curvature and distances.

Another consideration is if the perception of smooth continuous apparent motion is influenced by the proprioception of the forearm. It is rare that the forearm would stay in a certain stationary position for a long

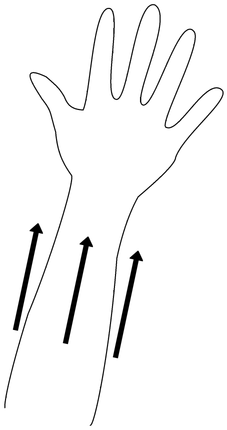


Figure 1.1: If smooth continuous apparent motion travels along the arm, would there be a difference in perception of smoothness depending on the side of the arm travelled?

time. The position of any proposed device on the forearm relative to the body's center is thus highly variable. This relative repositioning of the forearm along with subcutaneous changes due to muscles contracting or stretching and the forearm supinating or pronating may influence the perception of smoothness.

To create a workable parameter model for experimentation on these issues we look into the related literature in the next chapter. Then, in Chapter 3, we formulate our research aims and objectives and state research questions and hypotheses to investigate. Chapters 5 and 6 are respectively dedicated to an experiment investigating the issues of perception differences with apparent motion traveling along the arm and across the arm respectively. In Chapter 7 we present a third experiment combining proprioception of the forearm and apparent motion direction. Chapter 8 details a small study on perceiving motion direction in an uncontrolled environment. We conclude and present some directions that can be taken in future works in Chapter 9.

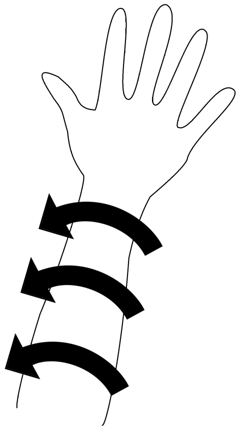


Figure 1.2: If smooth continuous apparent motion travels across the arm, would there be a difference in perception of smoothness depending on the degree of curvature of the forearm at different locations along the forearm?

Chapter 2

Related Literature

The following literature overview is divided into three categories: literature on temporal aspects of apparent motion (2.2), literature on spatial aspects of apparent motion (2.3) and literature on the relation between temporal and spatial aspects (2.4). Based on these categories we will discuss what findings can be applied to the open issues introduced in Chapter 1 in designing a forearm device (2.5). But first we will discuss some common techniques that are used when talking about apparent motion (2.1).

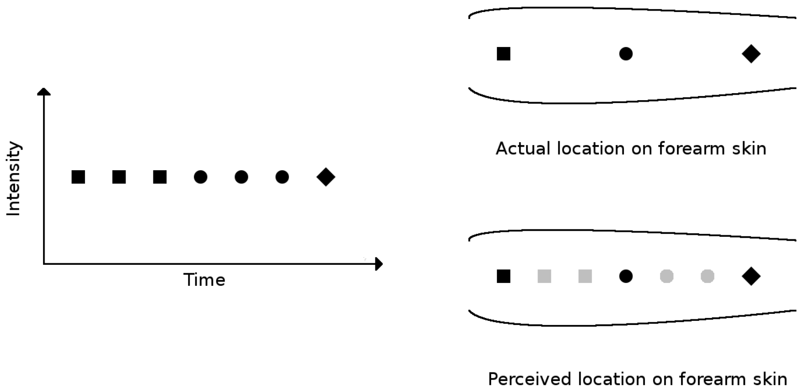
2.1 Apparent Motion Techniques

There are various techniques associated with the apparent motion illusion. One of the earliest methods discovered is *saltation* (also referred to as the *cutaneous rabbit illusion* in literature). It is elicited by a sequence of taps to one area of the skin followed by a sequence of taps to another area of the skin. If the taps are properly timed, this is then felt as if the taps travel in between the two areas at approximate equal distances, described by the original author as "if a tiny rabbit were hopping [. . .]" [4]. For a visual representation please look at Figure 2.1a.

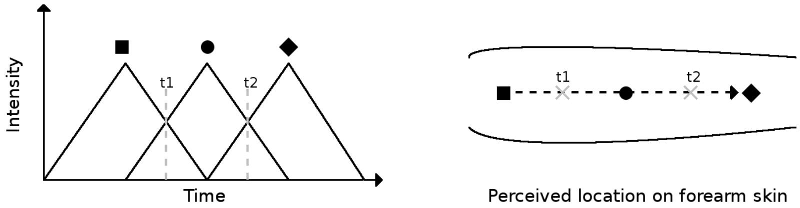
Another technique in use is *funneling*. Funneling is achieved by simultaneously vibrating two adjacent actuators. When the actuators vibrate with the same intensity the perceived vibration location seems to be in the middle in between the two actuators. When one actuator has a higher intensity than the other the vibration location is perceived closer to the actuator with the higher intensity. By varying intensity over time, with one actuator ramping up in intensity and one actuator ramping down, a sensation of the vibration moving can be created. Where saltation only allows for discrete taps, funneling allows for a smooth movement. See also Figure 2.1b.

A third technique is to combine elements from both saltation and funneling to create motion. The apparent motion is invoked by setting a certain amount of time in between activating subsequent actuators such that the end result feels as a singular motion. It resembles saltation on the fact that actuators only have one intensity setting but differs from saltation as an actuator only activates once in a sequence. Zhao, Israr, and Klatzky found that adding linear or logarithmic onset and decay to an actuator signal did significantly better than using no onset and decay [16]. Sometimes these onset and decay functions are added to help transitions from actuator to actuator where it then becomes funneling.

As was stated earlier we want to focus on smooth continuous apparent motion. In this regard saltation does not fit our needs. Funneling does allow for continuous apparent motion. Therefore we will use funneling to achieve the motion we want to create on the forearm. But no matter which technique is used, one of the most important factors is the sequencing of actuators in a timely manner given a certain inter-actuator distance such that it evokes the sense of movement of a singular source. Many of the early papers on the subject try to establish a range and relation for temporal parameters usable for apparent motion.



(a) An example of saltation. On the left we have the vibration signals spread over time. Three actuators are depicted by a square, circle and diamond respectively. The first two actuator vibrate three times and the last actuator vibrates once. On the right we see how this is perceived by a person. The black icons are the actual actuator locations but the second and third signal of the first actuator feel like they move in the direction of the second actuator and analogously between the second and the third. As such the vibrations feel evenly spaced along the path.



(b) An example of funneling. On the left we have a graph of three actuators that are sequentially activated with an onset and a decay in intensity, partially overlapping. This lets the apparent motion feel 'smooth' in transition from the first actuator to the last actuator. The times t1 and t2 on the left will be perceived at location t1 and t2 on the right.

Figure 2.1: **(a)** Saltation sequence and perceived locations. **(b)** Funneling sequence and perceived locations.

2.2 Temporal Parameters and Factors

Getting the timing right to elicit apparent motion is not a trivial feat. Actuators should not be activated too short as the vibration may not be registered and they should not be too long as the transition from actuator to actuator would become obvious. Moreover actuators should not vibrate with too long intermediate pauses from each other as that would lead to feeling discontinuities in the case of funneling and feeling irregular hops in the case of saltation. The length of time that an actuator is active is called the *duration of stimulus* (DOS) and the length of time in between the starts of subsequent activators is called the *stimulus onset asynchrony* (SOA). SOA is also sometimes referred to in literature as *inter-stimulus onset interval* (ISOI). The natural questions that arise are under which values of DOS and SOA apparent motion is experienced, if there is an interaction between the two parameters and if this is technique dependent. To this end Sherrick and Rogers performed an experiment to establish if the relation between SOA and DOS was the same for tactile apparent motion as it was observed to occur in visual apparent motion [14]. The most basic case of using only two vibrotactile actuators was used on the skin of the ventral thigh. Each actuator vibrated only once for a short DOS at a near constant intensity. It was found that the 'optimal' SOA value increased as the DOS value increased, comparable with data obtained from a study on visual apparent movement.

In a later study performed on the fleshy pads of the tip of the right index finger, using the same technique as Sherrick and Rogers, Kirman also confirmed the significance of both the SOA and DOS and their relation towards each other [8]. He observed that the optimal values of SOA across the DOS range tested were consistently lower than observed by Sherrick and Rogers which he believed to be due to the difference in diameter of the actuators used or the difference of the body location. The results of Kirman's experiments also indicate that while the relationship between DOS and SOA remains the same no matter if it were tested on the thigh or finger, the values for optimal SOA vary for different body parts when DOS are equal. In an experiment conducted by Hill and Bliss subjects were subjected to small air blasts with a duration of 10 ms each on the fingers. These air blasts would be delivered to either two or three of the possible 24 inter-joint locations of the fingers as the thumbs were excluded. As it was possible for the same location to be stimulated more than once in the same trial the method could be best described as saltation. Hill and Bliss found a relationship between DOS and SOA that agreed with earlier work but found that the variability of the ratings given by subjects was high. They posit that this may have been due to a varying definition of what consists in 'good' apparent motion [5].

One last temporal aspect that was investigated on the skin over the biceps by Niwa et al. was the necessary amount of time in between apparent motion paths all going in one and the same direction to be perceived as the correct direction with a certain accuracy. The actuators all had the same intensity and the vibrations could overlap in time depending on the SOA. Results show that the time between repetitions needed to be at least 400 ms to reach an accuracy of 95% [12]. This shows us that there is a time limit in between successive repetition of motion to be recognized. As the upper arm is quite similar in sensitivity to the forearm it could be assumed that the forearm would have a similar limit. This shows us that rapid repetitive motions will not be accurately perceived as such, but instead may introduce inaccuracies in the perception of motion direction of a person.

Thus we find that there is a relation between DOS and SOA to perceive apparent motion. This should then also be expected to be true for the forearm. Therefore, our device employing apparent motion on the forearm should use values of DOS and SOA that adhere to this relationship. Furthermore, the arm should not be exposed to rapid successions of apparent motion as the discrimination of the direction of motion will suffer. But what would be the correct choice of DOS and SOA for funneling on the forearm? The difference in sensitivity across sides of the forearm, the curvature of the forearm skin and the proprioception of the arm are problems that also include spatial factors. It could very well be possible that the DOS and SOA appropriate for funneling are dependent on spatial attributes of the forearm.

2.3 Spatial Parameters and Factors

As was stated earlier, the skin is not equally sensitive all across the body. The spatial sensitivity of the arm is greater than the spatial sensitivity than the back. This means that the minimum distance for which two points of contact are distinguishable is smaller on the forearm than on the back. As such, actuators can be put closer together and still be felt distinct when activated separately. As we want to limit the amount of actuators to a reasonable degree we must find what kind of limit there is to funneling and inter-actuator distance.

Cholewiak and Collins found that localization on the arm was best at the shoulder, elbow and wrist or the joint areas of the bottom of the arm [3]. This notion was later supported in [1] where Barghout et al. investigated the localization accuracy of subjects when exposed to either stationary signals or traveling signals through funneling on the top of the forearm. They found that localization was still best at wrist and elbow although using funneling reduced the difference slightly. Luckily this shows that the illusion still works even when the sensitivity is slightly different along the forearm but it also means that there is an influence on the perception accuracy of apparent motion near the wrist or elbow in comparison to the area in between the wrist and the elbow.

Cha, Rahal, and El Saddik performed a two point apparent motion test using funneling on the top of the forearm where motion travelled from elbow to wrist. Distances exceeding 80 mm broke the illusion and with distances closer than 20 mm subjects could no longer distinguish the two points. The best results were observed at 60 mm [2]. While designing an actuator configuration for the arm we then must take into account that distances smaller than 20 mm are not recommended, giving us a lower bound for the placement of actuators upon the skin.

A part of motion on the skin is of course the direction of motion. It is therefore also important to see if there are any limitations on what people can discern on the forearm in terms of direction of motion depending on the placement of actuators. Oakley et al. found that localization along the longitudinal axis of the forearm was significantly more accurate than localization along the latitudinal axis when using a grid of 3x3 actuators on the top of the forearm, placed centrally in between elbow and wrist [13]. Wilson et al. performed two experiments with an 8x8 ultrasonic actuator grid, a static localization test and a motion perception test. A subject's hand would rest on a table with the palm faced upwards and the hand open. The ultrasonic actuator grid would stimulate the hand from a certain distance above the hand, delivering air pulses to the palm. The average error of localization was higher along the longitudinal axis, showing a similar result as [13]. There was however no significant difference in score based on which direction the motion went [15].

From these works we can take that apparent motion near the wrist or elbow may feel more intense when using the same intensity levels for all actuators. However, given that the illusion still works and even mitigates the difference in perception of locations slightly we can use a uniform intensity setting in the direction along the forearm. Each other side of the arm (left and right) will most likely have similar negligible difference in sensitivity between elbow area, wrist area and in between. Furthermore, the direction of motion should not influence our design or actuator placement. We also know that a distance of 6 cm is an appropriate distance for apparent motion for using funneling on the top of the forearm and a usable range of 2 to 8 cm in which funneling still functioned to some degree. Yet, these papers hold no information on if this distance range also works for actuators arranged along the left or right side of the forearm or for motion along actuators arranged across the forearm.

2.4 Relation Between Temporal and Spatial

We have discussed temporal and spatial aspects separately until now, but there are also studies that combine both to answer problems where the relation between the two may play a role in the results. We know that different body parts lead to different appropriate values for both DOS and SOA. To obtain a range of SOA suitable for apparent motion Israr and Poupyrev performed a study comparing similar apparent motion patterns on both the top of the forearm and the back using vibration patterns where each actuator in the pattern vibrates only once with a constant intensity. The results showed that the effect of DOS on SOA was significant, agreeing with Kirman, Sherrick and Rogers, and showing that the effect of the location was also significant. The SOA space for the forearm was found to be smaller than that of the back under all tested conditions. The authors argue that this comes from the greater spatial resolution that the forearm possesses in comparison to the back. The range of SOA was around 50 to 80 ms at a DOS of 120 ms and 60 to 100 at a DOS of 240 ms. The varying of frequency and intensity of actuators did not lead to a significant change [6]. This gives us a first indication of what combination of DOS and SOA could work on the forearm.

Kirman examined if the shape and type of motion had any impact on the SOA values at which good apparent motion is perceived by delivering constant intensity vibrations in a grid of 15 x 15 actuators on the four fingers excluding the thumb. A variety of spatiotemporal vibrotactile patterns were tested: moving dots and lines, rotating lines, and expanding squares, boundaries and holes. He found that shape and type of motion had little to no impact on the DOS and SOA for which good apparent motion was reported [9]. This bodes well for not having to vary settings to allow for different types of motion on the forearm, simplifying the requirements of the hardware and software necessary.

Kohli et al. used three rings of five equidistantly spaced actuators around the upper arm. For three different DOS values with three SOA values each the ability of subjects to differentiate four different patterns was tested (Up, Down, Clockwise, Counter-clockwise). Overall subjects had little difficulty distinguishing the patterns [10]. In this experiment as well the direction of apparent motion had no meaningful impact. It would seem therefore that the direction of the motion would not be an influencing factor in experimentation.

In summary changing the intensity and frequency of actuators or the direction of motion does not significantly influence the relation between DOS and SOA. These factors shall therefore not be considered further. It seems that the forearm is generally suitable for rapid apparent motion where the DOS remains around 120 and 240 ms. The associated SOA range lies between 50 and 100 ms. This gives us an appropriate parameter space and relation for both DOS and SOA to start with on the forearm. For funneling the SOA is always half the DOS and choosing correct parameter values for smooth apparent motion using funneling is thus dependent on choosing the right DOS. This follows the relationship between DOS and SOA established in [6] for the forearm. In our device design SOA will thus be a factor derived from the employed DOS and does not have to be further considered. But the issues introduced in section 1 can still not be answered.

2.5 Open Issues in Using Funneling on the Forearm

To create a device capable of funneling on the forearm we need to identify the parameters and their value ranges involved with perceiving a smooth transition. When it comes to motion traveling along the arm over the top of the forearm there is much known already. Given the body of work presented we now have a parameter space established for funneling along the top of the forearm. The DOS appropriate for apparent motion on the top of the forearm lies around 120 and 240 ms and with funneling the SOA value is always half of the DOS value, so differing SOA do not have to be considered. The inter-actuator distance should stay between 2 and 8 cm. However, this does not necessarily hold for the other sides of the arms. Research on the relation between the arms sides and the DOS parameter values appropriate for smooth funneling is lacking. Yet there is no reason to believe it is not possible to create similar funneling on the other sides of the forearm. There are probably differences in sensitivity between differing sides due to muscle placement, bone placement and differences in concentration of nerve cells sensitive to vibration. But it is not shown if these differences are large enough to impact the perception of smooth funneling. Therefore the first experiment of this thesis needs to compare the perception of funneling for certain DOS on the top, left and right side. Given that the sides of the arm are relatively close together the DOS values that need to be investigated will also be centered around 120 and 240 ms. We will opt for 60, 120, 180, 240 and 300 ms to test a range of DOS allowing for a bit a leeway on either side of the range that works for on top of the forearm as it might be that the best smoothness occurs there for other sides. The inter-actuator distance will be held at 6 cm as this was an optimal distance for on top of the forearm according to [2]. With this experiment we identify possible differences in DOS ranges appropriate for smooth funneling along the arm depending on the side of the arm.

Also lacking in the literature was examination and discussion of the the forearm's skin curvature. Works that have an actuator setup which (partially) wraps around the arm such as [10, 12] did not use funneling and even then assumed apparent motion would work over the curved surface. It is not known if the skin's curvature across the forearm has influence on the perception of smooth funneling. Therefore a second experiment is necessary to determine if the smoothness of funneling is affected by skin curvature for a range of DOS values constructed around optimal values found in the first experiment. It is reasonable to assume that the optimal DOS values for smooth funneling around the forearm would lie around the same range of under 300 ms as the general area of skin tested varies little from the first experiment. Given the general circumference of the forearm the inter-actuator distance will still tend to be in between 2 to 8 cm.

The results from these two experiments will give us insight into the perception of smooth funneling in two major directions on the forearm. We can then use this to test perception of motion direction under various different forearm positions relative to the torso in a third experiment. Because although motion direction was not important when pertaining to the relation of DOS and SOA or the classification of direction in the literature the tests were done using only a single positioning of the arm.

Chapter 3

Research Aims and Objectives

The aim of this research is to investigate if smooth funneling can be achieved on the forearm under numerous conditions. We investigate experimentally the issues of possible differences in perception of funneling smoothness based on the side of the arm and due to the forearm's skin curvature. The data acquired from these experiments will then be used to do a follow up experiment where we will investigate if perception of funneling smoothness is influenced by the proprioception of the arm relative to the torso. Lastly, we explore performance of apparent motion direction classification in a less controlled environment. Using the information from these experiments we will make design suggestions for further devices that wish to use funneling on the forearm. To achieve this aim:

1. We analyzed available literature to identify temporal and spatial parameter spaces usable for funneling on the forearm. From the literature we summarize that the DOS and SOA are related and that for good apparent motion the SOA should be about half the DOS. To feel smooth funneling along the forearm on the top the DOS should be around the 100 to 200 range. The distance between actuators should be between 2 and 8 cm. The vibration intensity of the actuators and direction of the apparent motion do not influence the perception of apparent motion and do not have to be regarded. The research is lacking on if these values are also appropriate for motion along the forearm on the left and right sides or for motion going across the arm over the right, top and left side.
2. We will build a prototype device that can deliver funneling motions through 9 actuators on the forearm using the restrictions and directions identified from the literature study.
3. We will design a within subjects experiment that uses the prototype to acquire data on if a difference in the side of the forearm leads to a difference in perception of funneling smoothness at 60, 120, 180, 240 and 300 ms DOS.
4. We will design a second within subjects experiment that uses the prototype to acquire data on if the forearm's skin curvature influences perception of funneling smoothness. The values of DOS will be guided by the results from the first experiment.
5. Using the information gathered from the two experiments we will design a third within subjects experiment to test the effect of proprioception and motion direction on the perception of motion direction.
6. Lastly, we will do a more informal experiment in which the prototype device is worn by participants while walking and being distracted by the environment, testing motion direction while allowing free movement of the arm.

Given the subject matter we want to study the following three research questions:

Question 1 (Q1) What is the influence of the top, right and left side of the arm and DOS on the perception of funneling smoothness at an inter-actuator distance of 6 cm?

Question 2 (Q2) What is the influence of the skin curvature at three different locations of the forearm spaced 6 cm apart and DOS on the perception of funneling smoothness?

Question 3 (Q3) What is the influence of the proprioception of the forearm and direction of apparent motion on the perception of motion direction for optimal DOS values identified by answering Q1 and Q2?

For Q1, Q2 and Q3 each we can define three null-hypotheses discussing the two independent variables. For Q1 these would be:

Hypothesis 1a (H1a) There is no significant difference in perception of funneling smoothness between the top, right and left side of the forearm.

Hypothesis 1b (H1b) There is no significant difference in perception of funneling smoothness between 60, 120, 180, 240 and 300 ms DOS on the forearm.

Hypothesis 1c (H1c) There is no significant interaction effect on the side of the forearm and DOS in perception of funneling smoothness.

And analogously for Q2:

Hypothesis 2a (H2a) There is no significant difference in perception of funneling smoothness between the three locations with differing skin curvature of the forearm.

Hypothesis 2b (H2b) There is no significant difference in perception of funneling smoothness between DOS values.

Hypothesis 2c (H2c) There is no significant interaction effect on location of the forearm and DOS in perception of funneling smoothness.

Lastly for Q3:

Hypothesis 3a (H3a) There is no significant difference in correct perception of motion direction between the six different positions of the forearm.

Hypothesis 3b (H3b) There is no significant difference in n correct perception of motion direction between apparent motion directions.

Hypothesis 3c (H3c) There is no significant interaction effect on location of the forearm and apparent motion direction in correct perception of motion direction.

Chapter 4

Hardware Implementation

To perform the experiments as described in the research aims we need a prototype device capable of driving a set of 9 actuators and capable of producing funneling using those actuators. For this we can use the device developed in [11]. This device mainly consists of a Wemos D1 board with an ESP 8266 microprocessor. This board allows up to 16 outputs that can be altered with *pulse-width modulation* (PWM) to control the amount of voltage given to connected devices. Since there is currently rarely any need to drive more than 3 actuators at any one time for the purposes of our prototype this board is powerful enough. The board also allows for communication via Wi-Fi with other devices. The board is small and compact and could be strapped onto the back or the upper arm to allow for mobility. An image of the Wemos board can be seen in Figure 4.1 on the left side, next to an extension to which the actuators are connected.

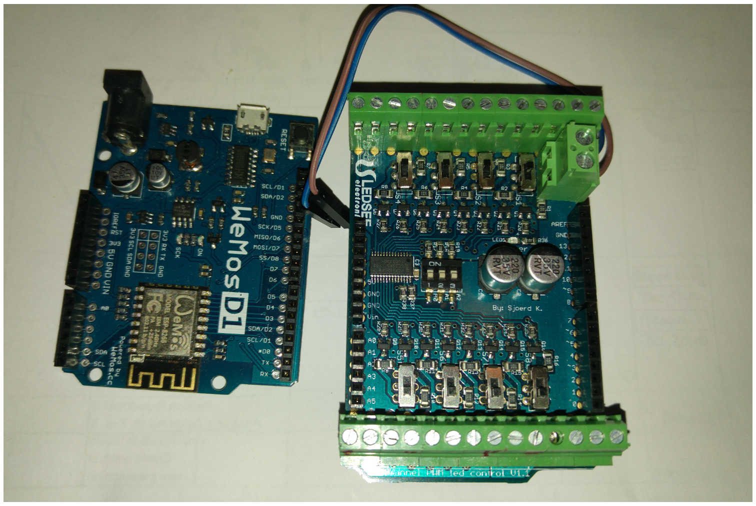


Figure 4.1: The Wemos board on the left, allowing for Wi-Fi communication and an extension for the Wemos Board that can be attached on top of the Wemos board. All actuators are then attached to the ports on the extension board.

The device does not inherently support funneling, but it does have a command that creates a ramp effect for a single actuator. This command takes an identifier for the actuator, a starting intensity value percentage, an ending intensity value percentage and how much time (DOS) the ramp effect should take in milliseconds. Using this command and sequencing them with the right timing and intensities we can create a funneling sequence. An example of a funneling sequence would then be:

$$F(1, 100, 0, 100)$$

$$F(2, 0, 100, 100)$$

$$wait(100)$$

$$F(2, 100, 0, 100)$$

$$F(3, 0, 100, 100)$$

The first two commands will be executed near simultaneously with less than a millisecond difference, creating a fade from actuator 1, which ramps down, to actuator 2, which ramps up. Then we wait for actuator 2 to ramp up fully before sending the next commands. Then we create a fade from actuator 2 to 3 to complete a funneling sequence. Such a sequence can be sent from devices that can connect via Wi-Fi to the Wemos D1.

As for the model of actuator we have chosen for an *eccentric rotating mass* (ERM) vibration motor from Precision Microdrives, see also Figure 4.2 for an image. The diameter of the round motor is 10mm and the height is 3mm. It has an operating voltage of 3V and a maximum frequency around 200Hz. This frequency is more than enough to be felt on the arm with a comfortable margin. By controlling the amount of voltage supplied to the actuator we control the frequency of the actuator. The size of the model allows to easily fit 9 actuators on the forearm with distance in between.

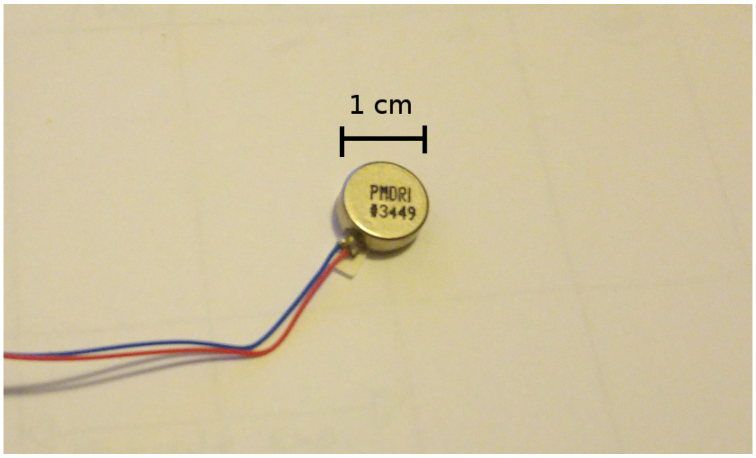


Figure 4.2: An ERM vibration motor from Precision Microdrives. The diameter is 1 cm across allowing for easy placement of 9 actuators on the forearm.

Chapter 5

Experiment 1: Difference in Perception of Funneling Smoothness on Different Sides of the Forearm

In the first experiment we investigate the issue if funneling traveling from elbow side to wrist side is perceived differently depending on which side of the forearm it is felt. From the literature we concluded that using the values of 60 to 300 ms DOS would be a good range for creating smooth funneling motion on the forearm. Based on this and research question Q1 the goal for this experiment is self evident.

(Q1) What is the influence of the top, right and left side of the arm and DOS on the perception of funneling smoothness at an inter-actuator distance of 6 cm?

5.1 Goal

The goal of this within subject experiment is to obtain insight on if the side of the forearm (top, left, right) influences the perception of funneling smoothness for different values of DOS (60 to 300 ms).

5.2 Setup

Nine vibrotactile actuators will be placed on the left forearm using sports tape, three on each side. The left forearm is chosen as the right arm and hand will operate a computer mouse. We do not expect a difference in ability to perceive funneling smoothness between the forearms due to the handedness of a person. On the top, left and right side on the middle of the forearm an actuator will be placed. As the length of forearms differ from person to person we chose the middle point of the forearm as an anchor so that between subjects we focus our design as much on the same area of the forearm as possible. This middle point is determined by measuring the forearm length from elbow crease to the wrist joint. The other two actuators are spaced 6 cm towards the elbow and 6 cm towards the wrist respectively. The 6 cm distance is based on the results of [2] where they found that at a distance of 6 cm funneling felt smoothest under varying speeds. This absolute distance was chosen as we want to compare our subjects under the same distance condition. The actuators on the left and right side of the forearm are placed by following the bone structure of the ulna and the radius. This leads to a variable distance between the sides depending on the circumference of the forearm. However, the placement as such does enforce that the left and right side consistently follow the bone structure of a subject. The bone structure of a person does not vary that much and so we can compare the areas around the same physical landmarks consistently.

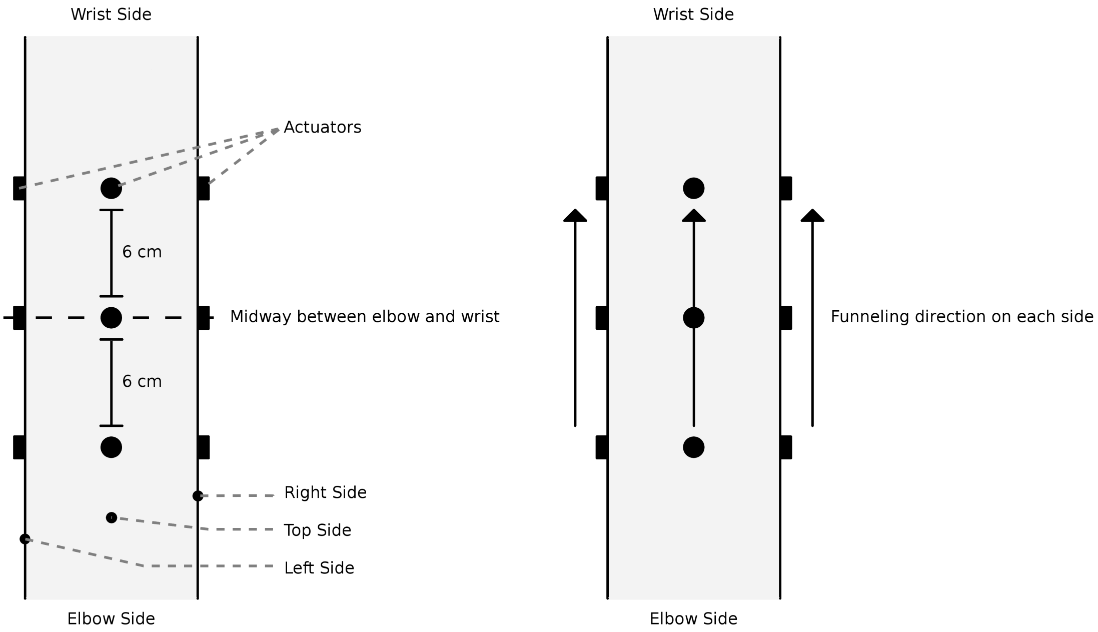


Figure 5.1: Actuator placement and funneling direction in Experiment 1. The actuators are placed on each of three sides (top, left and right) on the left forearm. Each actuator will be placed 6 cm from each other along the arm on each side.

The motion will travel from the actuator closest towards the elbow to the actuator closest towards the wrist on either the top, left or right side in a straight linear motion (see Figure 5.1). We do not consider the opposite direction as the related work showed that it does not influence the DOS and SOA appropriate for apparent motion. The forearm will rest in a neutral position, without supination or pronation. The hand will rest on the desk and the forearm will be free of contact with the desk, while the elbow will rest on an arm rest. See Figure 5.2 for a photo of a participant in the experiment.

The actuators are driven by a Wemos D1 board with custom software loaded to accept string commands over a WiFi connection. For a more in depth view of the Wemos board and the software we refer to [11]. The string commands are sent from a computer that runs a program that guides subjects through the trials. A computer mouse is connected to the computer to interact with the user interface of the program. Headphones are connected to the computer to play white noise during the trials to mask the sound of the actuators vibrating. We have the following variables:

Independent variables Forearm Side, we test three sides of the forearm:

- Left
- Top
- Right

The other independent variable is DOS, with values of:

- 60 ms
- 120 ms
- 180 ms

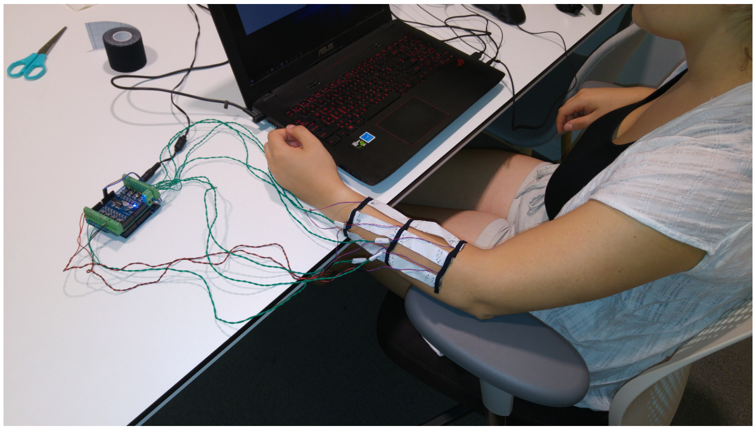


Figure 5.2: A person participating in Experiment 1, the hand rests on the table so that the actuators stay free from the table. The actuator distance is preserved by the white strips so that for each participant the inter-actuator distance is always 6 cm.

- 240 ms
- 300 ms

Dependent Variable The perception of funneling smoothness.

Experiment Design The experiment is done with a within subjects design. Each participant is exposed to all conditions and the conditions are repeated multiple times throughout the experiment. As we have three forearm sides and five DOS values, there is a total of 15 conditions. Each condition is repeated ten times during the experiment leading to 150 trials. The experiment exists of a practice session of 15 trials followed by three sessions of 50 trials. The trials are presented in a completely randomized order, meaning that all 150 trials are randomized and then distributed over the three sessions. The judgment of funneling smoothness during a trial is done with a two-alternative forced choice where subjects answer with either *yes* or *no* on if the motion felt smooth.

5.3 Process

First the subjects will be explained that they are going to experience a series of vibration signals delivered to the arm that will move over the arm from elbow to wrist on one of three sides. For each trial they have to judge the smoothness of the vibration signal. The subject will be asked to sign a consent form containing textual explanation of the process and the subject's rights while also being verbally informed of the right to stop at any time without giving a reason. Then we will record the age and gender and we will measure the forearm length. Afterwards the actuators are placed on the left forearm. Fifteen minutes is allocated for preparation and recording age, gender and measuring forearm length. When the actuators are placed the subjects will sit behind a desk before the computer with their left hand placed on the desk but leaving the forearm free of contact. There will be a computer in front of them with a program guiding them through the trials that will be controlled with a mouse. First all the actuators will be tested in a sequence where they are clearly felt separate from each other to verify if all actuators are in working order. Then the subject is explained with a scenario that smooth motion constitutes as a sensation that moves unbroken across the forearm. Subjects will be notified to not try to judge the presented sequences during the trials based on total stimulation length or perceived intensity and that they should try to judge purely if the sequence feels as a stimulation moving smoothly and without feeling gaps in the vibration. After this the subject will go through the trials. During each trial in a session a command is sent to the Wemos which then performs one of the sequence conditions. After the subject has felt the sequence the subject will choose either yes or no on the question if the motion was smooth and only then can they continue to the next trial. With an estimate of five seconds per trial total time for the trials will be 12,5 minutes. In between the sessions a break of four minutes will be instigated where the subject is encouraged to move their arms in an effort to remain comfortable. After the last session the actuators will be removed from the forearm and the subject will be informed as to the purpose of this particular experiment. The subject can ask questions or discuss, and is thanked for their participation. Five minutes is planned afterwards for informing the subject on the nature of the experiment and for further discussion and questions. In total, the entire experiment lasted approximately 40 minutes per subject.

5.4 Participants

30 participants took part in this experiment. Of the 30 participants 18 were male and 14 were female. 22 of the participants indicated to be right-handed, 4 left-handed and 4 mixed-handed. Forearm length ranged from 21 cm to 27.5 cm. Participants were not compensated for participating in this experiment.

5.5 Analyzing Results

The results will be analyzed using two-way repeated measures ANOVA. This will be done with the SPSS software package for statistical analysis. The raw data from the experiment will be pre-processed by adding all trials per condition per subject and calculating the proportion of yes answers out of ten. This gives us a data set with fifteen proportion values per subject.

The hypotheses H1a, H1b and H1c are all stated as null-hypotheses indicating no significant main effects or interaction effects. As we want to test for difference in perception of funneling smoothness along the sides of the arm we expect that there is a significant difference of perception between the sides of the arm, which would mean we reject H1a. We do not expect that this sensitivity is so different that all the DOS values are inappropriate for smooth funneling on the left and the right side. We do expect that if there is a difference between sides this may express itself more for higher DOS as subjects would get more time to process.

(H1a) There is no significant difference in perception of funneling smoothness between the top, right and left side of the forearm.

(H1b) There is no significant difference in perception of funneling smoothness between 60, 120, 180, 240 and 300 ms DOS on the forearm.

(H1c) There is no significant interaction effect on the side of the forearm and DOS in perception of funneling smoothness.

5.6 Results

When viewing the results in Figure 5.3 we can see that there are some differences in perception rate between the sides. In fact, there was a significant difference between sides ($F_{2,29} = 4.336$, $p < .05$). However for the lower values of 60, 120, and 180 ms the ratio of perception of smoothness follows the same trend among all three sides. It is when DOS increases to 240 or 300 ms that the perception of smoothness deviates more between sides with the left side having a noticeable drop at 240 ms. Indeed, there is a significant interaction effect between the side of the forearm and DOS ($F_{8,29} = 1.99$, $p < .05$). Meaning we reject hypothesis H1c. This also means that the main effect of the side must be put into context of this interaction. Post-hoc analysis of the simple effects over the various levels of DOS revealed the significant differences in mean ratios

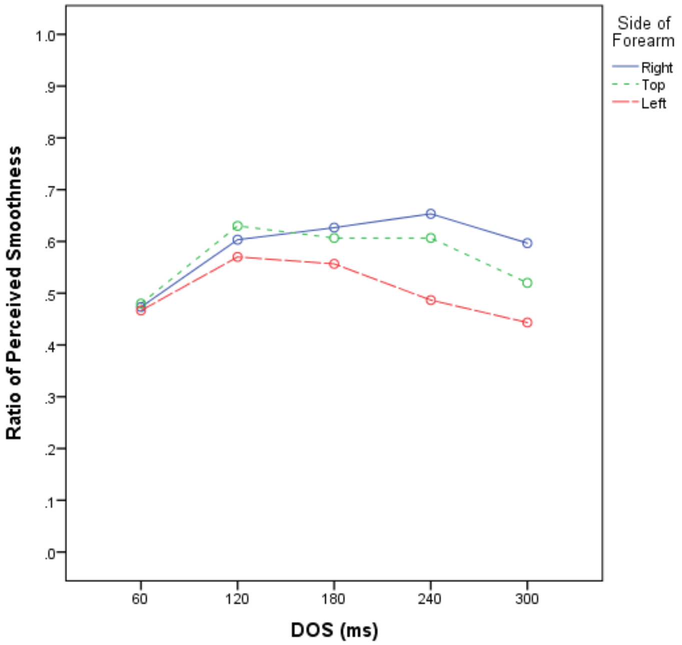


Figure 5.3: Results from Experiment 1 on if the side of the arm on which the funneling takes place influences the perception of smoothness for certain DOS. The perceived smoothness is a mean ratio of *yes* answers out of ten total answers over all subjects. The left side performs worse as DOS increases compared to the top and right side of the left forearm.

Table 5.1: Significant Simple Main Effects For Sides of the Forearm Over DOS

DOS	Side 1	Side 2	p
240 ms	Right	Left	< 0.01
240 ms	Top	Left	< 0.05
300 ms	Right	Left	< 0.01

as shown in Table 5.1. We can see that the significant differences always occur between the left side and the other two sides at higher DOS values. There was no significant differences between sides of the arm up to 180 ms. It is also interesting to see that the perception rate on the left side at 240 ms is about the same as 60 ms, at 0.487 and 0.467 respectively. The values ranged between 0.433 for the left side at 300 ms and 0.653 for the right side at 240 ms.

5.7 Discussion

It seems that the relative sensitivity of the side of the forearm has an increasing influence on the perception of smoothness as the DOS increases. Intuitively this makes sense. As the DOS value increases, so will the total time of exposure to vibrations. With more time and exposure a person might then be able to better localize the individual vibrating actuators. The difference in sensitivity in the sides of the forearm may come from the neutral position that subjects' forearms were the arm rested at the elbow and wrist on support structures. The added contact on what was essentially the left side of the forearm may have had an effect of increased sensitivity due to slight stretching of the skin. Also in general the ulna is more pronounced under the skin than the radius due to the biceps which may have led to a resonating in the ulna that may disturb the perception of smoothness. The performance at 60 ms and from 240 ms onward shows us that these values of DOS are not really useful for smooth linear funneling. The differences between sides at 60 ms are minimal and it is possible that it is too short a time to register what happens. In open discussion with subjects afterward multiple subject indicated that with the shorter trials it felt that the actuator near the wrist would not vibrate. As this is the last actuator to vibrate in a sequence we suspect that by the time a subject can register that movement is taking place between the first two actuators the actuator near the wrist is already done vibrating, making the sequence feel incomplete. At a performance of around 60 to 65% at best this is not really tenable for applying smooth funneling to pure haptic notifications. If the smoothness of the funneling would be critical to distinguish a haptic signal from another then it would be interesting to explore certain variables such as distance and intensity that have been constant here to examine if the perception ratio can be improved for funneling along the arm. The results do indicate that testing above 240 ms DOS will not be beneficial going forward so in Experiment 2 we do not test for 240 ms DOS. We can conclude that the side of the arm and the DOS both influence the perception of funneling smoothness when the DOS is of a value of 240 or higher. For values between 120 and 280 there should be no large discernible difference in perception ratio.

Chapter 6

Experiment 2: Difference in Perception of Funneling Smoothness Due to Skin's Degree of Curvature

In the previous experiment we tested funneling motion traveling along the forearm from elbow side to wrist side on the left, right and top side of the forearm to bring o light possible differences in perception of funneling smoothness. When apparent motion travels along the forearm in a straight line, generally there is not a drastic change in curvature over the length of the path. But if vibrations would be employed across the forearm instead of along the forearm this curvature angle becomes relatively large. This may influence perception of funneling smoothness. The curvature angle varies at different points of the forearm, as such we have chosen three points along the forearm in this experiment. In the Research Aims we asked the following research question:

(Q2) What is the influence of the skin curvature at three different locations of the forearm spaced 6 cm apart and DOS on the perception of funneling smoothness?

Then, the goal of this experiment is quite clear.

6.1 Goal

The goal of this within subject experiment is to obtain insight on if the curvature of the forearm (elbow-side, center, wrist-side) influences the perception of funneling smoothness for different values of DOS (60 to 240 ms) on three locations of the forearm.

6.2 Setup

Nine vibrotactile actuators will be placed on the left forearm in an arrangement as shown in Figure 6.1. The placement is the same as in Experiment 1 but the vibration motion will travel across the arm from the right to the left. We have chosen to take the same procedure in placement of actuators to ensure that between subjects the arc that is described by the actuators on the skin is generally the same even if distance is not. For people of normal stature and muscularity the inter-actuator distance would still lie in the range of 2 to 8 cm. We could argue that if this placement does work for most people and produces smooth funneling then a fixed distance smaller than that will too as long as it stays in range of 2 to 8 cm. If it does not work then it would become interesting in a third experiment to investigate under what parameters we could achieve

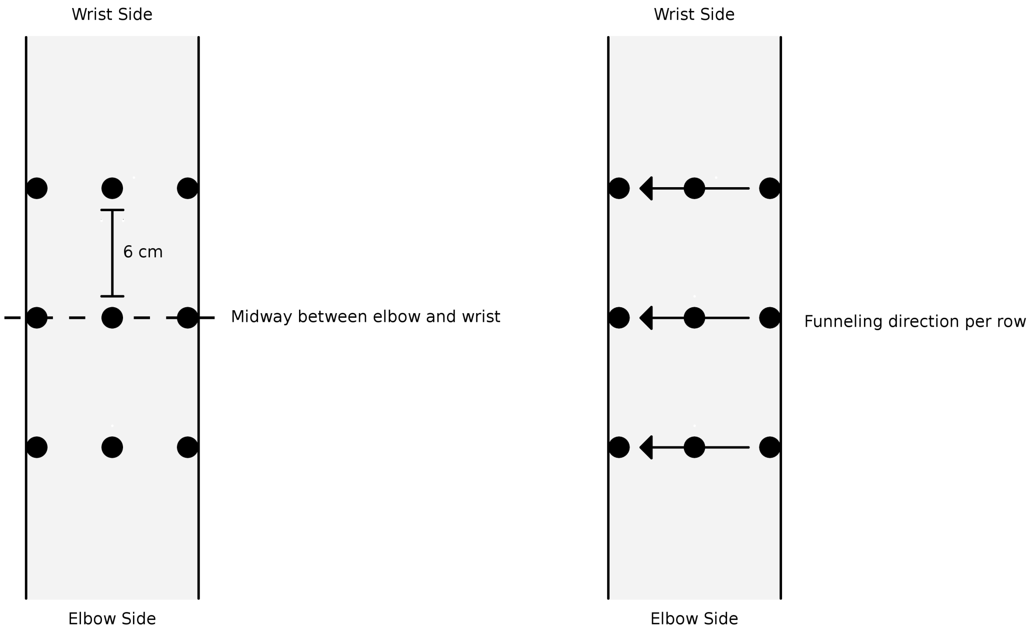


Figure 6.1: Actuator placement and funneling direction in Experiment 2. The actuators are placed in rows on the left forearm. The row distance is 6 cm.

smooth funneling. The forearm will rest in a neutral position, without supination or pronation. The hand will rest on the desk and the forearm will be free of contact with the desk, while the elbow will rest on an arm rest. The actuators are driven by the same Wemos D1 board as in Experiment 1. The string commands are sent from a computer that runs a program that guides subjects through the trials. A computer mouse is connected to the computer to interact with the user interface of the program. Headphones are connected to the computer to play white noise during the trials to mask the sound of the actuators vibrating. We have the following variables:

Independent variables Forearm location, we test three locations across the forearm:

- Wrist side
- Center side
- Elbow side

The other independent variable is DOS, with values of:

- 60 ms
- 120 ms
- 180 ms
- 240 ms

Dependent Variable The perception of funneling smoothness.

Experiment Design The experiment is done with a within subjects design. Each participant is exposed to all conditions and the conditions are repeated multiple times throughout the experiment. As we have three locations on the forearm (Wrist, Center, Elbow) and four DOS values, there is a total of 12 conditions. Each condition is repeated ten times during the experiment leading to 120 trials. The experiment exists of a practice session of 12 trials followed by three sessions of 40 trials. The trials are presented in a completely randomized order, meaning that all 120 trials are randomized and then distributed over the three sessions. The judgment of funneling smoothness during a trial is done once againg with a two-alternative forced choice where subjects answer with either *yes* or *no* on if the motion felt smooth.

6.3 Process

First the subjects will be explained that they are going to experience a series of vibration signals delivered to the arm that will move over the arm from right to left on one of three locations. For each trial they have to judge the smoothness of the vibration signal. The subject will be asked to sign a consent form containing textual explanation of the process and the subject's rights while also being verbally informed of the right to stop at any time without giving a reason. Then we will record the age and gender and we will measure the forearm circumference at the points where the actuators will be placed. Afterwards the actuators are placed on the left forearm. Fifteen minutes is allocated for preparation and recording age, gender and measuring forearm length. When the actuators are placed the subjects will sit behind a desk before the computer with their left hand placed on the desk but leaving the forearm free of contact. There will be a computer in front of them with a program guiding them through the trials that will be controlled with a mouse. First all the actuators will be tested in a sequence where they are clearly felt separate from each other to verify if all actuators are in working order. Then the subject is explained with a scenario that smooth motion constitutes as a sensation that moves unbroken across the forearm over the skin. Subjects will be notified to not try to judge the presented sequences during the trials based on total stimulation length or perceived intensity and that they should try to judge purely if the sequence feels as a stimulation moving smoothly and without feeling gaps in the vibration. After this the subject will go through the sessions with breaks in between. After the subject has felt the sequence the subject will choose either yes or no on the question if the motion was smooth and only then can they continue to the next trial. With an estimate of five seconds per trial total time for the trials will be 10 minutes. In between the sessions a break of three minutes will be instigated where the subject is encouraged to move their arms in an effort to remain comfortable. After the last session the actuators will be removed from the forearm and the subject will be informed as to the purpose of this particular experiment. The subject can ask questions or discuss and is thanked for their participation. Five minutes is planned for this final part. In total, the entire experiment will last approximately 35 minutes per subject.

6.4 Analyzing Results

The results will be analyzed using two-way repeated measures ANOVA. This will be done with the SPSS software package for statistical analysis. The raw data from the experiment will be pre-processed by adding all trials per condition per subject and calculating the proportion of yes answers out of ten. This gives us a data set with twelve proportion values per subject.

The hypotheses H2a, H2b and H2c are all stated as null-hypotheses indicating no significant main effects or interaction effects. We predict that the subject will be able to perceive smooth funneling on the skin across the forearm based on trends in a pilot test on apparent motion around the wrist and that there is no inherent discontinuity in skin sensitivity around the arm. To what rate remains to be seen. It is likely that again an interaction effect may occur between the location of the arm and the DOS since the inter-actuator distance is variable between the locations. A funneling motion with a certain DOS going across the arm at elbow-side will travel a longer distance than using a funneling motion with the same DOS going across the forearm at wrist-side. But, in general the inter-actuator distance will be less than 6 cm meaning that the 'gaps' to bridge will be smaller. As such we suspect that performance will be better than in Experiment 1.

(H2a) There is no significant difference in perception of funneling smoothness between the three locations with differing skin curvature of the forearm.

(H2b) There is no significant difference in perception of funneling smoothness between DOS values of 60, 120, 180 and 240 ms.

(H2c) There is no significant interaction effect on location of the forearm and DOS in perception of funneling smoothness.

6.5 Results

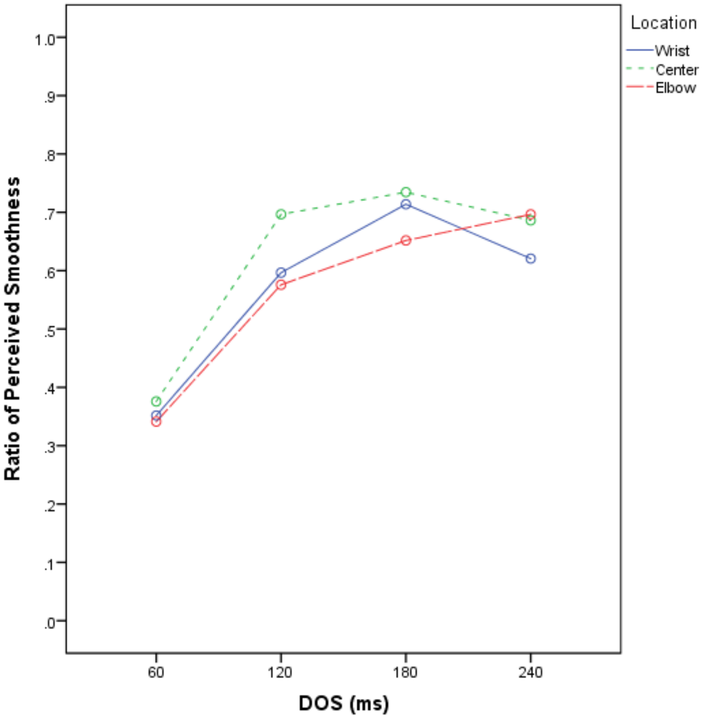


Figure 6.2: Results from Experiment 2 on if the curvature of the skin at certain locations of the forearm influences the perception of funneling smoothness for certain DOS. The perceived smoothness is a mean ratio of *yes* answers out of ten total answers over all subjects.

It is clear to see from the results as shown in Figure 6.2 that there is a performance difference at 60 ms DOS compared to other values of DOS over all the locations tested on the skin. Indeed there was a significant main effect of the chosen DOS ($F_{3,28} = 9.992$, $p < .0001$), meaning we reject hypothesis H2b. There was no significant difference based on skin location and the curvature of the skin in performance. Just as in Experiment 1 the optimum performance was at the values of 120, 180 and 240 ms with 180 ms showing the best performance. There seems to be a slight decline in performance for the skin near the wrist and the center of the forearm at 240 ms compared to 180 ms while there is a slight increase in performance for the elbow location.

6.6 Discussion

The results show that the most promising range of DOS for smooth funneling lies in between 120 and 240 ms. This is the same as in Experiment 1. It is quite clear that for a device that must produce smooth funneling on the forearm using a DOS of 60 ms will not function. As with Experiment 1 here also some participants mentioned that some trials felt so short that it did not feel like a motion or the motion felt incomplete. The significant lesser performance at 60 ms compared to other values of DOS is most likely a reflection of this. The slight increase in perception of smoothness at 240 ms for the elbow location as opposed to the slight decrease for the wrist and center location may be due to the difference in amount of muscle directly under the skin. In Experiment 1 the perception of smoothness was arguably the best at 180 ms DOS. In Experiment 2 180 ms DOS once again showed the best perception of smoothness. It is clear that going forward in Experiment 3 setting the DOS to 180 ms will give participants the highest chance of perceiving smooth funneling. In general the range of 120 to 240 ms has been shown to perform the best in terms of smoothness perception ratio. This then seems to agree with the effective ranges found in the literature for apparent motion on the upper arm. It seems likely that the between the upper arm and forearm the sensitivity to what is felt as smooth funneling will be the same. This would allow future possible vibrotactile devices to incorporate the upper arm as well as the forearm in one design. This has the advantage of no different hardware being necessary and could extend the lengths of motion possible considerably.

Chapter 7

Experiment 3: Influence of proprioception on the perception of movement direction.

Up until now we have only concerned ourselves with the notion of smoothness of motion and if various locations on the arm could support smooth funneling motion. From Experiments 1 and 2 it followed that for 180 ms the location did not significantly impact the rating of a motion as smooth. In these two experiments the direction of motion was not taken into account as the literature suggests that it would have no impact on the perception of motion on the forearm. However, the arm is a highly mobile limb and can take many orientations and configurations with respect to our torso. The proprioception of the arm is formed by information from striated muscles, tendons and joints and then combined with information from the vestibular system to create an internal reference frame of body position. Positioning, supination and pronation of the forearm may all have influence on the association of the direction felt from smooth funneling. This leads us to the following research question:

Question 3 (Q3) What is the influence of the proprioception of the forearm and direction of smooth funneling motion on the perception of motion direction for 180 ms DOS?

7.1 Setup

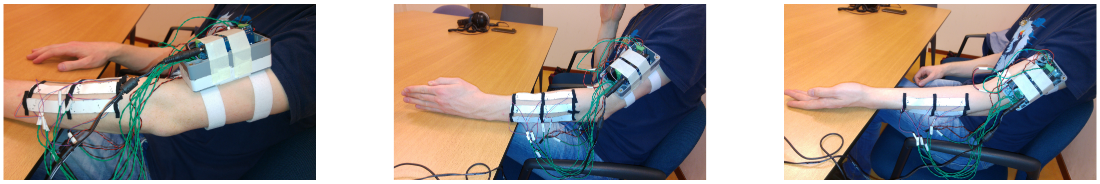
For the experiment the participant will be seated on a desk chair behind a table. Placement of the actuators will happen in the same manner as they did in Experiment 1 and 2. The Wemos board was mounted on the upper arm in preparation of the walking experiment in an uncontrolled environment that followed whenever it was possible. More details are in the next chapter.

During the experiment the participant can experience four different motion directions in six different forearm positions. The participant is asked to associate a location with a motion direction on the forearm and then verbally acknowledge this. If they were to feel a motion they were told to associate with the location 'Left' then they should say left. The position and rotation of the forearm may confuse the participant in a wrong association by thinking they felt a different motion direction on the forearm. The direction motion and the forearm position are therefore our independent variables.

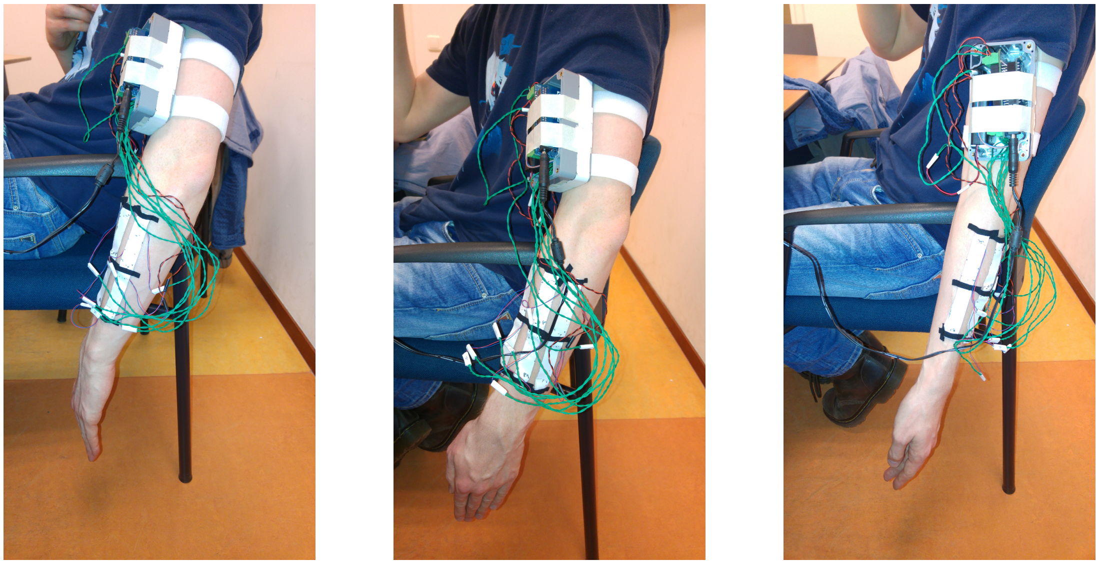
Independent Variables The forearm positions used in the experiment are:

1. Hand flat on table, forearm prone, palm downwards on table (TP).
2. Hand flat on table, forearm neutral (TN).

3. Hand flat on table, forearm supine, palm upwards on table (TS).
4. Hand hanging straight down along torso, forearm prone, palm facing behind (HP).
5. Hand hanging straight down along torso, forearm neutral, palm facing body (HN).
6. Hand hanging straight down along torso, forearm supine, palm facing front (HS).



(a) TP (b) TN (c) TS



(d) HP (e) HN (f) HS

Figure 7.1: The six arm positions used in Experiment 3. Images a to c show the arm positions on the table with the forearm prone, neutral and supine respectively. Images d to f show the arm hanging down alongside the body with the forearm prone, neutral and supine respectively.

The abbreviations are based on forearm position (Table or Hanging) and rotation (Prone, Neutral or Supine). Therefore 'hand on table, forearm prone' is TP. From here on out they will be referred to with abbreviations. These six configurations cover some of the more common forearm rotations and forearm positions in our daily lives while allowing to switch around relative directions when compared to absolute directions. For example having the forearm supine may let the subject associate a leftwards going motion on the forearm as going to the right due to the rotation of the forearm.

The directions of motions are:

1. The middle column, from elbow side to wrist side (Front).
2. The middle column, from wrist side to elbow side (Behind).
3. The middle row, from inside of the forearm to outside of the forearm (Left).

4. The middle row, from outside of the forearm to inside of the forearm (Right).

They can also be seen in Figure 7.2.

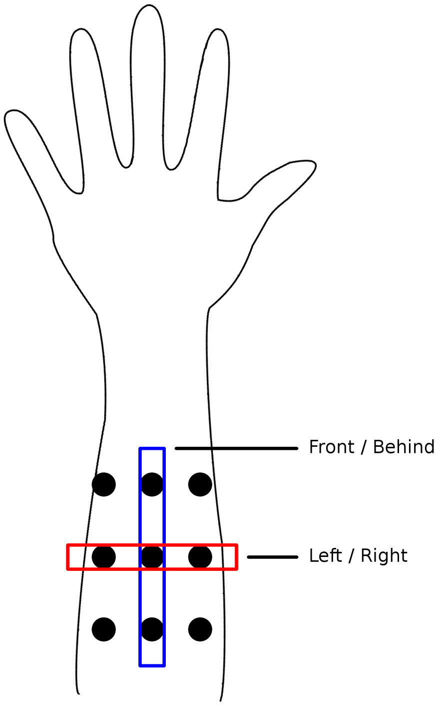


Figure 7.2: The used column and row of actuators in Experiment 3, top view of left forearm and hand. The center column (blue) is used for a forward motion from elbow side to wrist side (Front) and wrist side to elbow side (Behind). The center row (red) is used for a motion from the inside to the outside of the arm (Left) and outside to inside (Right).

Dependent Variable The dependent variable is the perception of smooth funneling direction.

Experiment Design The experiment uses a within subjects design. Each participant is exposed to all conditions and the conditions are repeated multiple times throughout the experiment. As we have six forearm positions and four directions, there is a total of 24 conditions. Each condition is repeated ten times during the experiment leading to 240 trials. The experiment exists of six sessions of 40 trials and a practice session of 12 trials. The practice session will always be held in the TP position. Each motion direction will occur 3 times and they are in a randomized order. Each real session is done with a different forearm position. Within a session the 40 trials, ten for each direction in a specific position, are randomized. To minimize influence from one forearm position to the next forearm position we use a Latin square so that each forearm position is only followed by another specific position once, see Table 7.1. Each participant would follow one of these orders during an experiment and each order is used among an equal amount of participants.

7.2 Process

First the participant will be explained that they are going to experience a series of vibration signals delivered to the arm that will move over the arm in one of four ways while in one of six positions. The participant

Table 7.1: Latin Square for session sequences in Experiment 3. P1 denotes the position used in the first session, P2 denotes the position used in the second session, and so on.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Order 1	TP	TN	HS	TS	HN	HP
Order 2	TN	TS	TP	HP	HS	HN
Order 3	TS	HP	TN	HN	TP	HS
Order 4	HP	HN	TS	HS	TN	TP
Order 5	HN	HS	HP	TP	TS	TN
Order 6	HS	TP	HN	TN	HP	TS

will be asked to sign a consent form containing textual explanation of the process and the participant's rights while also being verbally informed of the right to stop at any time without giving a reason. Then we will record the age, gender, handedness and general experience with vibrotactile systems on the forearm. Afterwards the participant will be seated behind a desk and the actuators will be placed on the forearm. Ten minutes is allocated for preparation and recording age, gender and experience. The participant will first go through a training session where the locations are associated with the motion patterns. After completing the training session the participant will go through six sessions of 40 trials with breaks in between. During each session the participant is instructed to assume a certain pose depending on which order they fall into. After the pose is assumed a command is sent to the Wemos which then performs one of the sequence conditions. After the participant has felt the sequence the participant will say the position (Front, Behind, Left, Right) or say that the could not determine a direction. With an estimate of five seconds per trial total time for the trials will be around 20 minutes. In between the sessions a break of three minutes will be instigated to remain comfortable and avoid fatigue. After the last session the participant is informed that the first part of the experiment has been completed and that we will continue on to the second part of the experiment.

7.3 Participants

30 participants took part in the first part of the experiment, 19 male and 11 female. The ages ranged from 20 to 35 with an average of 25.4 years. Of the 30 participants 25 were right-handed, one was left-handed, 3 were mixed-handed and one was ambidextrous. The participants were not compensated in for their participation.

7.4 Analyzing Results

The results will be analyzed using two-way repeated measures ANOVA. This will be done with the SPSS software package for statistical analysis. The raw data from the experiment will be pre-processed by adding all trials per condition per subject and calculating the proportion of correct associations out of ten possible. This gives us a data set with 24 proportion values per subject. From the raw participant data we can also create confusion matrices per forearm position to see more in depth if there is a consistent confusion in perceived motion direction. We suspect that Left and Right might be confused more when the arm is supinated. This would indicate a possible interaction effect and the rejection of hypothesis H3c.

(H3a) There is no significant difference in correct perception of motion direction between the six different positions of the forearm.

(H3b) There is no significant difference in n correct perception of motion direction between apparent motion directions.

(H3c) There is no significant interaction effect on location of the forearm and apparent motion direction in correct perception of motion direction.

7.5 Results

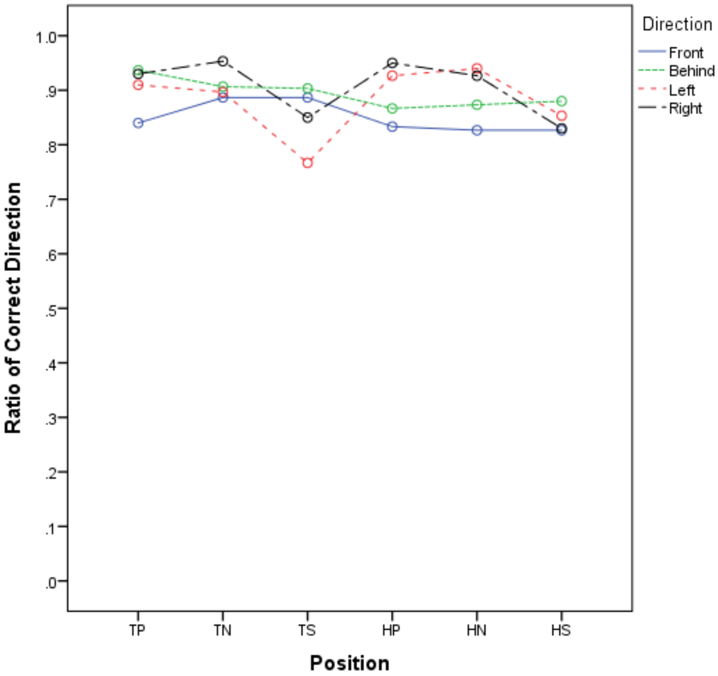


Figure 7.3: Results from Experiment 3 on the association of four locations with motion direction under six different positions of the forearm. The values are the means of all participants ratios of correctly associated location out of 10.

As can be seen in Figure 7.3 participants were able to associate the correct location with the felt direction in general. Correct association ranged from 0.767 (TS, Left) to 0.953 (TN, Right). The prone and neutral positions performed comparably while the supine positions performed less than the prone and neutral positions. Front and Behind directions were consistent in performance over all positions. Left and Right did better than Front and Behind if the position was neutral or prone, but worse if the position was supine. There were no main effects of forearm position or location. There was an interaction effect ($F_{15,29} = 3.375$, $p < .0001$). Comparison of simple effects showed no significant difference however. When looking at the amount of wrong classification per condition in Tables 7.2 and 7.3 Front was most often confused with Behind or Right but not as much with Left. In the supine positions Left was indeed confused most with Right an Right with both Left and Behind.

7.6 Discussion

In general the correct association values of the four directions stay close together. Left and Right do suffer when the forearm is supine. The first thought is that because of the rotation of the forearm left and right would be switched more often with each other. It can be summarized that the position of the forearm has some effect on the correct classification of apparent motion direction. In particular the left and right motion are confused more with others than front and behind when the forearm is in a supine position. It is probable that the interaction effect stems from this performance difference of Left and Right in supine or other positions. In day to day activities this effect may not have a real impact because many activities done by the hand and by extension the forearm will have the forearm generally in a neutral to prone rotation as those are more comfortable.

Table 7.2: Latin Square for session sequences in Experiment 3. P1 denotes the position used in the first session, P2 denotes the position used in the second session, and so on.

TP

		Perceived				
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front**	**252**	*21*	1	20	6
	Behind	*10*	**281**	3	5	1
	Left	4	*14*	**273**	3	6
	Right	2	*16*	3	**279**	0

TN

		Perceived				
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front**	**266**	12	4	*14*	4
	Behind	*16*	**272**	5	6	1
	Left	5	*17*	**269**	4	5
	Right	3	*8*	1	**286**	2

TS

		Perceived				
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front**	**266**	10	8	*12*	4
	Behind	*12*	**271**	5	11	1
	Left	8	24	**230**	*28*	10
	Right	6	9	*24*	**255**	6

Table 7.3: Latin Square for session sequences in Experiment 3. P1 denotes the position used in the first session, P2 denotes the position used in the second session, and so on.

			HP			
			Perceived			
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front**	**250**	11	8	*26*	5
	Behind	11	**260**	*15*	8	6
	Left	*12*	5	**278**	0	5
	Right	1	*10*	2	**285**	2

			HN			
			Perceived			
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front**	**248**	11	9	*28*	4
	Behind	*11*	**262**	*11*	7	9
	Left	3	*12*	**282**	1	2
	Right	1	*16*	2	**278**	3

			HS			
			Perceived			
	Front	**Behind**	**Left**	**Right**	**None**	
Actual	**Front**	**248**	17	8	*25*	2
	Behind	9	**264**	*15*	6	6
	Left	9	11	**256**	*19*	5
	Right	6	*28*	14	**249**	3

Chapter 8

Motion Perception in Uncontrolled Environment

As an additional experiment we took participants on a walk. During the walk they could receive a motion on any column or row and were asked to identify the correct location as in Experiment 3. The participant would be pulled into conversation and distracted by background activity while walking. The nature of this more informal experiment is to observe and get an indication if putting participants in a more natural, uncontrolled setting would allow them to still recognize motion direction correctly.

8.1 Setup

For the second part the participant must be able to walk around and as such the hardware must be made mobile. The Wemos board will be powered by a battery pack and both the board and battery pack are then mounted on the left upper arm of the participant and fastened with Velcro, see Figure 8.1. Pattern instructions will be sent from a mobile phone that is connected to the Wi-Fi network of the Wemos board.

Independent Variable There are four directions with their associated locations (Front, Behind, Left, Right), the same as in Experiment 3. Each pattern will be repeated 12 times. Different from Experiment 3 is that the location of the pattern occurring on the arm can differ. For Front and Behind the patterns can move over the locations as described in Experiment 1 and for Left and Right the patterns can move over the locations as described in Experiment 2, see also Figure 8.2. To differentiate between patterns with the same motion direction but using a different set of actuators they have been named as follows:

- Front 1 / Behind 1: Uses the column of actuators on the inner side of the forearm.
- Front 2 / Behind 2: The center column.
- Front 3 / Behind 3: Uses the column of actuators on the outer side of the forearm.
- Left 1 / Right 1: Uses the bottom row of actuators.
- Left 2 / Right 2: Uses the center row of actuators.
- Left 3 / Right 3: Uses the top row of actuators.

Dependent Variable The dependent variable is the perception of smooth funneling direction.

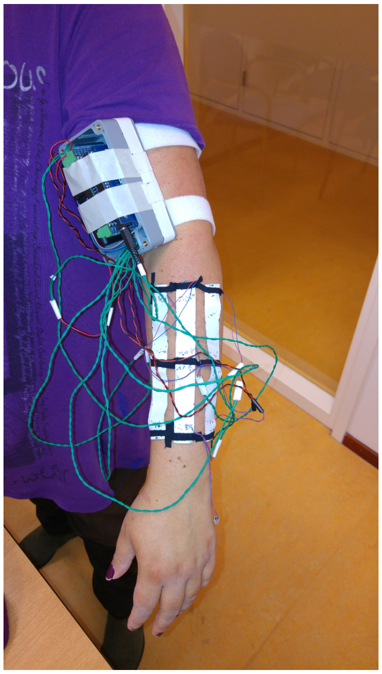


Figure 8.1: The prototype device mounted on a participant. The Wemos board and battery pack are fastened to the upper arm with Velcro.

Experiment Design The experiment is a within-subjects design. The four possible motions are repeated 12 times (four for each possible location on the arm) during the walk. This gives us a total of 48 trials. These trials are spread out over the course of the walk. The trials will be presented in a randomized order.

8.2 Process

The participant will be informed that they will take a walk with the experimenter and that during the walk they will feel apparent motion patterns during the walk. The participant is to verbally respond the position associated with the direction pattern as in the first part of the experiment when they perceive the pattern. The examiner will record the answer of the participant. The device will be detached from the wall power socket and made to run on battery. The examiner then connects to the Wemos device via Wi-Fi on a mobile application. The examiner then runs a test sequence that activates all vibrotactile actuators one by one to test the connection. The examiner will take the participant on a course during which the trials can occur. The start and the end point of the walk is the room used for the first part of the experiment. After returning from the walk the experiment ends and the device is removed. The participant is thanked for their participation and may discuss the experiment and ask questions.

8.3 Participants

22 participants took part in the second part of the experiment, 14 male and 12 female. Ages ranged from 20 to 35 with an average of 22.9 years. The participants were not compensated in for their participation. These are a subgroup of the same participants as in Experiment 3. As with Experiment 3 we were aiming for 30 people to partake in this stud but time restrictions for 5 participants did not allow for this. Also in three cases the mobile phone lost the Wi-Fi connection temporarily and could not find it again due to many interfering Wi-Fi signals in the neighborhood during walking.

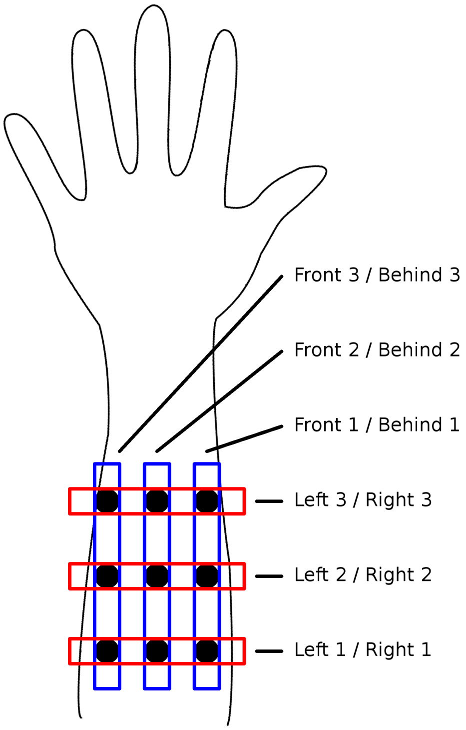


Figure 8.2: Naming convention for possible funneling motion directions based over which actuator set the apparent motion goes.

8.4 Analyzing Results

The intention of this experiment is to investigate if trends emerge from the data gathered in a partly uncontrolled environment. As such no significance testing is done. We explore instead the average correct direction classification per condition and the confusion matrix to find if trends emerge. We suspect for example that, although the results are not directly comparable with Experiment 3, there will be a general decline in recognition due to distraction when compared to the controlled setting of Experiment 3.

8.5 Results

When looking at each possible direction and location separately we see in Figure 8.3 that correct perception of the direction is generally low when compared to the results from the first part of Experiment 3. Although not directly comparable this trend of general lower correct perception is also seen for conditions not used in the first part of Experiment 3. In the cases of the Front, Behind and Right the L2, B2 and R2 lanes performed slightly better than the outer lanes. For left L2 and L3 performed equally well. In Table 8.1 an overview can be seen on cumulative answers per condition. Here we see that for Behind and Left conditions there is no clear trend in how participants confuse directions. For Front conditions, there is a trend towards confusing it with Right and, although not as strongly, Right gets confused with Behind more than Left or Front. The participants had no difficulty perceiving a vibration pattern even if they did not perceive the direction at all times as within each condition the amount of not being able to discern a motion this number never exceeded four cases.

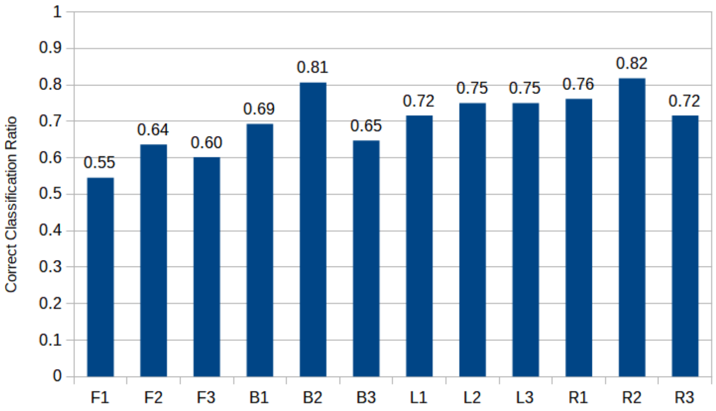


Figure 8.3: Correct classification of associated location to direction motion. There seems to be a trend of decreased correct classification when compared to the controlled setting.

8.6 Discussion

Although there is no significance the general decline in correct classification shows a trend that people may have more difficulty correctly interpreting vibration signals on the forearm when they are distracted performing other tasks than when focusing on the device, which may be an issue. A more in depth study could lead to a clearer view of the issue. This is however beyond the scope of this project. The specific confusion between the Front conditions and Right conditions may be explained by the natural forearm position people take when walking and conversing. In general people will have their forearms somewhere in between a neutral and prone rotation while walking and doing no significant hand signaling. As the actuators follow the skin when the forearm becomes more prone the lanes of actuators become slightly more diagonal and a forwards motion may feel more as a rightwards motion when distracted. This would not explain why Right then is confused more with Behind than with Front as you would expect. These confusions between Front and Right and Right and Behind were also present in the result of part 1 of this experiment, albeit with less wrong classification. A more specific follow up experiment may give more insight into this phenomenon. The amount of times a motion was not perceived was generally very low. This would suggest that people do not have difficulty registering *a* motion even if they then incorrectly classify it. Given that some of the conditions were only perceived around 55 percent of the time it suggests the system as it is now would not be suited for pure tactile notification using funneling. There could be a use for combining smooth funneling with visuals and audio to enhance experiences in VR or AR where the missing information for correct classification of some signal could then be inferred from multiple sensory inputs, increasing redundancy.

Table 8.1: Confusion table for all conditions. The most classified location is printed in bold, the most wrongly classified location is printed in italic.

		Perceived				
		Front	**Behind**	**Left**	**Right**	**None**
Actual	**Front 1**	**48**	2	13	*23*	2
	Front 2	**56**	4	5	*20*	3
	Front 3	**53**	5	14	*15*	1
	Behind 1	4	**61**	6	*16*	1
	Behind 2	2	**71**	*8*	3	4
	Behind 3	5	**57**	*14*	9	3
	Left 1	8	*9*	**63**	4	4
	Left 2	5	*12*	**66**	2	3
	Left 3	*12*	5	**66**	4	1
	Right 1	2	*14*	2	**67**	3
	Right 2	3	*13*	0	**72**	0
	Right 3	10	*11*	2	**63**	2

Chapter 9

Conclusion & Future Works

In this body of work we have found that people can indeed perceive smooth funneling with the application of an actuator grid on the forearm using relatively small and affordable hardware. The effective range for DOS at which there is a high chance of perceiving smooth funneling for both motion moving along the forearm or across the forearm was between 120 ms and 240 ms with 180 ms performing the best in our experimentation. A DOS of 60 ms is not advised with this device as participants reported as the motions feeling incomplete or not feeling any motion at all. Using smooth funneling at 180 ms DOS we further found that participants had little difficulty perceiving direction despite holding their arms in different positions or the forearm being rotated. There is a high indication that when distracted by the environment incorrect classification increases. We have built a prototype device that is wearable on the body and can be used for smooth funneling on the forearm. Yet there is still a lot of improvement that can be made with the prototype device. From a hardware standpoint it might be interesting to explore other connection methods than over a Wi-Fi network. The device maintaining a network drains energy quite fast from the battery unit, making it not very efficient. Also allowing devices without Wi-Fi but with other connectivity options such as Bluetooth to connect could greatly increase the usability and versatility of the grid based actuator device. For example it could communicate with game controllers in a game setting. For this experiment the battery unit was also designed as a quick and replaceable unit but it was quite large and heavy, making the device ultimately fatiguing to wear for longer times. Improving the device on size and efficiency to increase ease of use and mobility might be a nice subject to work on as a small research project.

Another subject to investigate could be to optimize parameter values to use for smooth funneling on the forearm. While 150 Hz for actuator vibration and 6 cm inter-actuator distance is well within what is proven to work in the literature it might not be the optimal solution in our case. Exploring such a single parameter in depth may fill a small research project. Exploring multiple parameters may lead to a more comprehensive body of work depending on the complexity.

Of course we only tested some straightforward motion directions such as straight left and right but we did not consider more complex directions such as diagonals or more complex patterns such as combined sequenced motions. This area is largely unexplored on the forearm using smooth apparent motion. In the line of thought of diagonal motion there is also potential in exploring different actuator layouts on the forearm. A square grid sounds like a good first suggestion but it might be that using a diamond layout for example allows for a better perception of smooth funneling.

The funneling haptic device could also be combined with visuals in a navigation exercise as an added channel of information. Especially in games or VR where the visuals can be important visual navigation cues might be distracting. By adding haptic direction motion on the forearm visual cues may not have to be emphasized as much while still maintaining an equal level of navigating ability.

Using this device as a starting point we can further integrate smooth apparent motion to enhance experiences in gaming, VR and AR.

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