Effect of Vibration Frequency Mismatch on Apparent Tactile Motion

by

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Effet de la disparité en fréquence vibratoire sur le mouvement tactile apparent

Shirin Kasaei

RÉSUMÉ

La rétroaction vibrotactile est du plus en plus présente dans notre vie courante. Cette croissance de la rétroaction haptique a engendré une exigence de rétroaction de qualité supérieure améliorant ainsi l'expérience des utilisateurs dans leur communication avec différents dispositifs. L'expérience d'un retour haptique sophistiqué peut encore être améliorée par l'utilisation simultanée de plusieurs dispositifs haptiques. Une combinaison de différents dispositifs haptiques pourrait également favoriser la perception d'illusions telles que le mouvement tactile apparent et la sensation tactile fantôme. L'illusion du mouvement tactile apparent, en particulier, permet la perception d'un mouvement continu d'un stimulus en présence d'au moins deux stimuli immobiles produits à des intervalles de temps et de distance spécifiques. Cette illusion pourrait par exemple créer une sensation de flux entre de multiples dispositifs haptiques, tel qu'une montre intelligente et une manette. Des questions se posent, cependant, lorsque les dispositifs haptiques utilisés ne sont pas conçus pour opérer ensemble, tel qu'il peut arriver avec des produits commerciaux. Comment un décalage de la fréquence de résonance de deux actionneurs peut-elle influencer la détection des illusions tactiles, et plus spécifiquement le mouvement tactile apparent? Cette illusion disparaît-elle lorsque la non-concordance des fréquences croît?

Bien que les illusions perceptuelles aient été investiguées depuis plus d'un siècle, la plupart des études portant sur l'influence de paramètres sur la perception des mouvements ont considéré que les actionneurs utilisés à deux endroits du corps étaient identiques et produisaient donc des vibrations de même amplitude et de même fréquence. Nous avons donc conduit deux expériences pour étudier l'effet d'un décalage de la fréquence vibratoire sur la perception du mouvement tactile apparent. Nous avons demandé aux participants de déterminer la direction du mouvement tactile alors que la fréquence était décalée, l'intensité perçue était normalisée, et la distance entre les actionneurs et les paramètres de synchronisation étaient fixes. Nous avons simulé la présence d'actionneurs aux propriétés différentes en modifiant la fréquence et l'amplitude des impulsions de vibration produites par un actionneur à large bande. Nous avons fait varier les fréquences de 50 à 250 Hz et adjusté l'amplitude pour normaliser l'intensité perçue. Les résultats suggèrent que l'illusion de mouvement tactile apparent est robuste aux disparités des actionneurs de vibration et qu'elle peut donc être utilisée avec des dispositifs haptiques fabriqués avec des spécifications différentes.

Mots-clés: haptique, mouvement tactile apparent, illusion, fréquence

Effect of Vibration Frequency Mismatch on Apparent Tactile Motion

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ABSTRACT

Vibrotactile feedback is increasingly common in our daily life. This growth in haptic feedback usage has produced a demand for higher quality feedback that improves users' experience when they communicate with different devices. The experience of sophisticated haptic feedback could further improve when more than one haptic devices are used simultaneously. A combination of different haptic devices could for example make it possible to feel illusions such as apparent tactile motion and phantom tactile sensations. The apparent tactile motion illusion, in particular, allows the perception of a continuously moving stimulus when two or more non-moving stimuli are produced with specific timing and distance intervals. This illusion could for example create a sensation of flow between multiple haptic devices, such as between a smartwatch and a handheld controller. Questions arise, however, when the haptic devices used are not designed to operate together, as may be the case for commercial products. How does a mismatch in the resonant frequency of two actuators affect the detection of tactile illusions, and more specifically apparent tactile motion? Does this illusion break down as the frequency mismatch increases?

While perceptual illusions have been investigated for more than a century, most studies that investigate the influence of parameters on motion perception have assumed that the actuators used at two body locations are identical and therefore produced vibrations with the same amplitude and frequency. We ran two experiments to investigate the effect of mismatching vibratory frequency on the perception of apparent tactile motion. We asked participants to judge the tactile motion direction while the frequency was mismatched, the perceived intensity was normalized, and the distance between actuators and timing parameters were fixed. We simulated having actuators with different properties by changing the frequency and amplitude of the vibration pulses produced by a wide-band actuator. We varied frequencies in a range from 50 to 250 Hz and adjusted the amplitude to normalize the perceived intensity. The results suggest that the apparent tactile motion illusion is robust to mismatches in resonant frequency of actuators and that it can therefore be used with haptic devices manufactured with different specifications.

Keywords: haptic, apparent tactile motion, illusion, frequency

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATIONS

ETS	École de Technologie Supérieure
SOA	Stimulus Onset Asynchrony
ATM	Apparent Tactile Motion
SD	Stimulus Duration
ISI	Interstimulus Interval
ISOI	Inter Stimulus Onset Interval
BD	Burst Duration
DCT	DC Motor Based Tactor
VCT	Voice-Coil Type Tactor
ERM	Eccentric Rotating Mass Motor
LRA	Linear Resonant Actuator
PCM	Pulse-Code Modulation
USB	Universal Serial Bus
AWG	Arbitrary Waveform Generator
DLL	Dynamic-Link Library
USART	Universal Synchronous/Asynchronous Receiver/Transmitter
HID	Human Interface Device

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

cm	centimeter
msec	millisecond
Hz	Hertz
mm	millimeter
V	Volt
g	gram
G	gravitational acceleration of 9.8 m/s^2
Ω	ohms
kHz	kiloHertz
dB	decibel
GS/s	giga samples per second
ns	nanosecond
MHz	megahertz
A	Ampere

INTRODUCTION

Haptic displays open a new way of presenting information without overburdening other senses such as vision (Gallace, Tan & Spence, 2007; Tan, Gray, Young & Taylor, 2003). Also, such displays improve communication with different types of systems from virtual reality to handheld gaming controllers. In fact, with the advent of mobile phones and tablets, haptic displays are becoming more widely used. For instance, cellphones produce a vibration to announce receiving a message or call. In this case, it is an efficient way to transmit information from device to user by haptic display.

This project investigates the added value and feasibility of using multiple devices with haptic capabilities together. For instance, the combination of two haptic devices could produce a moving vibration from the wrist to the palm when a user wears a haptic wristband and a haptic glove. We are investigating how the use of two actuators with different resonant frequencies affects the perception of such apparent tactile motion. It is well known in the literature that tactile illusions such as this one can be created by carefully controlling the timing and amplitude of vibrations at two locations on the body (Israr & Poupyrev, 2011a). A sequence of vibrations can give the impression of a vibration that occurs at a location between two actuators or that flows from one actuator to the other. The literature, however, typically assumes that both actuators are identical, which is unlikely to be the case in practical situations where devices are manufactured by different companies. Here, we are investigating whether these tactile illusions can be produced when the actuators are not matched and how much of an impact this mismatch has on the quality of apparent tactile motion.

This project fills a gap in our understanding of the psychophysics of touch and the perception of tactile illusions when multiple haptic devices are used together. More practically, we expect the results to inform how two actuators with different resonant vibratory frequencies can be combined to create more complex and realistic haptic effects.

Our findings may help to improve illusion perception when, for example, an illusion of apparent tactile motion is created between a smartwatch and a game controller that have different haptic features.

Our objective is to understand how a mismatch in vibrotactile actuators will affect the perception of a tactile illusion (apparent tactile motion). More specifically, we want to understand how a mismatch in the resonant frequency of two vibrotactile actuators will alter the perception of a tactile illusion. We study two locations of the body, the forearm and the wrist, by placing actuators at these locations. Our goal is to understand if creating tactile illusions is possible with mismatched actuators and how sensitive the illusions are to this mismatch. We expect to find that a vibratory frequency mismatch will affect the perception of apparent tactile motion. We hypothesize that with increasing frequency mismatch, the error rate in perceived direction increases.

The structure of the thesis is as follows: Chapter 1 describes basic concepts related to haptic illusions. Chapter 2 reviews the literature on the effect of different parameters on haptic illusions. Chapter 3 describes the hardware and software that was developed and used for our work. Chapter 4 reports the design, results and analysis of two pilot studies and an experiment. Finally, we covers the conclusion, and future work.

CHAPTER 1

BACKGROUND

Before we review the literature and the experiment setup, we need to know about the most common terms that are used to describe parameters in tactile illusions, the human sensory system, and haptic devices. We separate this Chapter into three sections. Section 1.1 covers a general understanding of touch and the human sensory system that was used in different studies. Then, Section 1.2 describes some terms used to explain haptic feedbacks and terms that are used to describe timing parameters. Finally, Section 1.3 addresses devices and systems related to the haptic field.

1.1 Human Haptics

Sense of touch: The sense of touch combines two different senses: the cutaneous sense and the kinesthetic sense. With the first, we can experience stimulation on our skin. The second provides information about body posture and forces. These two sensations are different in mechanism, not in their functionality (Loomis & Lederman, 1986).

- **Kinesthetic sense:** Kinesthesia is a term that describes the sense of movement and force, and it is typically associated with force-displacement (Loomis & Lederman, 1986). "Kinesthetic sensations, such as forces and torques, are sensed in the muscles, tendons, and joints" (Culbertson, Schorr & Okamura, 2018). Whenever cutaneous stimulation does not affect the tactile perception, we can consider this perception as kinesthetic (Loomis & Lederman, 1986). In other words, it is considered as a sense of the muscle (Henry, 1953).

- **Cutaneous sense:** The cutaneous sense refers to the human perception of an object through the skin. Cutaneous receptors cover the body's whole outer surface in both hairy and non-hairy parts of the skin (Lederman & Klatzky, 2009). This sense includes 4 different submodalities that depend on "tactile, thermal, painful and pruritic (itch) information", as well as a fifth submodality "that conveys positive affective (pleasant) properties. This system gives information about “the spatial and temporal localization of events on the body surface” (McGlone & Reilly, 2010).

Haptic: Any type of movement involving touch is referred to as haptics. Max Dessoir (1867–1947) introduced the term “Haptic”, which was a mix of two words: ‘optic’ and ‘acoustic’ (as cited in (Hayward, 2016), pp. 328). Haptic perception corresponds to the situation in which both the cutaneous and kinesthetic sensations mediate information about external stimuli (Loomis & Lederman, 1986).

Tactile: "Tactile sensations, such as pressure, shear, and vibration, are sensed by specialized sensory end organs known as mechanoreceptors that are embedded in the skin" (Culbertson *et al.*, 2018). Also, Loomis & Lederman (1986) relate the perception of tactile sensation to the variation of cutaneous stimulation. Tactile perception was introduced as the perception of an object’s properties like texture (Fernandes & Albuquerque, 2012).

Mechanoreceptor: Tactile sensation emerges when there is displacement or pressure on the skin. The skin movement is sent to the nervous system through mechanoreceptors. Based on their function, mechanoreceptors are grouped into 4 different categories: slowly adapting I (SA I), slowly-adapting II (SA II), rapidly-adapting (RA), and Pacinian corpuscle (PC). Among these categories, RA is responsible for the detection of vibrations in low frequencies, and PC is responsible for high frequencies (Johnson, 2001; Konietzny & Hensel, 1977).

1.2 Tactile illusions and parameters

Detection Threshold: The minimum stimulation intensity that humans perceive by touch is called the detection threshold (Choi & Kuchenbecker, 2012). Different parameters affect the detection threshold including age, gender, the environment, and the stimulation signal’s characteristics. In the range of 20 to 1000 Hz, the detection threshold has a U-shaped curve with a maximum sensitivity at 250 Hz (Verrillo, 1962).

Illusion: "An illusion is a percept that arises from a stimulus combining two separable components. One component is fixed, and the observer attends to it. What makes it an illusion is that the perception of this component is strongly contingent on the variation of a second component, perplexing the person made aware of the unchanging component of the stimulus" (Hayward, 2016). The various definitions for illusions all have a common concept: a difference between perception and reality. Humans' sensory system can perceive various illusions via different senses such as sight, hearing, and touch. In the past, researchers considered vision as the only sensory channel for illusion perception (Hayward, 2016). At the end of the 17th century and begining of the 18th century, touch was considered to be a verification input for other input modalities (George Berkeley (1685–1753), Étienne Bonnot de Condillac (1714–1780)). Today, we consider different body parts from the skin to the eyes or ears as units that transmit data to the brain.

Tactile Illusion: Hayward (2016) considers tactile illusions as something that happens when an object' quality is not perceived the same as its physical characteristics. He also mentions that a tactile illusion could be produced or prevented to have higher quality haptic displays in different conditions.

- **Apparent Tactile Motion:** One of the haptic illusions that produce a feeling of movement is called apparent tactile motion, or phi or beta movement. When two vibration actuators drive signals with overlapping actuator activations, a feeling of movement (continuous and unitary movement) is produced instead of the perception of two discrete vibrations on the skin (Figure 1.2 and 1.1). If two locations on the skin are stimulated in close proximity, the perception of a continuous movement that travels from one actuator to another is produced (Sherrick & Rogers, 1966; Israr & Poupyrev, 2011b). In this thesis, we will focus on apparent tactile motion.

- **Phantom Tactile Sensation:** Another type of haptic illusion is called a phantom tactile sensation or the funneling illusion (Figure 1.2). This illusion is produced when two actuators

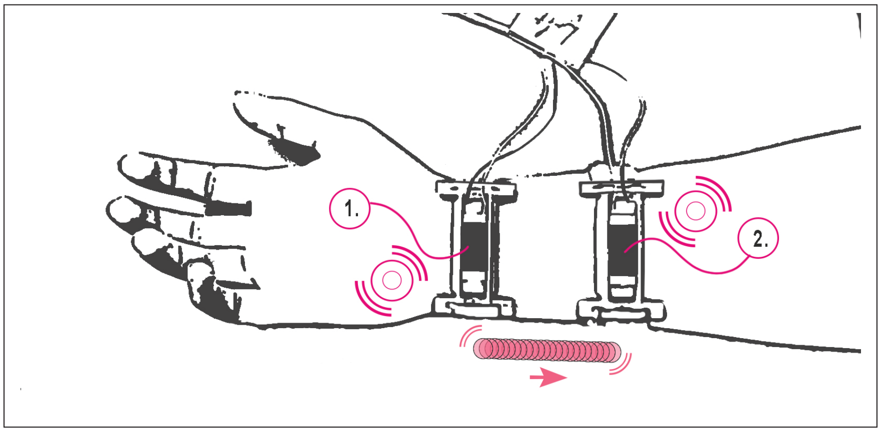

Figure 1.1 Perception of apparent tactile motion with two actuators on the forearm and the wrist

placed close to each other vibrate at the same time, producing a sensation that appears to come from between the actuators (Alles, 1970).

Stimulus Onset Asynchrony (SOA): The Stimulus Onset Asynchrony (SOA) is the interval between the onsets of two vibrations. In early articles, it was also called the interval between stimulus onsets (ISOI).

Duration of stimulus (SD): The amount of time an actuator is turned on is called the duration of stimulus (SD). In some research, this parameter is called the burst duration (BD).

Interstimulus Interval (ISI): The ISI is the amount of time that passes between the offset of the first stimulus and the onset of the second stimulus.

It is important to note that the ISI and the SOA are different (Guettler, 2004). In Figure 1.3, for example, two actuators vibrate for 200 msec, the duration of stimulus (SD) is 200 msec, the SOA between two stimulus is 250 msec, and the ISI is 50 msec.

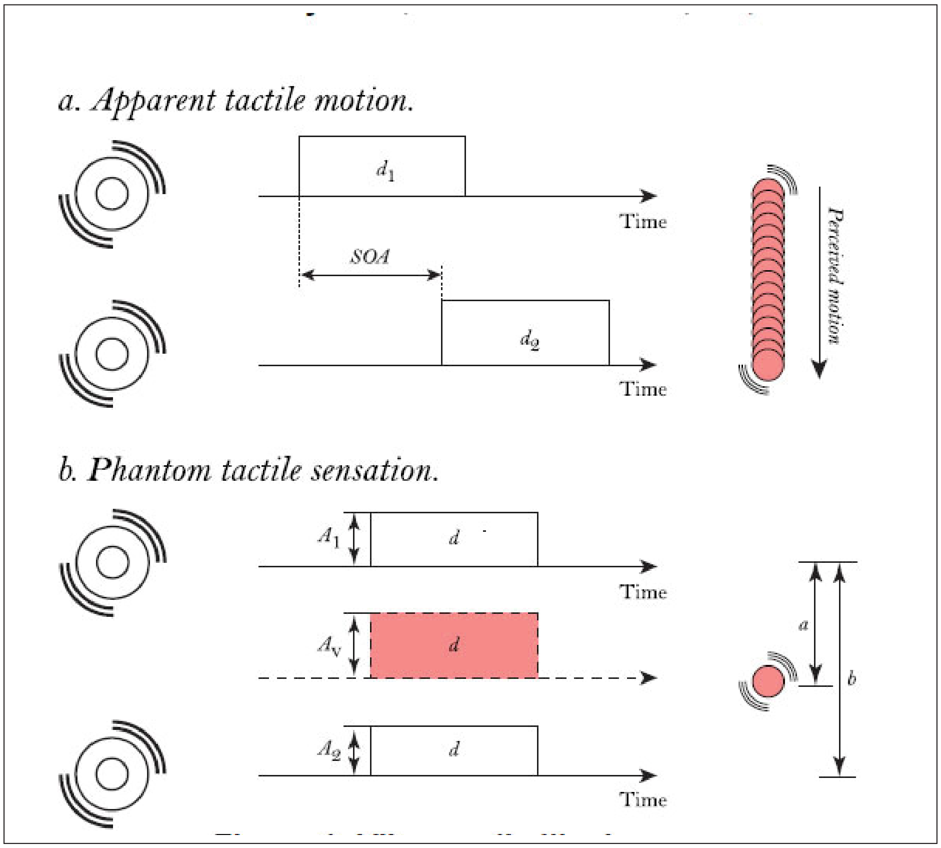

Figure 1.2 Two tactile illusions: (a) Apparent Tactile Motion produces the feeling of movement from one actuator to another and (b) phantom tactile sensation produces the feeling of a vibration between two actuators
Taken from Israr & Poupyrev (2011b)

1.3 Haptic Devices

Wearable Haptic Devices: There are different types of haptic devices. We focus on wearable ones. The Cambridge University Press dictionary defines a wearable object as something which is “suitable for wear or able to be worn.” According to this definition, the smartwatch can be considered a haptic wearable since it can be easily worn as a standard wristwatch (Whitmire, Benko, Holz, Ofek & Sinclair, 2018). Wearable haptic devices are considered to be wearable systems that are typically tactile (cutaneous) devices mounted to the hands or other parts of the body and that display sensations directly to the skin. "They can provide cues such as vibration,

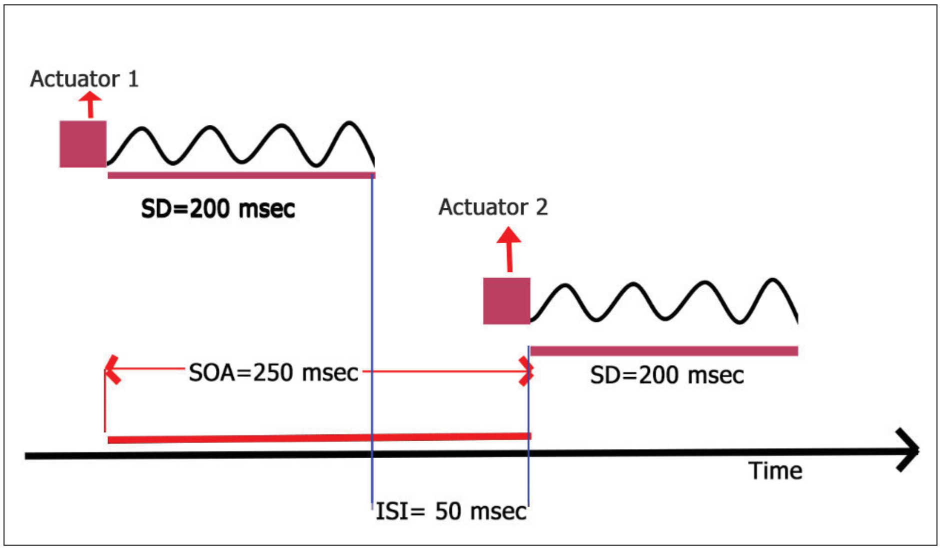

Figure 1.3 Example of timing parameters: the SOA, the ISI, and the SD. The SOA is the temporal gap between the onset of the first stimuli and the onset of the second stimuli, ISI is the gap time between the offset of the first stimuli and the onset of the second stimuli, the SD is the amount of time an actuator is turned on

lateral skin stretch, and normal skin deformation. They may also be body-grounded devices, such as an exoskeleton, that provide a kinesthetic cue to the user by creating a reaction force on a less sensitive part of the body" (Culbertson *et al.*, 2018).

Tactile Display: A tactile display is a system that simulates the tactile properties of an object as closely as possible, from shape to roughness or temperature. Tactile displays can be classified into different categories based on their applications. One of these classifications is vibrotactile displays, as used in our work. In vibrotactile systems, an actuator is used to vibrate the skin by converting electrical energy to mechanical energy, thereby stimulating mechanoreceptors (Jones & Sarter, 2008).

Vibrotactile Actuators: Vibrotactile actuators have a significant effect on haptic perception. There are different types of actuators that each produce different tactile stimulation, e.g, eccentric rotating mass (ERM) motors, linear resonant actuators (LRA), and piezoelectric actuators. ERM or LRA are the most common actuators in most research due to their easy use in prototypes and their low price (Blum, Fortin, Al Taha, Alirezaee, Demers, Weill-Duflos & Cooperstock, 2019).

- **ERM:** To produce a vibration, an ERM (Figure 1.4) rotates an unbalanced weight with a DC motor. The disadvantages of ERM actuators are their high power consumption, their slow response time (up to 100 msec), and that their vibration amplitude can't be controlled independently from their vibration frequency (Motola-Barnes, 2019).

- **LRA:** An LRA actuator (Figure 1.5) has a magnetic coil that moves a mass linearly to create vibrations. The advantages of this type of actuator are a cleaner stimulation than ERM, and its ease of control because of its low driving voltage. The disadvantage of the LRA is its limited range of optimal frequencies, but the range of amplitudes is more flexible than ERM (Motola-Barnes, 2019).

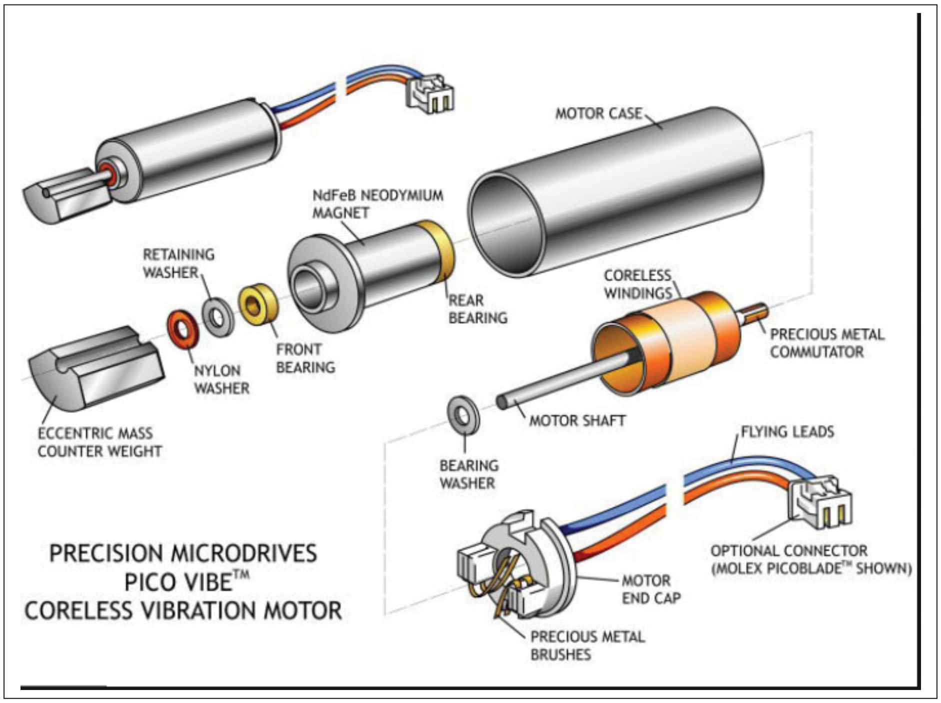

Figure 1.4 An exploded view of Eccentric rotating mass (ERM) motor[1]

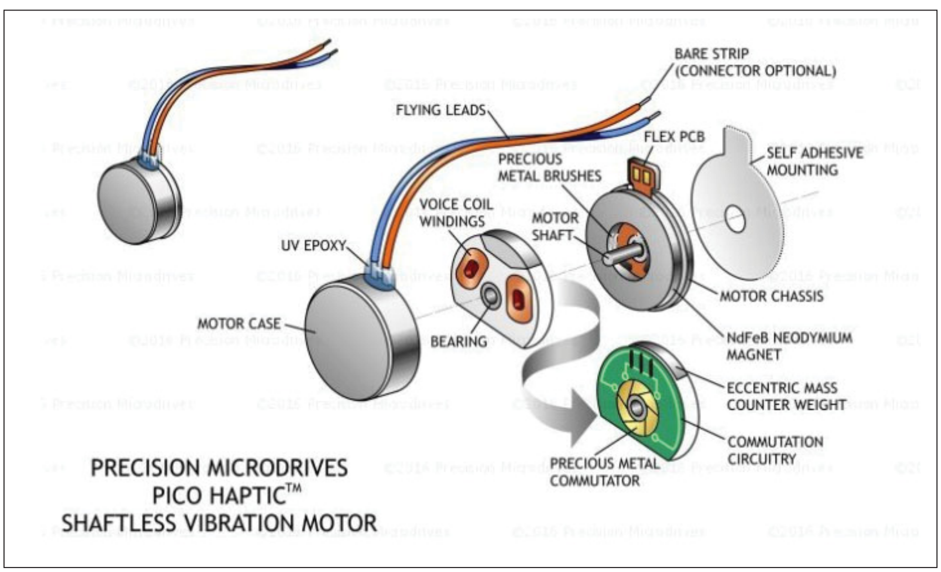

Figure 1.5 An illustration of a linear resonant actuator (LRA) [2]

[1] https://www.precisionmicrodrives.com

[2] https://www.precisionmicrodrives.com

- **Piezoelectric actuators:** Piezoelectric actuators (Figure 1.6) use the piezoelectric effect to produce vibrations. They comprise two components of piezoelectric material that change shape when exposed to an electrical signal. Typically, different ceramic layers in the shape of a beam or disk are used in vibrotactile displays. One of these actuators' advantages is that they have a quick response time (1 msec) compared to ERMs and LRAs. Also, it is possible to control their vibration frequency and amplitude separately, and therefore to produce more sophisticated signals. However, piezoelectric actuators need a high driving voltage signal (up to about 200 V) which complicates integration compared to other actuators (Choi & Kuchenbecker, 2012; Motola-Barnes, 2019).

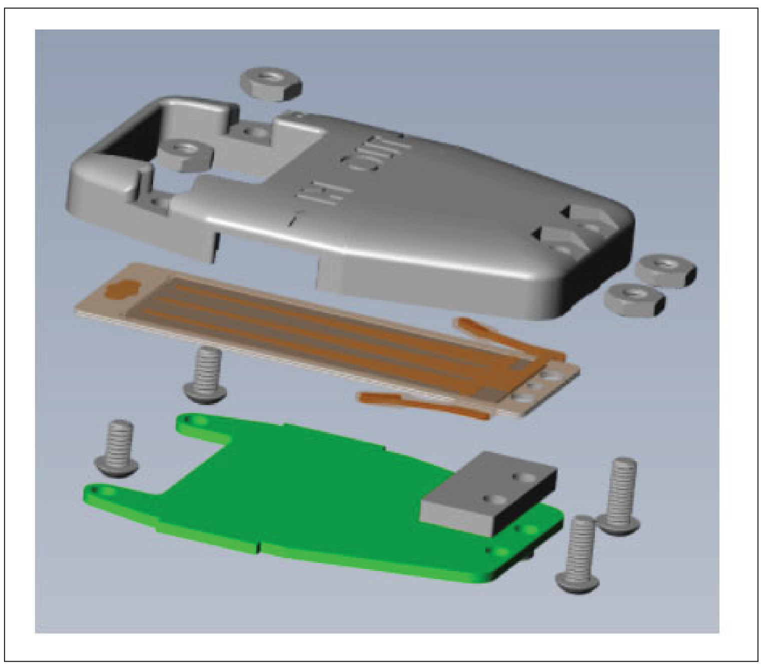

Figure 1.6 An exploded view of Piezoelectric actuators[3]

- **Voice coil actuators:** Voice coil actuators are easy to use, and the availability of data from previous work makes them a preferable option for use in different tactile displays (Choi & Kuchenbecker, 2012). Tactile patterns are perceived better when frequency and amplitude can

[3] https://blog.piezo.com/haptic-actuators-comparing-piezo-erm-lra

be varied separately (Israr & Poupyrev, 2011b). As a result, voice coil actuators are the preferable choice for our work. In Chapter 3, we will look at the voice coil actuators that we used in our work.

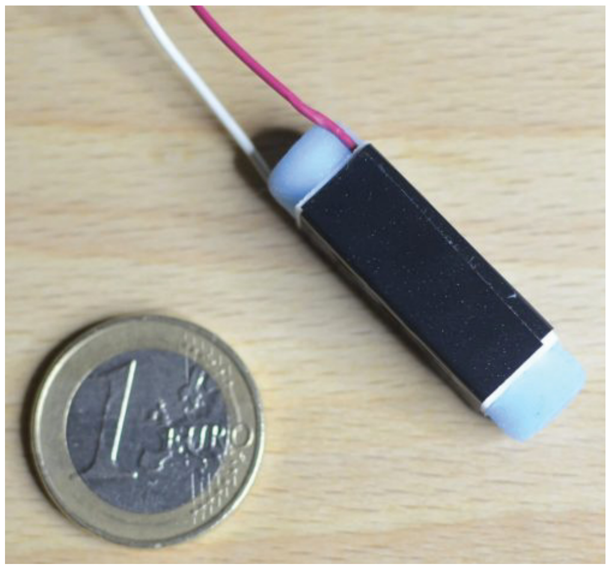

Figure 1.7 Haptuator MM3C-HF series[4]

In this Chapter, we learned about the terminology of haptics. For example, Section 1.1 helps to know about common terms used in most studies. In Section 1.2, we learned about illusions and timing parameters that are important parameters to produce different illusions. Section 1.3 will be used to design the experimental setup in Chapter 3. In Chapter 2, a series of studies in different parameters of tactile illusions are reported, such as the range of frequencies, timing parameters,and the distance between actuators.

[4] http://tactilelabs.com/products/haptics/mmxc/

CHAPTER 2

LITERATURE REVIEW

We review articles that cover the different parameters that affect the perception of tactile illusions. This chapter helps us know about previous works, finding important parameters that affect the perception of tactile illusions and how they affect it. In Section 2.1, we summarize the effect of stimuli duration and asynchrony. We then discuss in Section 2.2 the effect of frequency and amplitude on the perception of apparent tactile motion. We also look at the effect of the body part on apparent tactile motion perception in Section 2.3. Finally, we discuss how the physical characteristics of the actuators affect the perception of vibrotactile stimuli in Section 2.4.

2.1 Timing Parameters

Many studies focus on timing parameters of the stimulation, including both the duration of the stimulation and the interval between two stimulations. In fact, these two parameters are the most important to produce apparent tactile motion (Van Erp et al., 2002).

In this Section, we first look at the early studies that focused on timing parameters; then, we look at the works that study the effect of timing parameters on psychological aspects such as smoothness or length. We also cover the effect of the distance between actuators on the timing parameters; then, we look at the effect of timing parameters on the detection of tactile patterns and their speed.

2.1.1 Early Studies

In early studies, the sensation of movement could be produced on the body without exactly feeling or detecting the extent and direction of the movement. As a result, Hall & Donaldson (1885) proposed movement as a primary sensation. Most investigations were about timing parameters such as duration of the actuator vibration or the gap time between activation of the two actuators (Von Frey & Metzner, 1902; Benussi, 1916; Burtt, 1917).

Sumby (1965) was one of the first researchers who found that 200-msec bursts and 100-msec interstimulus intervals lead to a good apparent tactile motion perception. He also found that the SOA is a major factor for a better perception of illusions and determined what is the optimal interval.

Sherrick & Rogers (1966) produced successive bursts of vibration in the thorax, which participants felt as a rotational motion. They found a relation between the duration of the stimulus and stimulus onsets for a smooth apparent tactile motion. They estimated the optimal SOA, although their method did not evaluate quantitively the movement's effectiveness. They found that duration is one of the major elements of the optimal SOA. In detail, they found a good motion when the duration of the stimulus was under 100 msec. They determined that a range of 100 to 400 msec for interstimulus intervals leads to optimal movement. Also, shorter intervals (shorter than 48 msec) lead to a poor judgment for direction (with two actuators) (Bice, 1969).

To further investigate the effect of timing, Kirman (1974) has conducted a series of studies that focus on stimulus duration and interstimulus onset interval. Furthermore, he tried to determine the other conditions that lead to an excellent apparent tactile motion, such as the effect of timing on the perception of simultaneity or successive movement. Kirman asked participants to classify their perception of illusory movement in four categories ranging between complete movement and non-movement. The quality of apparent tactile motion was a function of the SOA, and the result showed that by increasing the amount of the SOA, quality of apparent tactile motion increased and then decreased. Also, increasing stimulation duration affected the optimal SOA; to have a good apparent tactile motion, the SOA decreases and then increases as stimulus duration rises. These findings confirm Sherrick and Roger's findings, but the range of the SOA in Kirman's experiments is lower than the range of the SOA obtained by Sherrick and Rogers. Sherrick and Rogers found that the SOA was one of the important elements of apparent tactile motion. He also calculated the optimal SOA as a function of stimulus duration. Regarding the perception of movement, increasing the SOA leads to a failure of the judgment of simultaneity but improves the successiveness judgment. The perception of simultaneity did not change when the SD was raised, while the perception of successiveness of movement decreased sharply.

He found that to perceive a high-quality apparent tactile motion, the SD should be less than 200 msec. Most importantly, the best SD was 150 msec for an excellent apparent tactile motion.

2.1.2 Effect of timing parameters on psychological aspects of apparent tactile motion

Cholewiak & Collins (2000) had a complete study on different parameters that affect the perception of illusions on three different parts of the body while manipulating the different aspects of timing. They asked participants to judge psychological aspects of a vibration such as the perception of length, straightness distribution, and smoothness. They found that the SD and the SOA were the most significant parameters that affect the perception of two types of illusions (apparent tactile motion and phantom tactile sensation). This study's most important finding was that the effective parameters on these two types of illusions behave in the same pattern. Like previous studies, they found that timing affects the quality of stimulation, but that the best stimulation is related to the accuracy of judgment and the locations on the body (finger, arm and back). The perceived length was better when the ISI and the SD increased. In detail, the quality of length perception increased when raising the value of SD in all three parts of the body. ISI does not affect the perception of length.

On the other hand, the quality of smoothness had a relation with the ISI. The spatial distribution improves with shorter ISI. Shorter SD and ISI improved the feeling of straight lines. Another study of different parameters that affect the apparent tactile motion is (Israr & Poupyrev, 2011a). They designed a series of experiments to find a range of SOA that produces a continuous movement on two different parts of the body when different parameters are varied. They found that the value of the SOA is related to the SD. In detail, increasing the SD increased the value of the upper and lower threshold. Zhao, Israr & Klatzky (2015) have similarly found that the quality of apparent tactile motion depends on the timing parameters. A smooth movement was produced when the SOA was long and amplitude low. When the SD was 100, 400 and 700 msec, the optimal SOA to produce smooth movement was 78.7, 190, and 244 msec, respectively. There was a linear relation between the SD and the SOA ($SOA = 0.28 \times SD + 60.7$).

2.1.3 Effect of distance between actuators on of optimal timing parameters

Eid, Korres & Jensen (2015) studied timing parameters and the distance between actuators to produce continuous apparent tactile motion. In general, they found that by increasing the SD, the difference between the perception of discrete and continuous apparent tactile motion occurred with the lower SOA value. The SOA can control the perceived speed of the apparent tactile motion. Increasing the SD led to raising the upper and lower thresholds. The value of SD affects the minimum and maximum SOA for perceiving the stimulation of motion. With the larger SD, we could have a more significant gap between minimum and maximum possible SOA to produce a continuous motion.

2.1.4 Effect of timing parameters on the detection of tactile patterns

The SD and the SOA also affect the detection of different tactile patterns such as "S" shaped pattern. In this regard, Shimizu (1982) observed that raising the SD increased the pattern detection rate. Although he did not find an impact of the interval on the precision of identification, Shimizu noticed that raising the interval produced quicker responses to the task.

Cholewiak & Craig (1984) detected the effect of different stimulus vibration patterns on three parts of the body (finger, palm, thigh). The main result showed that the SOA was the function of identification of patterns, and performance rates across body locations depends on the SD.

Linear apparent tactile motion was not the only study topic.Niwa, Lindeman, Itoh & Kishino (2009) focused on finding parameters that affect linear and circular apparent tactile motion's quality on the arm. They found a 400 msec gap time between the two same patterns. If there is not enough time interval between the repetition of a pattern, it may feel like a continuous movement and be considered as one pattern. They experimented to find the minimum amount of gap time. In one of the experiments, two actuators settled on the forearm and vibrated up and down. Four different SOA and SD sets were tested when interval time varied in 11 steps from

0 to 1000 msec. When the interval time increased, the rate of correct answers also increased (around 95% correct answers).

Israr & Poupyrev (2011a) compared two different stimulation patterns, The first pattern was produced with stimulation of four actuators from left to right (linear movement) on their back. The second pattern was produced with a 4 X 4 array of actuators that were activated sequentially and participants perceived a "S" shaped movement across their backs. They have found that the SOA threshold rang was smaller with S pattern than with linear movement.

2.1.5 Effect of timing parameters on the perception of the Apparent Tactile Motion's speed

One of the other important topics is the perception of the apparent tactile motion's speed. In this regard, Kohli, Niwa, Noma, Susami, Yanagida, Lindeman, Hosaka & Kume (2006) conducted a study to find the human sensitivity to various apparent tactile motion speeds and the detection accuracy of some patterns with three different speeds. They found that pattern recognition is more effortless than detection of different speeds of apparent tactile motion. They found a range of SOA and SD that produced slow, medium, and fast movement. Results show that participants could distinguish slow movement from fast and medium speed movement, but they had difficulty distinguishing between medium and fast speeds; the error in both was around 20%.

In summary, there have been many reports on the quality of apparent tactile motion and the best timing parameters for high-quality apparent tactile motion (Kirman, 1974; Kohli *et al.*, 2006; Niwa, Yanagida, Noma, Hosaka & Kume, 2004; Israr & Poupyrev, 2011a). Israr & Poupyrev (2011b) introduced a formula to calculate the SOA based on duration of stimulus (SD) to produce continuous movement: "SOA=0.32 SD + 47.3". Also, Kohli *et al.* (2006) presented a table that describes three different speeds of perception of apparent tactile motion based on the SOA and the SD (table 2.1). Based on three different SD and nine differents the SOA, they considered three different speeds of apparent tactile motion: fast, medium, and high. When the speed of apparent tactile motion was considered fast, the SOA's value was almost half of the SD for all three different SD's. In the medium speed, the SOA was almost more than the SD, and in the slow movement, the SOA was almost two times more than the SD.

Table 2.1 Different speed of apparent tactile motion based on timing parameters
Taken from Kohli *et al.* (2006)

SD	**Low SOA (fast)**	**Medium SOA (medium)**	**High SOA (slow)**
100 msec	30 msec	110 msec	190 msec
200 msec	100 msec	220 msec	340 msec
400 msec	200 msec	320 msec	440 msec

It is clear that some of the most important parameters that affect the apparent tactile motion are timing parameters. In our work, we select the SOA and the SD values that produce simultaneous movement. To produce the illusion, we decided to use a SD of 200 msec and a SOA of 111 msec, which are expected to result in a fast apparent tactile motion. To produce two entirely separate vibrations, we used a SD of 1000 msec and a SOA of 1500 msec.

2.2 Intensity, frequency, and amplitude

Today, vibrotactile feedback is increasingly used on mobile phones, tablets, and handheld controllers. These devices are designed with different types of actuators that each produce vibration with a specific range of frequencies and amplitudes. From the literature, we know that vibrotactile stimuli are produced by variation of amplitude and frequency. Simultaneously, the perceived intensity of vibration depends on these two parameters (Cha, Rahal & El Saddik, 2008). There has been different research and conclusions regarding the effect of these parameters on the perception of apparent tactile motion.

There are various conclusions and research about the effect of frequency on the tactile stimuli. For example, Cholewiak & Collins (2003) found that changing frequency in the range of 100 to 250 Hz does not impact the detection of the stimulation location. Israr & Poupyrev (2011a) have similarly found that frequency (200 and 270 Hz) and intensity do not affect the optimal SOA for the perception of apparent tactile motion.

In contrast, Israr & Poupyrev (2011b) observed that variations of frequencies (between 150 and 270 Hz) impact the optimal threshold of SOA. In detail, increasing the frequency decreases the range of optimal SOA. It is better to use the lower part of this range of frequencies to produce continuous apparent tactile motion.

Lim, Kwon & Park (2012) studied the effect of frequency variation (between 1 and 250 Hz) on the perception of apparent tactile motion between two fingers. They found that variations of frequency (logarithmic and linear) did not affect the perception of movement. The frequency difference between the two stimuli is a significant factor in determining the location of stimulation. It is important to note that when the frequency difference between the two stimulations was small, participants could not correctly detect the location of stimulation.

In another study that focused on the motion of vibration when varying the frequency of two actuators connected to a plate, Kang, Lee, Kim, Cho, Wang & Ryu (2012) found that frequency is an important factor in producing continuous movement. They mention that a displacement of the plate between the actuator and the skin could produce smoother movement when increasing frequency from zero to the resonant frequency; it felt like extra actuators. Vibration moved to the center when the frequency was raised (from 15 to 245 Hz). It is important to note that from 15 to 120 Hz, there was no apparent motion. In fact, the range of displacement of movement did not linearly increase when frequency increased. They found that frequency was the major parameter to feel the length of movement when the frequency was not constant.

Zhao *et al.* (2015) ran a set of experiments to find all critical parameters affecting the continuous vibration movement on handheld devices. They found that the detection threshold of vibrations falls when the frequency is raised. The frequency did not affect the perception of motion, but affected the illusion.

Closest to our work, Kwon, Park, Sakamoto & Mito (2021) study the effect of vibratory frequency and interval timing on the index finger. This is different from our work as we studied the effect of frequency vibratory mismatch on the forearm and the wrist and normalised the vibration amplitude to have the same perceived intensity at all vibration frequencies. Kwon *et al.* (2021)

focused on the effect of variations in a set of five frequencies (10, 20, 40, 100 and 200 Hz) and SOA between 0 and 400 msec on apparent tactile motion on the fingertip. They found that apparent tactile motion was felt with a combination of a stimulation's frequency at 40 Hz with other frequencies. In all low-frequency and high-frequency combinations, apparent tactile motion was felt completely. Regarding timing intervals, apparent tactile motion was felt with SOA in the range of 105 msec to 125 msec.

Regarding the velocity of tactile motion, Cholewiak & Collins (2000) found that increasing the velocity decreases the perceived length of stimulation.

More articles focused on the effect of amplitude on the quality of apparent tactile motion's perception in recent years. Seo & Choi (2010) produced tactile illusions on a mobile device by changing amplitude values linearly and logarithmically. With the linear method, the perception of vibration could move more than the logarithmic method. The method of changing amplitude has more effect than duration on the perception of distance of vibration. Changing amplitude using a logarithmic scale has more effect on the perception of intensity than with a linear scale. Perception of intensity was more stable with the logarithmic method. Also, Hwang, Seo, Kim & Choi (2013) found that raising the amplitude increased the perceived intensity.

In the same way, Rogers (1970) observed that increasing the amplitude improves the detection of the displacement of tactile stimuli. However, Rahal, Cha, El Saddik, Kammerl & Steinbach (2009) found that participants perceive a better movement when amplitude increases linearly. Furthermore, Kang *et al.* (2012) found that amplitude affected perceived length in the same condition. Also, when the signal's ending is smooth, participants feel a longer distance than with a sharp ending. They found that using two or three of these parameters at the same time could improve the smoothness of movement. Regarding intensity perception, the shape of the ending was the most important parameter to affect the intensity perception. When the ending is smoother, the perception has fewer fluctuations than the sharp end. Similarly, Zhao *et al.* (2015) found that smooth variations (increase and then decrease) of amplitude produce a smoother vibration movement than a sharp increase and decrease of the amplitude.

2.3 Body part

One of the other parameters that affect the perception of illusions is the body part. Many studies focus on body parts from the whole body to the finger. In this Section, we cover a sample of these works.

Early research by Bice (1969) indicated that judgment of direction in the palm was more error-prone than on the abdomen.Craig & Lyle (2002) later provided evidence that the body part with the highest receptor density is more sensitive to tactile stimulation, and that the accuracy of responses in these parts is higher than elsewhere. However, Kirman (1974) reported in a pilot study that there was no special effect of the body part on high-quality apparent tactile motion perception.

Nevertheless, Cholewiak & Craig (1984) found that the detection of shapes in short duration such as 52 msec improves when the pattern is on the thigh or palm. In another study, Cholewiak & Collins (2000) did not observe any relationship between the body part and perceived quality of length or smoothness. Interestingly, Israr & Poupyrev (2011a) found that both direction and distance of actuators influenced SOA on the forearm, but that only one parameter (direction) affects the value of optimal SOA on the back. Regarding the body joints, Cholewiak & Collins (2003) found that participants were more accurate in localizing the vibration on joints like the elbow and wrist than between these two parts.

2.4 Actuator characteristics

In this part, we review a sample of studies that focus on topics such as the distance between actuators, the type of actuator, and the number of actuators.

2.4.1 Distance between actuators

In early research, Bice (1969) provided evidence that the distance between actuators was not a significant parameter to reach a good illusion of movement. In another study, Rogers (1970) focused on the effect of distance on detecting stimulation when the distance of the two stimulators was 2 and 6-mm on fingertips. He found that the detection of stimulation with a 2-mm distance was more problematic than a 6-mm distance. In contrast, Kirman (1974) observed that distance did not affect the quality of the apparent tactile motion. Similar to Rogers, Cholewiak & Collins (2003) observed the same results regarding localization. Regarding the perception of motion, Cha *et al.* (2008) observed that motion could be felt with 20, 40, and 60 mm distances, and that motion perception starts to become unclear at 80 and 100-mm. Also, Niwa *et al.* (2009) found that participants could better detect the direction with a small spacing than with a large spacing around the arm.

Similarly, Rahal *et al.* (2009) observed a better motion perception rate when the two actuator's distance was 50 mm, and amplitude changed linearly. On the other hand, Eid *et al.* (2015) also detected that timing parameters did not relate to the distance between actuators, and that participants could feel the movement when the distance between two actuators was between 4 and 20 cm. With increased distances between the two actuators, the relation between SD and SOA was more linear.

2.4.2 Type and number of actuators

One of the earliest studies that compares the effect of two different actuators on apparent tactile motion quality is (Sherrick & Rogers, 1966). They found that an optimal apparent tactile motion is not dependent on the type of actuators, as using vibrotactile and electrocutaneous displays produced almost the same results. Later, Kirman (1974) related the smaller SOA threshold to the type of actuators (a smaller size of actuator compared to the results of (Sherrick & Rogers, 1966).

In another study, he observed that with four actuators, the perception of movement was better than with two actuators. A high-quality movement was achieved with four actuators in the short ISI compared with two simulators with the same SD. The quality of apparent tactile motion perception depends more on the lower SOA for four actuators compared to two actuators. The highest percentage of apparent tactile motion perception for four actuators was reached when the SOA was 50 msec and this value almost doubled for two actuators. The number of actuators did not affect the SD of optimal apparent tactile motion. When the number of active actuators increased, the value of optimal SOA decreased (Kirman, 1975). Sumby (1965) also noticed that it is possible with two actuators that the participants received a good movement, and the number of actuators did not affect the perception quality.

In contrast with Sumby, Bice (1969) found that distinguishing direction was better with 4 actuators. Also, it would be possible to have a shorter interval (48 msec) to have a good movement with more actuators. Regarding the type of actuator, Niwa *et al.* (2009) and Niwa *et al.* (2004), in two sets of studies, compared the effect of two types of motors (DC actuator-based tactor (DCT) and a voice-coil type tactor (VCT)) on the quality of apparent tactile motion perception. Participants feel better apparent tactile motion when the SOA and the SD are the same with a DC motor. Regarding the VCT actuator, when the difference between SOA and SD was less than 50 msec or more than 400 msec, apparent tactile motion did not occur. When SOA was higher than 200 msec, the actuators' type did not matter for apparent tactile motion perception. The VCT actuator worked better when the SD was less than 200 msec. They concluded that the VCT actuator could work in a broader range of SOA and the SD. They found that a 400-msec temporal gap between the same two patterns and the use of at least 4 actuators improves the perception of both linear and circular movements.

This Section helps us decide about other parameters such as distance, number, and the orientation of actuators for the experiments. We decide to focus on the wrist and forearm; the distance of two actuators from center to center of actuators should be 8 cm, and with two actuators, we can produce apparent tactile motion.

2.4.3 Direction and orientation of actuators

Other parameters that affect the perception of tactile stimuli are the orientation and direction of the actuators. Cholewiak & Collins (2000) mention that the direction of illusions does not affect the perception of stimulation. Israr & Poupyrev (2011a) found that, on the forearm, both direction and distance of actuators influenced optimal SOA, but on the back, only one parameter (direction) affects the value of SOA. Regarding the orientation of two actuators, Rahal *et al.* (2009) found that a linear variation is always preferred when two actuators have longitudinal orientation. However, there was no relation between the type of amplitude variation (linear or logarithmic) and the two actuators' had transverse orientation. They relate these results to the human sensory system and the fact that the two actuators are under the same strap in a vertical movement.

CHAPTER 3

EXPERIMENTAL SETUP

In this thesis, we are focusing on the effect of vibration frequency on the perception of a tactile illusion. In this Chapter, we explain the experimental setup that we will use for the experiment described in chapter 4. The chapters 1 and 2 informed the design of this experimental setup.

The experiment setup includes hardware and software components. Figure 3.1 and 3.2 show the main core, a laptop with software that generate vibration waves. The laptop has communication with a USB audio card via USB ports and an Interface Device that has a display, knobs, and keypads to communicate with the user. In detail, all communication between the software and the hardware occurs via two USB cables. The generated wave is transferred to the USB audio card; actuators connected to the audio card via a stereo jack they vibrate as they receive the wave signal.

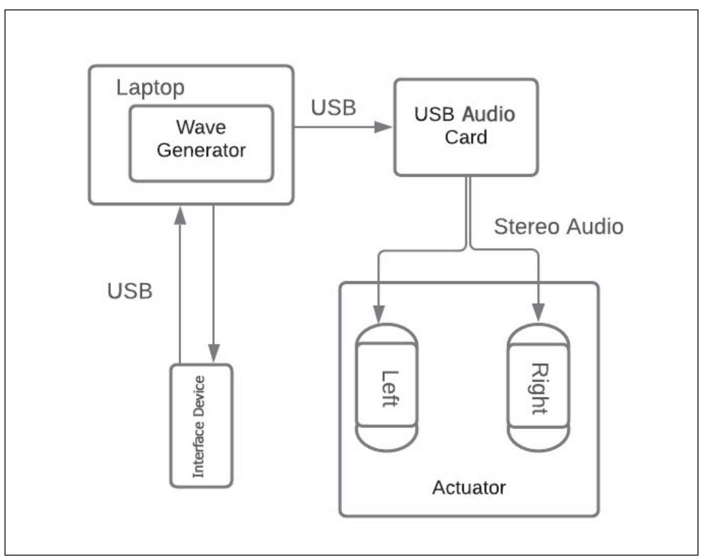

Figure 3.1 Block diagram of the experimental

In Sections 3.1, 3.2 and 3.3, we explain the hardware components. Then we cover the software developed to produce signals (Section 3.4). Finally, we describe the Interface Device (Section 3.5) that was designed to communicate with participants during the experiments.

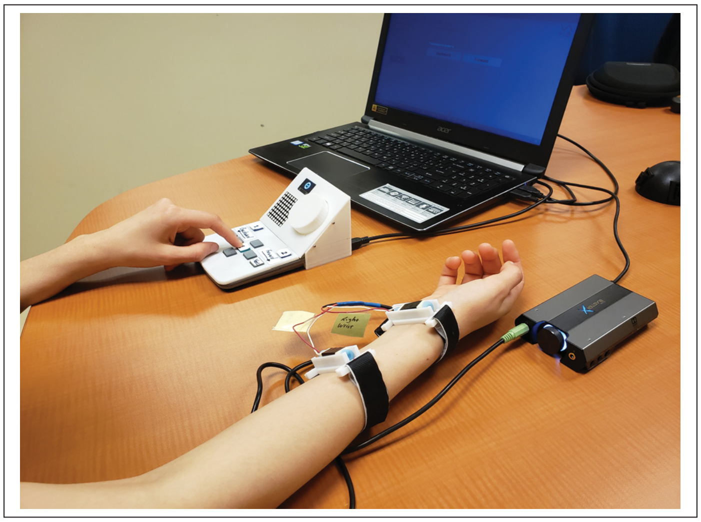

Figure 3.2 Experimental setup

3.1 Actuators

After studying different actuators and comparing their specifications in Chapter 2, we decided to use the Haptuator MM3C-HF series (Figure 1.7), a vibrotactile actuator of the voice coil family. We want to study the effect of vibratory frequency mismatch on the apparent tactile motion, so we need to be able to vary the frequency independently of the intensity in the experiment, which we can do with this type of actuator. By varying the frequency we can simulate a wide range of other actuators typically used in commercial products. This specific actuator model has increased the acceleration density because its improved design produces higher displacement than previous versions. Another advantage is a more comprehensive range of frequencies that creates a better vibrotactile outcome. Table 3.1 and Figure 3.3 show more information about the actuator (TactileLabs, 2021).

As you can see from Figure 3.4, these actuators are convenient because they are driven by audio equipment just like speakers. We use the left and right audio channels to drive the two actuators separately.

Table 3.1 Characteristic of Haptuator MM3C-HF

Model	**Units**	**MM3C-HF**
Dimensions	mm	36x9.5x9.5
Weight	g	9
Resonance frequency	Hz	85
Acceleration @ 1V input, @ res. freq.	G	5.5
Maximum acceleration @ res. freq.	G	7.5
Rated Bandwidth	Hz	30-1000
Typical Impedance	Ω	5.5
Maximum Input Voltage	Volt	5
Maximum Input Current	A	1

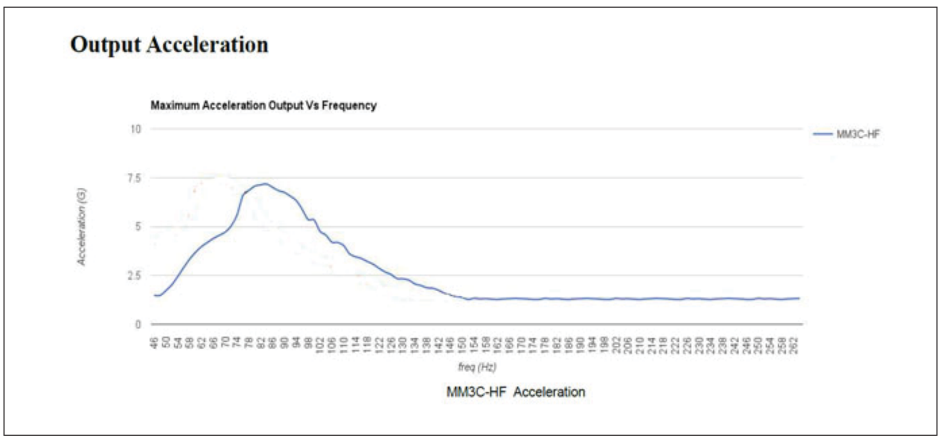

Figure 3.3 Representation of relationship between frequency and acceleration

3.2 Wearable attachment

As we need to attach the vibrotactile actuators to the wrist and forearm in the experiment, we decide to look at different possible wristbands and select the best option that it is comfortable, has good contact with the skin, and transmits vibrations well.

Different wristbands were developed and tested to control and render apparent tactile motion and achieve these goals. The design of the wristband evolved through different iterations, as problems were discovered and addressed.

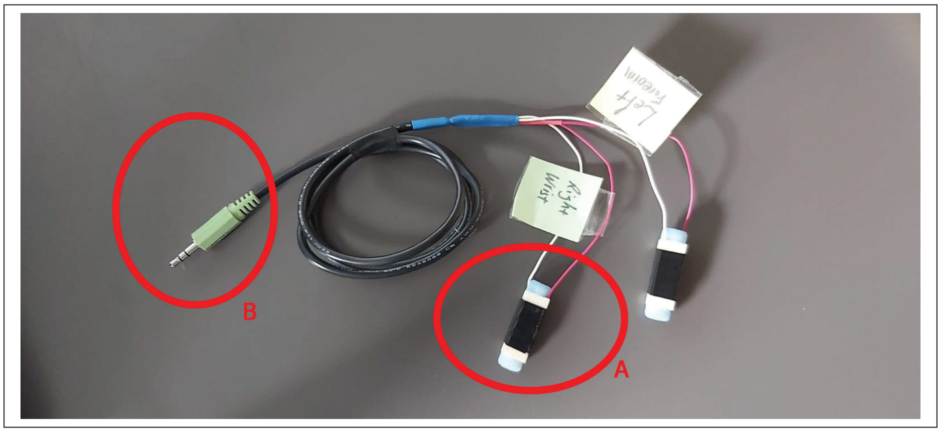

Figure 3.4 Connection of actuator Haptuator MM3C-HF (A) and stereo jack (B)

In the first iterations, we found that when using tape, a fabric velcro or cotton sleeves as a wristband (Figure 3.5), the actuator's position could change over time as it was not fixed very well in its position. Participants may loosen or tighten the fabric velcro, and, as a result, the actuator could move during the experiment. The participants may then not all experience the same conditions. Another problem was that the vibrations propagated through the entire fabric strap and were therefore felt in a larger area of the arm than intended.

For the second set of iterations, we decided to design a custom 3D printed wristband to keep the actuator in the same position for all participants. We designed four different versions and improved the wristband design in each version. The specification of each version are explained below.

- **Version 1:** We designed a plastic frame to hold the actuators. The first version consists of two plastic holders filled with silicon (Figure 3.6. The silicon was added to increase the strength of vibrations, but in practice it absorbed the vibrations and decreased sensations perceived by users. Figure 3.7 shows the position of the actuator and the wristband. Also, the user could not tighten this wristband.

- **Version 2:** In the second version, we removed the silicon layer as it absorbed the actuator's vibrations and reduced the vibrations felt by users. Instead of the silicon layer, we designed a

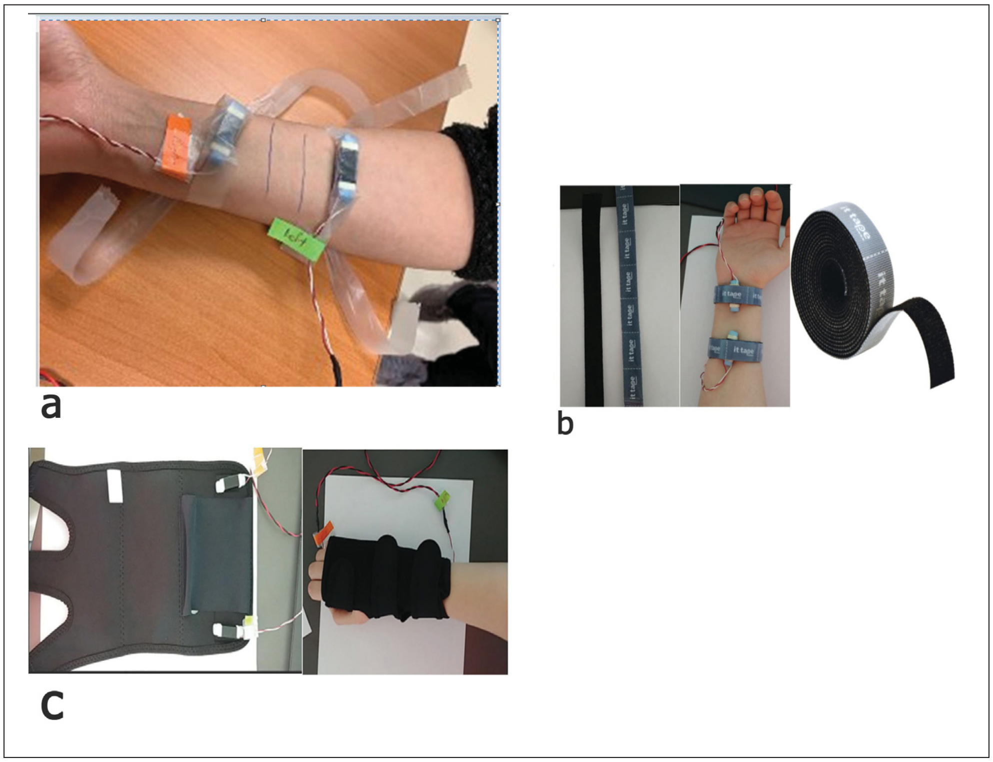

Figure 3.5   First iterations of wristbands: a) tape, b) fabric velcro, and c) wrist brace

2-mm plastic support to suspend the actuators, with the intention of having less damping of the vibrations than with silicon (Figure 3.6).

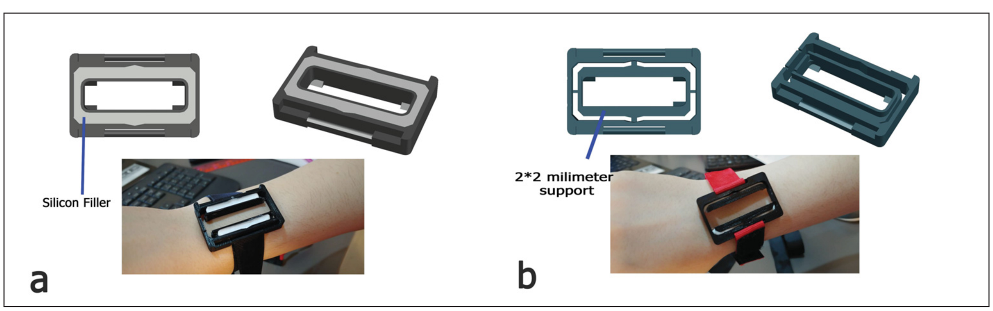

Figure 3.6   First two versions of second iterations of wristbands: a) Version 1, b) Version 2

Also, we decided to change the actuator's orientation on the wrist. The displacement of the actuator's mass and apparent tactile motion were both along the length of the arm in the first two versions (Figure 3.7), so we were concerned that participants could estimate the direction via the displacement of the mass instead of the movement of the illusion. We decided to change the orientation of the actuator to be perpendicular to the arm (Figure 3.7) so that the actuator movement and the produced illusion would be orthogonal.

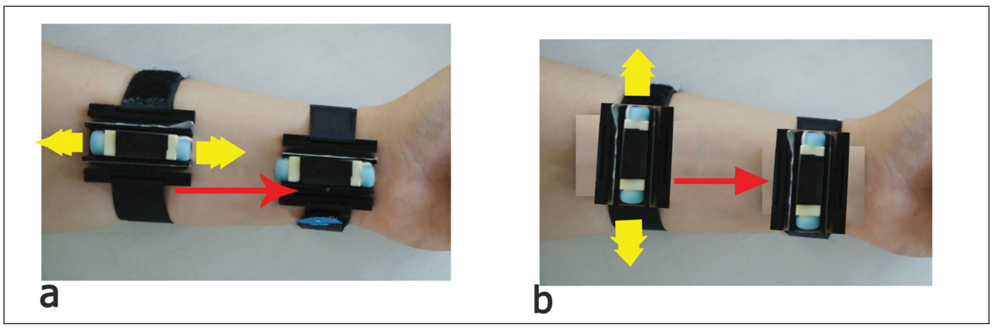

Figure 3.7 The two actuator's orientation: a)the movement of actuator's mass and illusion were in the same axis, b) the movement of actuator's mass and illusion were orthogonal

- **Version 3:** After more experimentation, we designed a third version (Figure 3.8) that removes all supports. We realized that a solid frame without any plastic holders or support material produced a more uniform distribution of vibration on the skin. Solid frames are also used in commercial wristbands with haptic features, such as the Lofelt Basslet and smartwatches.

- **Version 4:** For the last version, we added a column that prevents the actuator from dislodging itself from the case with vibrations. The wristband size is 0.2 by 40 by 60-mm with a fabric strap joint to the plastic frame on both sides to keep the frame on the wrist and dorsal forearm (Figure 3.8).

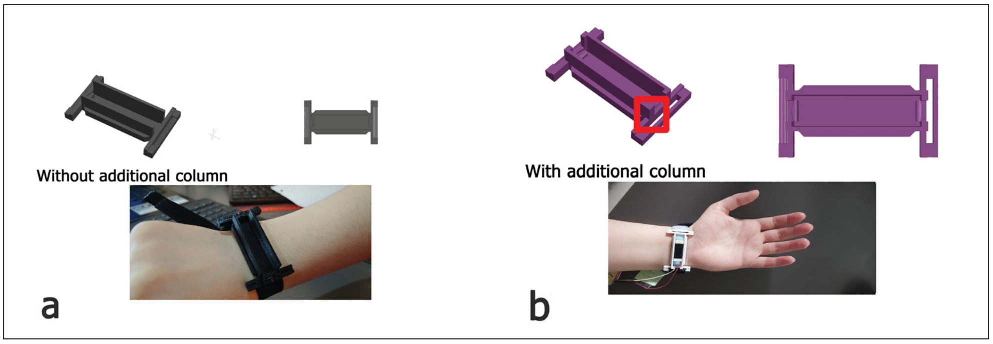

Figure 3.8 Last two versions of the second iterations of wristband:
a) Version 3, b) Version 4

3.3 Signal generation

The actuators vibrate as they receive audio signals from a sound card. The wave form is sent to an audio card, and the actuator connected to the audio card vibrates as it receives the audio signal. We found that a typical audio card is not sufficient as the output signal quality is low and there is cross-talk between the two channels of the stereo output. To solve these problems, we compared different audio cards and decided to use the Sound BlasterX G6 audio USB card (Figure 3.9) as it could work with a high gain without any signal interference. The left and right channels use discrete amplification circuits; in other words, the Xamp discrete headphone Bi-amp allows sound to be produced in a dual mono configuration. This sound card is used for gaming purposes to improve audio quality and offers higher quality signals than a typical sound card, including eliminating crosstalk between the stereo channels.

3.4 Software

The software was programmed to generate sinusoidal signals to be output by the sound card to drive the actuators. It also has a graphical user interface for communication with participant and experimenter. The software has two components: a library that generates and plays audio files, and the graphical user interface that controls the experiment. We developed this software in C#. We explain below each part of the software (Figure 3.10).

Figure 3.9 Picture of the Sound BlasterX G6 USB sound card

3.4.1 Frequency Generator Library

We developed a library to generate, play, and save all vibrator wave forms in a WAV format. This library has a class (WaveFrequencyGenerator) and a method (generateFrequency) that can generate, play, and save audio files using predefined properties such as frequency, amplitude, the SD, and the SOA for each waveform. This library has nine different properties shown in Figure 3.11. It is possible to get and set data for each property. To produce a WAV file, the library should be called as a reference, then an instantiation of the class should be created, and finally each property should be set. In this step, the method could generate, play and save the desired WAV file with a specific file name using test number, current date, and time of the system.

3.4.2 Main class and Graphical User Interfaces

We have different components: Main class, GUI's, and an Excel file. Main class provides the communication between the GUI, Frequency Generator Library, and an Excel file.

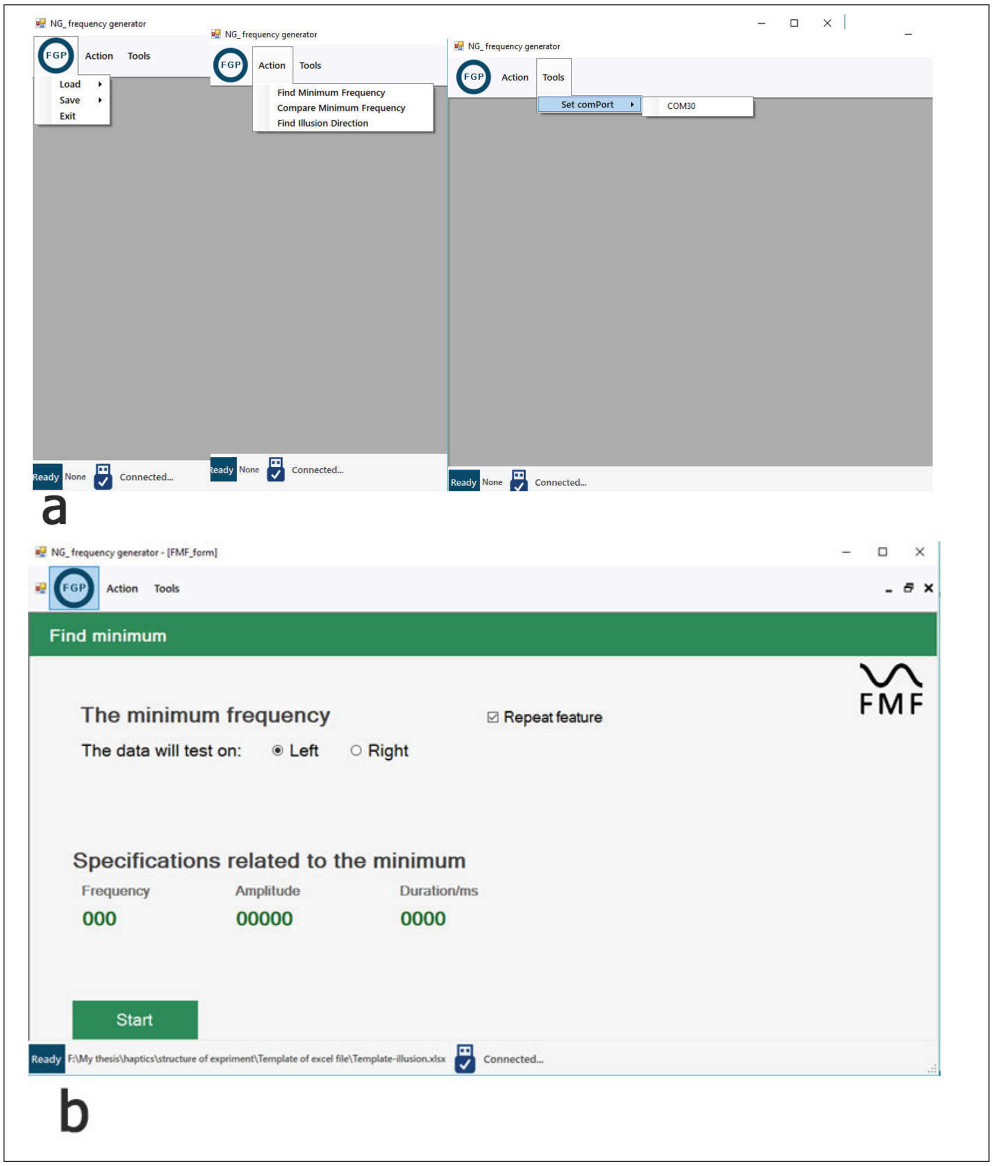

Figure 3.10 Two different pages of software: a) main Form, b) sample of child form

We used an Excel file to read parameters such as frequency, SOA, the SD, and amplitude; we also saved data from participants in the Excel file.

We developed a GUI to control the different parts of our experiment. For each part, we designed a different form. We design the GUI to communicate with the participants and show the status of the Interface Device in real-time. In the paragraphs below, we will explain each component separately.

Regarding the main class, in the "Frequency Generator Platform," we have a main form that manages and controls all the main tasks. This class communicates with an Excel file with predefined data related to each test. This class reads the value of each parameter, for example, frequency or amplitude, and writes the data that comes from the inputs of participants in the Excel file; it uses a DLL called “Microsoft.Office.Interop.Excel” to fetch and save data in the Excel file. In fact, as we have nine properties to generate each WAV file. The main form could connect to the three different componentss: the library that we developed, called “Frequency Generator DLL”, the library to read and write data from the Excel file, and the Interface Device.

In each test, we used an Excel file to specify a list of waveforms with different properties such as frequency and amplitude. This data needs to be defined before running each part of the test, so we decided to use an Excel file as our database. Moreover, the participant’s response for each trial needs to be recorded in the Excel file for later analysis.

We have four different child forms by the name of “CMF_form”, “FID_Form”, “FMF_form”, and “questionDialog” as the GUI’s. We designed these forms for different parts of our experiments. They are connected directly to the "questiondialog" form, as shown in Figure 3.11. As a result, these forms can load the question and send or receive data from the user via "questionDialog" form. Therefore the main class can communicate with the user through these four child forms. All data from the Interface Device are sent via a serial port to the main class, and then the four child forms use that data, for example, changing the knob status or pressing a key. Also, if each child form wants to send data to the Interface Device, they pass their data to the main class, and then via a serial port, the data is sent to the Interface Device.

3.5 Interface Device

We designed an integrated Interface Device for taking inputs from and sending outputs to the participants. There were different commercially available keyboards and knobs that work

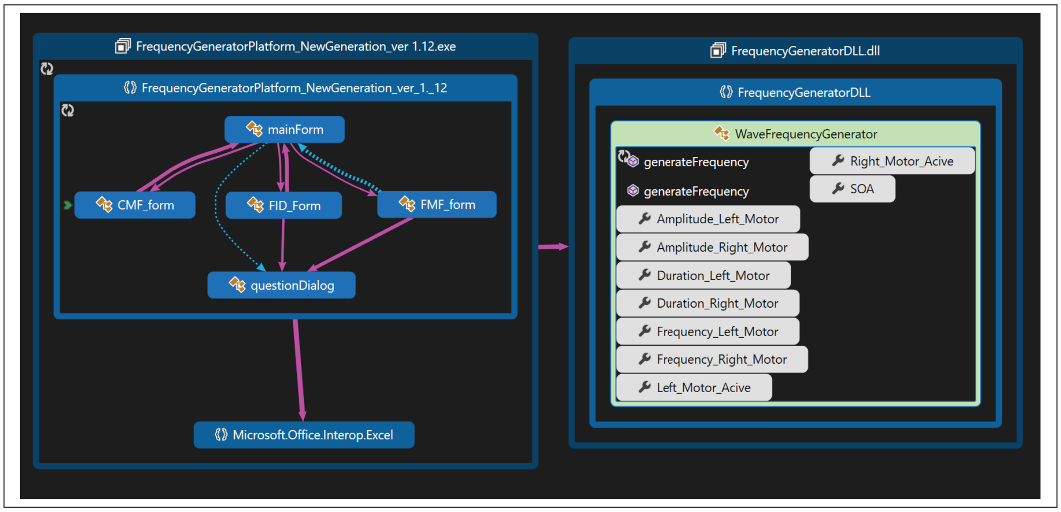

Figure 3.11 Two blocks of software: The left block is the Frequency Generator Platform with its main and child forms, and the right block is the Frequency Generator DLL with its 9 properties and two methods

separately. Commercial knobs can change the master volume of the system but can't connect to custom software to change a parameter (such as the vibration amplitude in our software). Commercial knobs can also change the volume with only a resolution of 100 units (from 0 to 100), but we needed a knob to change the amplitude from 0 to 32000 as the accuracy of the wave's amplitude can change in 32000 steps. The knob also allows the participants in our experiments to easily adjust the intensity of vibrations with their non-dominant hand while their dominant hand's arm wears the haptic devices. We therefore decided to design an Interface Device that combines a knob and a keypad in a single device to make communication with the system easier for the participants. It has keys and a knob that participants use to communicate with the software; it also has an OLED and Matrix LED display to show data (Figure 3.12). The specification of the components of the Interface Device are in Appendix I, Figure-A I-1.

3.5.1 Interface Device Code and Component Communication

The Interface Device has different components that are connected to Arduino microcontroller (Figure 3.13). Each component has a different type of communication with the Arduino. For

Figure 3.12 The Interface Device

example, the connection of the knob is by interrupt, but the OLED display communicates with the I2C protocol. The Interface Device is connected to a computer via the USB port.

C/C++ code was developed to control the Interface Device components that send and receive real-time data. The code has three significant parts: initialize, loop, and interrupt. First, the code initializes all different hardware components of the Interface Device. Next, The main loop controls keypad and OLED and LED Matrix; simultaneously, there is an interrupt to check the status of the knob as this action has priority compared to other actions (Appendix I, Figure-A I-2).

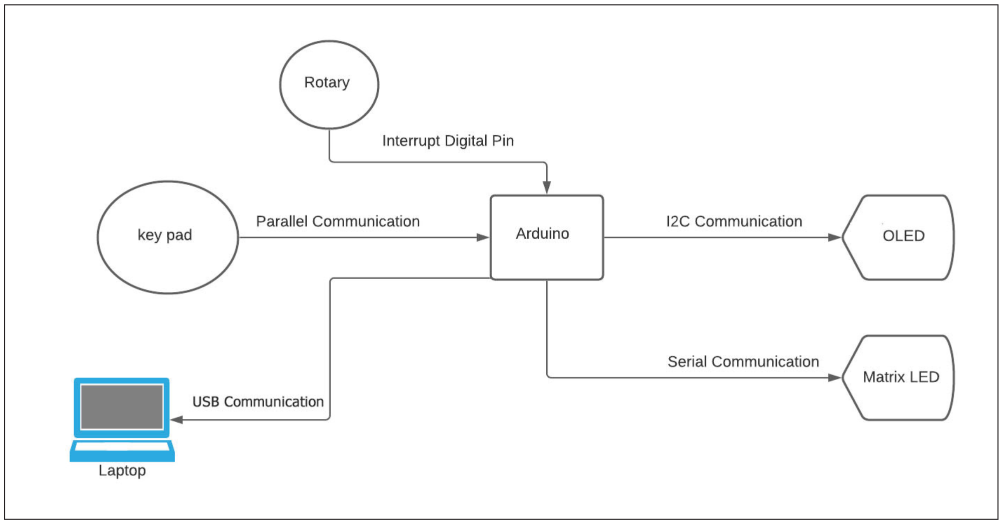

Figure 3.13 Block diagram of the Interface Device and communication between its different components

CHAPTER 4

EXPERIMENTS

In this Section, we report an investigation of the effect of frequency variations on the detection of a tactile illusion. More specifically, we want to know how apparent tactile motion is perceived when the two stimulations' frequencies are not the same. Two pilot studies allowed us to investigate the optimal parameters for the experiments and also to improve the experimental protocol. These parameters were the duration, the range of frequency, and the amplitude. The next step was to conduct two experiments with 15 participants, with the goal of finding the effect of mismatched vibration frequencies on the illusion. We hypothesized that in a forced-choice task where the user is subjected to two vibrations at different locations at nearly the same time, as the frequency mismatch increases, there is an increasing error rate of the perceived direction of motion. We assumed that the rate of apparent tactile motion detection would be high when the two frequencies are the same and that by increasing the difference between these two vibratory frequencies, the rate of apparent tactile motion detection would decrease.

Chapter 4 is as follows: Section 4.1 and Section 4.2 describe the two pilot studies and two experiments. Section 4.3, we analyze the data from each study. Finally, Section 4.4 concludes the experiments and report of the effect of a frequency mismatch of the apparent tactile motion illusion.

4.1 Methodology

4.1.1 Participants

Overall, we had 25 participants in four studies. 44% of participants were female, and 56% were male. Only two participants were left-handed, and 23 participants were right-handed. All participants were naive regarding haptic illusions. The data of two participants was removed from the analysis as the participants stopped the test in the middle of the experiment. In Table 4.1, you can find all details regarding the participants for each experiment. We labeled participants with the letter P and a number; for example, P1 means participant 1.

Table 4.1 Participant information for each experiment

Experiment	**Number of Participants**	**Labels**	**Removed from analysis**
Pilot 1	6	P1–P6	P6
Pilot 2	4	P7–P10	N/A
Experiment 1	5	P11–P15	P15
Experiment 2	10	P16–P25	N/A

4.1.2 Experimental setup

We thoroughly explained all devices used during the experiments in Chapter 3. In summary, two custom-designed frames held the two actuators and were placed perpendicular to the arm bone on the dorsal forearm and wrist. Figure 3.7 shows a person wearing the two wristbands. During all experiments, the distance between the two actuators (from center to center) was 8 cm. We asked participants to wear the wristbands on the arm of their dominant hand.

4.1.3 Stimulation parameters

Different parameters affect the perception of vibration and apparent tactile motion. In the following Section, we explain the major parameters and the reason for selecting these parameters.

4.1.3.1 Frequency

We decide to focus on 11 frequencies: 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, and 300 Hz. We know from the literature review that the most sensitive range of frequency for humans is 200-300 Hz (Verrillo, 1985). Also, the highest mechanical resonance of the actuators is between 85 and 125 Hz. Then for continuous apparent tactile motion, the lower range of frequency is preferable to the higher range (Israr & Poupyrev, 2011b). The selected range of frequencies covers all these important ranges. It is important to note that based on previous studies, distinguishing two frequencies is possible with a 10% difference in frequency, so the difference between all 11 steps of frequencies in our research is equal to or greater than approximately 10% (MacLean & Enriquez, 2003).

4.1.3.2 Timing

One of the major parameters for the perception of apparent tactile motion is the Stimulus Onset Asynchrony (SOA). If the SOA is below or above a certain range the apparent tactile motion will not be felt. In fact, the vibration of two actuators will be felt as a single vibration or as two separate vibrations, respectively (Israr & Poupyrev, 2011a).
Before conducting the experiment, it was important to select an appropriate SOA value that produces apparent tactile motion. Based on the findings of Israr & Poupyrev (2011b) and Kohli *et al.* (2006), we decided to use SD=200 msec and SOA=111 msec, which is expected to produce a fast apparent tactile motion. In some parts of the experiment, we need participants to feel the two vibrations completely separately, so we use SD=1000 msec and SOA=1500 msec (pleases see section 2.1 for more details).

4.1.3.3 Waveform

Vibration pulses produced as sinusoidal waves are more distinguishable than other wave forms like saw-tooth or square (Kohli *et al.*, 2006). We decided to use sinusoidal waveform for our studies.

4.2 Experiments

The study's goal was to find the effect of the discrepancy between frequencies of the first and second actuators in two body locations on the detection of apparent tactile motion. To determine whether that apparent tactile motion has been felt, we ask the participant to detect the direction of the motion. To achieve our goal, we did a sequence of two pilot studies to improve the protocol and determine how many trials can be run in a 90-minute session. Then we ran the actual study with more participants in two separate experiments.

Generally, in all pilot studies and experiments, we have two parts: **Normalization** and **Detection**. For the Normalization part, we have two steps: first, we find the frequency that produces the lowest perceived intensity and then normalize all other frequencies to it. In the first step, we find the frequency (out of our set of frequencies, see Section 4.1.3.1) that results in the lowest perceived intensity. We called this frequency the weakest frequency. In the second step, we adjust the perceived intensity at all frequencies to match that of the weakest frequency (the frequency with the lowest perceived intensity). In order to reduce the effect of the perceived intensity on the detection of the illusion and only examine the effect of different frequencies, we decided to make the perceived intensity the same at each vibratory frequency. In Detection part, we asked participants to detect the direction of apparent tactile motion.

4.2.1 Pilot study 1

We ran pilot study 1 on one pair of locations on the body: the forearm and the wrist. The distance between the center of the two actuators was 8 cm. The forearm site was studied in many research. In the paragraphs below, we describe each step and then briefly explain the results of pilot study 1.

- **Step1-Finding the Weakest Frequency:** In this first step, we find the frequency with the lowest perceived intensity between the set of frequencies from 50 to 300 Hz. In details, we asked participants to find the frequency that produces the minimum perceived intensity between 11 frequencies with a two-alternative forced-choice paired comparison paradigm (Leek, 2001). After a short training session, participants began the study. To compare two different frequencies, the actuator was attached on participants' dorsal forearm. They received two vibrations with two different frequencies and the same amplitude. Participants received two vibrations with the same duration (SD = 1000 msec and the SOA = 1500 msec) and two different frequencies in the same locus, and then selected the frequency that produced the weakest intensity. Next, the selected frequency was compared with a new frequency from the set of frequencies. Again, the participants selected the weakest one. This process continued until the end of the frequency list.

The frequency list was from 50 to 300 Hz (10 different comparisons), and participants could repeat each pair of vibrations until they found the weakest one. Also, the order was randomized for each participant. During the study, participants were instructed to press a button labelled “1” on the keypad of the Interface Device if they felt that the first vibration was weaker than the second; otherwise they pressed a button labelled “2” (Figure 4.1). After pressing one of these buttons, the next pair was produced automatically. The vibrations were assigned to 1 and 2 randomly. Participants were allowed to rest after this part for 10 minutes to be ready for the next step. The time of this part of the pilot test was around 10 minutes.

- **Step 2-Normalization against Weakest Frequency:**

In the second step of the study, we adjust the vibration amplitude at each frequency and body location. Based on prior works, we assume that the perceived intensity on the forearm is always weaker than the wrist so, we therefore assume that the Weakest Frequency at the forearm is always the weakest one in both the forearm and the wrist and we normalized all frequencies and locations to match it.

In the first block, we adjust amplitude when the Weakest Frequency is produced on the forearm, and all frequencies are also produced on the forearm. In the second block, we adjust the perceived intensity of frequencies when the Weakest Frequency is produced on the forearm and all other frequencies are produced on the wrist. We asked the participant to normalize each vibration’s perceived intensity so that it matches the Weakest Frequency that determined from previous step. They received the Weakest Frequency for 1000 msec with the maximum amplitude, and after 1500 msec they received the second frequency and changed its amplitude until they felt that both vibrations produced the same perceived intensity. Then, a vibration with another frequency was compared with the Weakest Frequency. The participants had a 10 minute break between the first and second block. The set of frequencies that were compared with the Weakest Frequency was from 50 to 300 Hz (table 4.11).

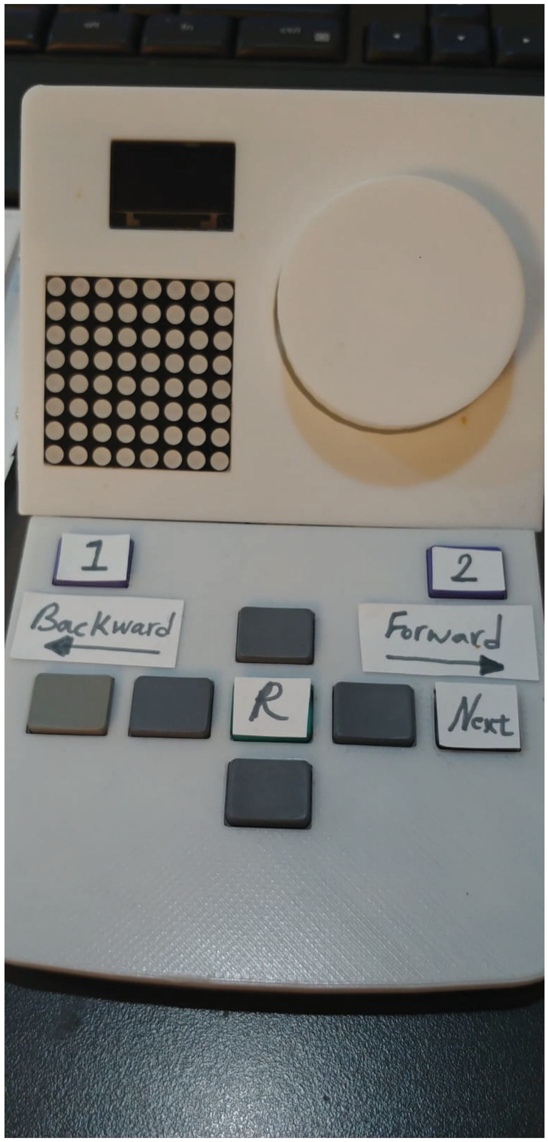

Figure 4.1 Interface Device with labelled buttons used for these experiments

As step 2 started, the participants received both vibrations. If they felt that both vibrations have the same intensity, they pressed the button with the label "Next". If they felt that the two vibrations have different intensities, they decreased the second vibration's amplitude using the knob and pressed the button with the label "R" to feel the new adjustments. Every time that they pressed "R", they received both vibrations. When they felt that both vibrations had the same intensity after unlimited repetitions, they pressed "Next" to receive the next pair of vibrations. There were 11 vibration pairs on the forearm and 11 pairs on the forearm and the wrist. There were 22 sets in total. The duration of this part of the pilot test was around 35 minutes.

- **Detection:** We want to know how vibratory frequency mismatch affects the apparent tactile motion, so we ask participants to detect the direction of apparent tactile motion. We assume that if they detect the direction, they understand the start and endpoint of the vibratory motion. This part aimed to find the effect of mismatched vibratory frequencies on the detection of the direction of apparent tactile motion when the perceived intensity at all frequencies and body locations was normalized based on the results of the normalization study. Also, the order of vibratory pairs was randomized for each participant. We used the normalized amplitude to be sure that the two actuators felt equally strong at all frequencies and locations.

  In each trial, we had two different vibration frequencies and fixed timing parameters (SD=200 msec and SOA=111 msec). The apparent tactile motion was produced in one of two directions: Forward or Backward. We consider the direction as "Forward" (Figure 4.2) when the vibration moves from the forearm to the wrist. The actuators then produced a vibration on the forearm with one of the reference frequencies (50, 125, or 300 Hz), followed by a vibration on the wrist with a vibration frequency from the list of frequencies (50 to 300 Hz). To produce the Backward movement (Figure 4.2), the vibration moved in the reverse direction, from the wrist to the forearm. The wrist vibrated first with a reference frequency of 50, 125 or 30 Hz, and then the forearm with a vibration frequency from 50 to 300 Hz.

  Therefore 66 pair of stimuli were produced (Appendix II, Table-A II-3) and repeated 3 times. Each individual set of illusions was also repeated three times with a 1500 msec gap between each repetition. After three repetitions of pairs of stimuli in each trial, participants had to select the direction with a two-alternative forced-choice. If they detected that the illusion direction was Forward, they pressed the button with the label Forward. If they felt that the illusion was Backward, they pressed the button with the label Backward. As soon as they pressed one of the two buttons, the next vibration was produced. The duration of this part of the study was around 35 minutes. We recorded their answers for a total of 198 trials.

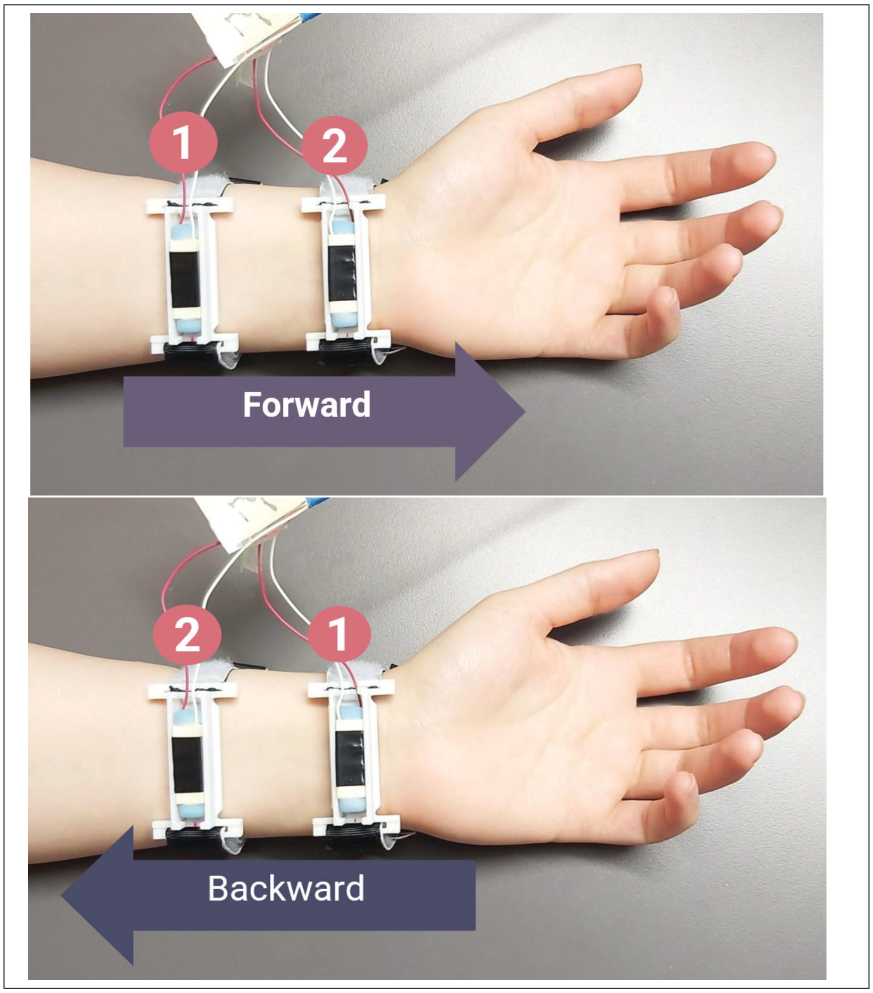

Figure 4.2 Two different directions of movement. up) Forward: vibration was from the forearm to the wrist, down) Backward: vibration was from the wrist to the forearm

- **Results:** The results from the first step show that vibrations with a frequency of 300 Hz produce the weakest feeling of intensity. The actuator response to changing frequency (Figure 3.3) shows the highest acceleration of the actuator was at 96 Hz, and after this peak, the output acceleration goes down. So the acceleration of the actuator is not high in 300 Hz; thus, participants selected this frequency as the weakest one.

From an analysis of the data of the second step (Appendix II, Table-A II-2, II-1), we found that frequencies between 50 and 100 Hz are stronger, which means that we have to set their amplitude to 6% to match the weaker vibrations at 300 Hz. This difference is especially felt when the Weakest Frequency was stimulated on the forearm and another on the wrist. We assume three reasons for that. Firstly, the actuator's maximum acceleration output is in the range of 46 and 146 Hz with a peak of 96 Hz, and the acceleration decreases to less than 2.5 G for higher frequencies (TactileLabs, 2021). Therefore, the intensity of frequencies in this range should be decreased sharply to have the same feeling of intensity with 300 Hz. Secondly, the actuator output acceleration is low at 300 Hz, so participants found 300 Hz to be the weakest frequency. Finally, the forearm's detection threshold as a function of frequency is almost two times higher than the hand (Jones & Sarter, 2008).

Regarding the effect of mismatched vibration frequency on the detection of the direction of apparent tactile motion, the results indicate that the frequency gap between two actuators is not a significant parameter to change the successes of detection ($F(10,44) = 0.356$, $p = 0.959$). The data was analyzed with a one-way repeated measure ANOVA with one factor: the difference in frequency between two actuators (Appendix II, Figure-A II-1). The null hypothesis was that the frequency gap between two actuators is not a significant parameter that changes the success of motion direction detection.

We assume that using only 6% of the maximum vibration amplitude was too low and could affect the results, so we decided to remove the last two frequencies (275 and 300 Hz) from the frequencies and consider 250 Hz as a Weakest Frequency and then run the all three parts again in the pilot test 2 with this new range of frequencies.

4.2.2 Pilot study 2

We found that the frequency mismatch did not affect the detection of the direction of movement in pilot study 1; we assumed that these results might be because the signals are too weak when adjusting the perceived intensity of all frequencies with 300 Hz. So we decided to rerun all three parts as a pilot study 2, but this time, we reduced the range of frequency from 300 to 250 Hz.

We ran the second pilot with the same parts and parameters, and just the range of frequencies decreased. In the paragraph below, we explain the process.

- **Step1-Finding the Weakest Frequency:** For the first step participants ordered the frequency list again from 50 to 250 Hz. There were 8 pairs of comparisons. All other steps and parameters were the same as on pilot study 1.

- **Step 2-Normalization against Weakest Frequency:** For the second step, participants compared and normalized the frequency list with the Weakest Frequency from step 1. The 18 pairs of frequencies were compared.

- **Detection:** In this part, we try to find the effect of mismatch frequency vibratory on the detection of motion. After reducing the range of frequencies, we had a new range of frequencies from 50 to 250 Hz. We changed one of the reference frequencies. We had 125 Hz as a Reference Frequency in pilot study, but we changed this value to 150 Hz. Then with the new range of frequency, we have three reference frequencies (50, 150 and 250 Hz) with the same interval (100 Hz). As a result, we had 54 pairs of different trials, with each trial repeated 3 times, and we had a total 162 trials. The duration of this part of the pilot test was around 30 minutes. We recorded their answers for a total of 162 trials. All other steps or parameters were the same as pilot study 1.

- **Results:** The result shows that participants selected 250 Hz as the frequency that produced the weakest perceived intensity.We found that the average selected intensity for the lower range frequencies at the wrist increased at least to 10% of the maximum possible intensity in that range. As a result, we had stronger vibrations with 250 Hz than 300 Hz as a Weakest Frequency.

  Regarding the detection of direction, we found that there was again no significant effect of the mismatch in frequency (Appendix II, Figure-A II-2) on the detection of direction of apparent tactile motion ($F(8,27) = 0.189$, $p = 0.99$). The data was again analyzed with one-way repeated measure ANOVA with one factor. We assume that it might be related to the fact that we ran the normalization only once per participant, and that the results may therefore not be sufficiently accurate. So we decided to run the normalization of perceived intensity three times for each frequency for the next experiment. As in one session experiment, it was impossible to run normalization three times and detect the direction of illusion multiple times; we decide to separate these two parts in two different experiments.

From the two pilot studies, we decided to change three items for the experiment: We removed first step (Finding the weakest Frequency) as we assume that 250 Hz will be the frequency at which the sensations are the weakest. Starting with pilot study 2, we decreased the frequencies from 11 items to 9 items (we removed the last two frequencies) to improve the intensity of vibration in the lower range of frequencies. As a result, we produced vibrations with higher intensity. As our goal was to increase the accuracy of the normalization by increasing the number of repetitions, we separate the normalization and detection parts in two different experiments. Another reason was that participants reported that they felt tired after the first and the second part of the test, and it also was impossible to run all trials in one session (90 minutes).

4.2.3 Experiment

From the result of pilot studies 1 and 2, we hypothesized that increasing the accuracy of the normalization data may improve the final results. So we decided to normalize the perceived intensity of each frequency multiple times, and we designed a new experiment with two sub experiments with two groups of participants. First, in Experiment 1, we normalized frequencies from 50 to 250 Hz against a Weakest Frequency of 250 Hz. Then in the second experiment, we used the result of experiment 1 to adjust the perceived intensity and ran experiment 2 to find the effect of mismatched vibratory frequencies on the detection of the direction of apparent tactile motion. In the two subsections below, we describe each experiment.

4.2.3.1 Experiment 1

In Experiment 1, the goal was to adjust the perceived intensity for each frequency multiple times. We asked participants to normalize the perceived intensity of the frequencies on both forearm and the wrist when they received the Weakest Frequency on the forearm. As we mentioned in pilot study 2, participants received 9 different frequencies on the forearm, and for each one, they decreased the vibration amplitude until they felt the same intensity as the Weakest Frequency. Each participant repeated 3 times the normalization of the intensity for each frequency. Other parameters were the same as the two previous pilot studies.

We removed the data of P15 as this participant felt tired and did not complete the experiment. Tables 4.2 and 4.3 show the mean amplitude for each frequency for 4 participants, with all participants' mean for both the forearm and the wrist. See Appendix II for more detailed results. We used the mean of all participants for the next experiment to unify the perception of vibrations (from the amplitude side) of 9 different frequencies. In general, the selected amplitude increased when the range of frequency increased from 50 to 250 Hz. Participants almost selected the same amplitude when comparing 200, 225 and 250 Hz with the Weakest Frequency (250 Hz) on the forearm and the wrist.

Table 4.2 Selected amplitude for each participant and the mean of all participants on the forearm (Experiment 1)

Frequency (Hz)	**P11**	**P12**	**P13**	**P14**	**Average**
50	12%	16%	31%	16%	19%
75	8%	8%	11%	8%	9%
100	9%	8%	12%	8%	9%
125	11%	8%	14%	9%	11%
150	31%	11%	22%	13%	19%
175	42%	17%	69%	68%	49%
200	71%	65%	99%	76%	78%
225	100%	100%	97%	100%	99%
250	100%	100%	99%	100%	100%

4.2.3.2 Experiment 2

In this experiment, we had the same goal as in the detection part pilot studies 1 and 2. We aimed to find the effect of mismatched vibratory frequencies on the detection of the direction of apparent tactile motion. All conditions were the same as pilot study 2: 54 pairs of vibrations

Table 4.3 Selected amplitude for each participant and the mean of all participants on the wrist (Experiment 1)

Frequency (Hz)	**P11**	**P12**	**P13**	**P14**	**Average**
50	6%	7%	23%	7%	11%
75	6%	6%	10%	6%	7%
100	4%	5%	17%	4%	8%
125	8%	8%	21%	4%	10%
150	16%	11%	55%	11%	23%
175	20%	54%	89%	12%	43%
200	93%	63%	98%	45%	75%
225	94%	100%	100%	67%	90%
250	97%	76%	100%	48%	80%

were produced (table 4.4), and each pair of vibrations was repeated 5 times. Each session's duration was around 10 minutes, and we had 4 sessions with 3 breaks of 10 minutes. The duration of this experiment was around 70 minutes. We recorded their answers for a total of 270 trials. In each session, they received 68 trials.

4.2.4 Data Analysis

After the experiment 2 was finished, we prepared the data for the analysis part. Participants received 54 different pairs of vibration, and each pair was repeated five times. We therefore recorded 270 different responses for each participant. If participants detected the direction of apparent tactile motion correctly, we would consider one for that trial. If they answered incorrectly, then we considered zero for that trial. we calculated the average success of detection for both forward and backward detection. It is important to note that based on the previous results, it is very likely that participants felt complete motion .when we discuss with them informally at the end of the experiment, people reported the feeling motion; therefore, we had a good impression that this is actually detecting tactile motion, but we can guarantee it because our question did not ask that specifically and it is possible some participants feel the sequence and guess the direction from that.

Table 4.4 The Vibratory frequency for each trial (Experiment 2)

Forward Direction		Backward Direction	
Frequency on the forearm (Hz)	**Frequency on the wrist (Hz)**	**Frequency on the forearm (Hz)**	**Frequency on the wrist (Hz)**
50	50	50	50
50	75	75	50
50	100	100	50
50	125	125	50
50	150	150	50
50	175	175	50
50	200	200	50
50	225	225	50
50	250	250	50
150	50	50	150
150	75	75	150
150	100	100	150
150	125	125	150
150	150	150	150
150	175	175	150
150	200	200	150
150	225	225	150
150	250	250	150
250	50	50	250
250	75	75	250
250	100	100	250
250	125	125	250
250	150	150	250
250	175	175	250
250	200	200	250
250	225	225	250
250	250	250	250

4.3 Results

We analyze the data in three different aspects: first, we calculate the total mean and standard error of the success of illusion detection for 54 different pairs. Secondly, we tried to find the effect of frequency variations on two actuators by ordering the data based on the total frequency gap between two vibrations changed from 0 Hz difference (when the frequency of two actuators was equal) to 200 Hz (when the frequency of one actuator was 250 Hz another was 50 Hz); they were 9 different gaps. Finally, we analyze the data for each different Reference Frequency separately when one actuator vibrated with one Reference Frequency (for example, 50 Hz) and the second one changed from 50 to 250 Hz.

4.3.1 Mean, standard error of success rate

Figure 4.3 and Table 4.5 present the mean success for both the Backward and Forward direction of each Reference Frequency for the 10 participants, with standard error. The mean success for each reference frequencies is between 66% to 78% for two directions. In the forward direction, the mean of reference frequencies are almost the same, but for the backward direction, 150 Hz has the highest average rate of detection, and second and third are 250 and 50 Hz, respectively. The average detection rate without considering the direction (sum of two directions) is 77% for 150 and 250 Hz frequencies; This value for 50 Hz is 71%. The standard error for all direction and reference frequencies are equal to or less than 3% of the success rate. From these results we found that the illusion was felt by all participants in different conditions. The mean of direct detection for three reference frequencies and both backward and forward directions was almost the same. Therefore, we decide not to consider the success rate of direction separately and calculate the average rate of direct detection of both backward and forward.

Table 4.5 The mean success rate for Backward and Forward directions, with standard error (Three reference frequencies: 50, 150, and 250 Hz)

Mean			
	Mean Forward	**Mean Backward**	**Total**
50 Hz	77%	66%	72%
150 Hz	76%	78%	77%
250 Hz	77%	76%	77%
Standard error			
	Mean Forward	**Mean Backward**	**Total**
50 Hz	3%	2%	2%
150 Hz	2%	2%	2%
250 Hz	2%	2%	1%

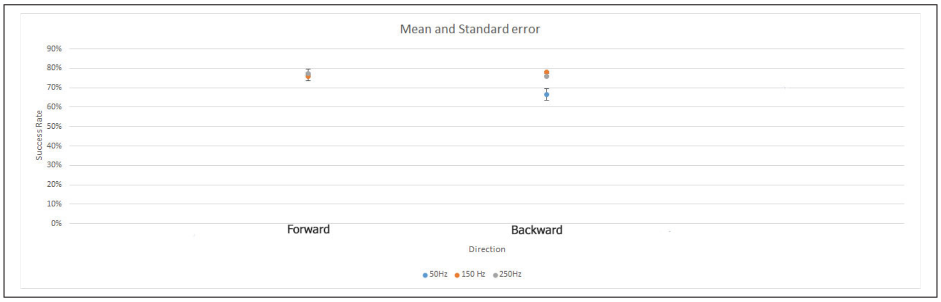

Figure 4.3 The mean success rate for Backward and Forward directions, with standard error (3 reference frequencies 50,150, and 250 Hz)

4.3.2 The effect of vibratory frequency's mismatch on detection based on Frequency differences

Table 4.6 and Figure 4.4 show the mean success of direction detection for each participant based on the difference in frequency between two vibrations where 0 Hz means the difference of frequency of two vibrations is equal to zero. We calculated the average rate of success for each participant whenever the frequency difference between two vibrations was, for example, zero and the average for each participant. Table 4.7 shows the normal distribution analysis for all observations; we perform Shapiro–Wilks's W test with the null hypothesis that the data is distributed normally. Since the p-value was more significant than 0.05 for all observations, we fail to reject the null hypothesis, and data were normally distributed. The data is analyzed with a one-way repeated measure ANOVA with one factor: the difference in frequency between two actuators. The results indicate that the frequency gap between two actuators is not a significant parameter to change the detection rate ($F(8,81) = 0.642$, $p = 0.74$).

4.3.3 Data analysis based on Reference Frequencies

Table 4.8 and Figure 4.5 show the average detection rate for different frequencies when the Reference Frequency on one of the actuators was 50 Hz. Each table cell corresponds to the average rate of detection in both forward and backward directions. The data was analyzed with

Table 4.6 The mean success rate of direct detection for each participant based on the difference frequency between two actuators (Experiment 2)

Participant	**0 Hz**	**25 Hz**	**50 Hz**	**75 Hz**	**100 Hz**	**125 Hz**	**150 Hz**	**175 Hz**	**200 Hz**
P16	78%	73%	75%	78%	55%	60%	80%	65%	70%
P17	80%	73%	63%	63%	83%	55%	75%	40%	75%
P18	78%	53%	83%	70%	65%	55%	75%	75%	75%
P19	83%	73%	78%	73%	78%	55%	50%	90%	75%
P20	88%	73%	75%	73%	68%	70%	80%	70%	65%
P21	70%	70%	83%	60%	80%	60%	70%	50%	95%
P22	95%	78%	83%	73%	75%	80%	90%	85%	85%
P23	73%	53%	65%	60%	60%	80%	55%	65%	50%
P24	85%	88%	95%	93%	85%	90%	95%	90%	80%
P25	95%	100%	93%	93%	88%	95%	95%	90%	100%

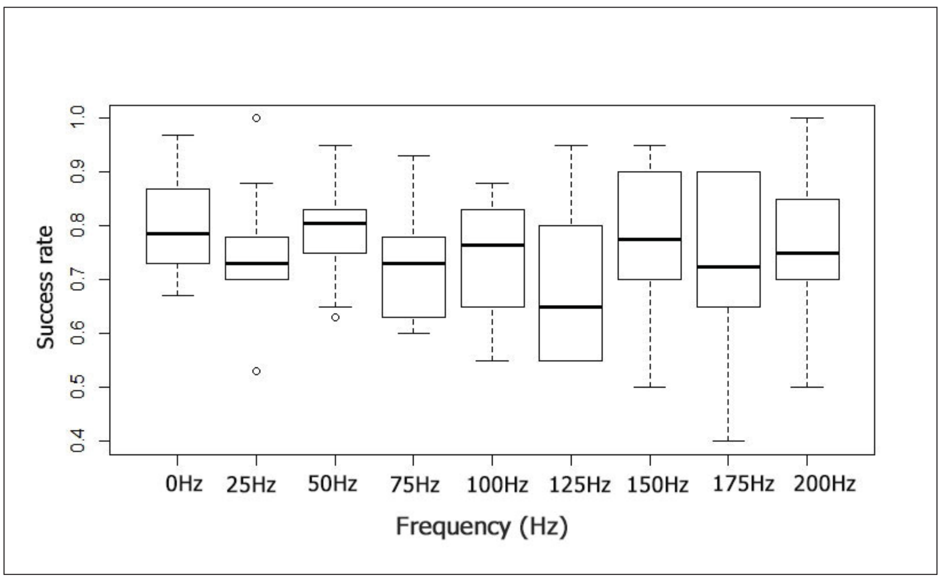

Figure 4.4 The mean success rate of direct detection for each participant based on the difference in frequency between two actuators

one-way repeated measure ANOVA with the one factor: the difference in frequency between two actuators. The results sugested that the frequency gap between two actuators was not a significant parameter to change the detection rate when one side's frequency was 50 Hz ($F(8,81) = 1.108$, $p = 0.366$).

Table 4.7 Shapiro–Wilks's W test for all conditions

The difference frequency between two actuators	W	p-value
0 Hz	0.9498	0.6664
25 Hz	0.9043	0.2443
50 Hz	0.9433	0.59
75 Hz	0.878	0.1239
100 Hz	0.946	0.6209
125 Hz	0.8673	0.0931
150 Hz	0.9241	0.392
175 Hz	0.9007	0.2231
200 Hz	0.9658	0.8495

Table 4.8 The average detection rate for different frequencies when Reference Frequency on one of the actuators was 50 Hz (Experiment 2)

Frequency	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25
50 Hz	40%	70%	90%	90%	80%	60%	90%	70%	80%	100%
75 Hz	60%	80%	60%	70%	60%	90%	70%	70%	80%	100%
100 Hz	70%	70%	80%	80%	70%	80%	80%	70%	90%	90%
125 Hz	60%	40%	70%	60%	80%	60%	70%	40%	100%	80%
150 Hz	40%	90%	40%	70%	60%	60%	100%	60%	100%	90%
175 Hz	60%	40%	80%	50%	80%	60%	80%	70%	80%	90%
200 Hz	80%	70%	80%	60%	60%	70%	90%	40%	100%	90%
225 Hz	60%	20%	60%	80%	60%	30%	70%	60%	80%	80%
250 Hz	60%	80%	80%	80%	60%	90%	80%	40%	80%	100%

Table 4.9 and the Figure 4.6 show the average detection rate for different frequencies when the actuators' Reference Frequency was 150 Hz. Each table cell corresponds to the average rate of detection in both forward and backward directions.

The data analyzed with one-way repeated measure ANOVA with the one factor: the difference in frequency between two actuators. There was no significant effect of frequency variation when one side of actuators frequency were 150 Hz ($F(8,81) = 1.186$, $p = 0.318$).

Table 4.10 and the Figure 4.7 show the average detection rate for different frequencies when the actuators' Reference Frequency was 250 Hz for 10 participants. There were no statistically

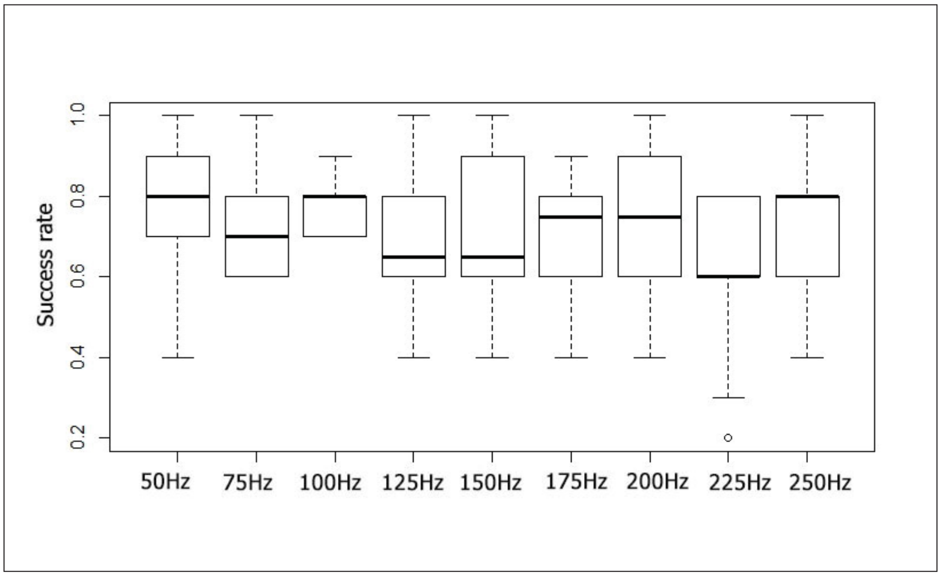

Figure 4.5 The average detection rate for different frequencies when Reference Frequency on one of the actuators was 50 Hz (Experiment 2)

Table 4.9 The average detection rate for different frequencies when Reference Frequency on one of the actuators was 150 Hz (Experiment 2)

Frequency	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**
50 Hz	70%	80%	80%	100%	90%	90%	40%	50%	100%	80%
75 Hz	90%	80%	90%	90%	90%	70%	70%	60%	80%	90%
100 Hz	70%	40%	80%	80%	90%	100%	90%	60%	90%	90%
125 Hz	90%	70%	70%	100%	70%	60%	60%	10%	100%	100%
150 Hz	90%	90%	80%	90%	90%	80%	100%	80%	90%	90%
175 Hz	70%	70%	40%	60%	80%	40%	90%	60%	80%	100%
200 Hz	80%	80%	90%	90%	80%	60%	70%	60%	100%	90%
225 Hz	70%	60%	70%	70%	60%	50%	60%	60%	100%	100%
250 Hz	70%	90%	100%	80%	60%	80%	70%	50%	70%	80%

significant differences between group means as determined by one-way ANOVA ($F(8,81) = 0.606$, $p = 0.77$).

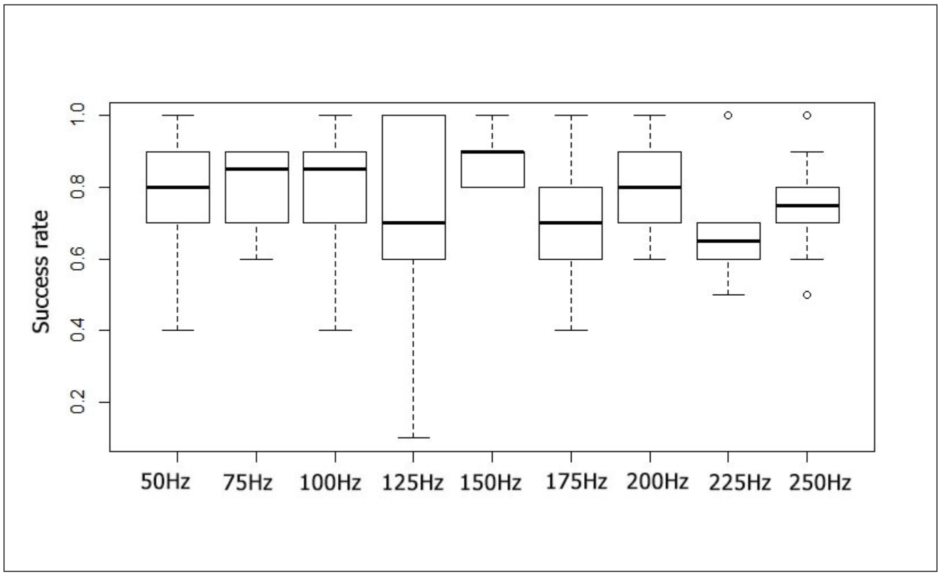

Figure 4.6 The average detection rate for different frequencies when the Reference Frequency on one of the actuators was 150 Hz (Experiment 2)

Table 4.10 The average detection rate for different frequencies when Reference Frequency on one of the actuators was 250 Hz (Experiment 2)

Frequency	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**
50 Hz	80%	70%	70%	70%	70%	100%	90%	60%	80%	100%
75 Hz	70%	60%	90%	100%	80%	70%	100%	70%	100%	100%
100 Hz	80%	80%	70%	40%	100%	70%	90%	70%	90%	100%
125 Hz	60%	70%	30%	60%	60%	60%	80%	90%	100%	100%
150 Hz	40%	70%	40%	60%	60%	90%	90%	80%	70%	100%
175 Hz	90%	70%	50%	70%	60%	60%	90%	80%	90%	100%
200 Hz	80%	60%	80%	60%	60%	90%	90%	70%	100%	100%
225 Hz	70%	70%	40%	60%	80%	90%	90%	70%	90%	100%
250 Hz	90%	70%	60%	60%	90%	60%	90%	60%	80%	100%

4.4 Discussion

This study focused on one of the parameters that affect apparent tactile motion. We considered fixed values for duration, intensity, and the distance between two actuators. Then we focused on

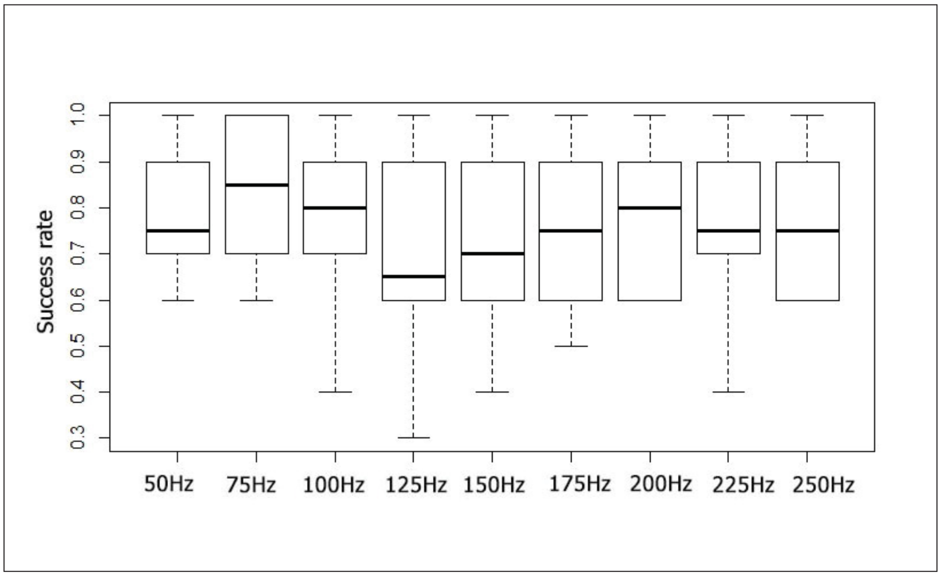

Figure 4.7 The average detection rate for different frequencies when the Reference Frequency on one of the actuators was 250 Hz (Experiment 2)

finding the effect of a vibratory frequency mismatch on apparent tactile motion. In table 4.11, we summarize different experiments and a list the frequencies used in each.

In Section 4.3, we found no statistically significant effect of having two different frequencies on the detection of apparent tactile motion. Looking at Figure 4.4, we found that the success of direction detection was not changed by increasing the difference in frequencies between the two vibrations. The difference in frequency was 0 Hz, the mean detection success rates with differences in frequency of 0 Hz and 200 Hz were almost equal. We found no pattern of increasing or decreasing illusion detection rate when the two actuators' frequency varied. We conclude that apparent tactile motion is perceived when there is a vibratory frequency mismatch, provided that the perceived intensity of the two vibrations is the same. Although not investigated directly in the experiments, our anecdotal evidence suggests that a mismatch in perceived intensity does affect the perception of apparent tactile motion.

It seems that apparent tactile motion can be detected almost as well at all frequency combinations, even when two vibration frequencies are not equal. This result is consistent with prior work,

Table 4.11 The different experiments' parameters

Experiments	**Weakest Frequency**	**Parts**	**Frequencies (Hz)**	**Number of Frequencies**	**Reference frequencies (Hz)**
Pilot1	300Hz	Finding Weakest Frequency	50, 75, 100, 125, 150, 175, 225, 250, 275, 300	11	50, 125, 300
		Normalization			
		Detection			
Pilot2	250Hz	Finding Weakest Frequency	50, 75, 100, 125, 150, 175, 225, 250	9	50, 125, 250
		Normalization			
		Detection			
Experiment 1	250Hz	Normalization	50, 75, 100, 125, 150, 175, 225, 250	9	N/A
Experiment 2	N/A	Detection	50, 75, 100, 125, 150, 175, 225, 250	9	50, 150, 250

which has found that some parameters affect the perception of apparent tactile motion, but typically not frequency. As explained by Sherrick & Rogers (1966) and Sherrick (1968), the SD and the SOA are the most important parameters that affect the apparent tactile motion perception, and frequency variation doesn't have a significant effect on illusion detection. More importantly, other studies like Cholewiak & Collins (2003) and Israr & Poupyrev (2011a) mention that there is no effective influence of frequency variation on detection of locus or boundary of the SOA. However, Israr & Poupyrev (2011b) mention that using a lower range of frequency improves the perception of apparent tactile movement.

A possible explanation for the lack of effect of frequency on apparent tactile movement could be found in the cooperation of various mechanoreceptors for vibration perception in a wide range of frequencies (Bolanowski Jr, Gescheider, Verrillo & Checkosky, 1988; Romo & Salinas, 2003). This may explain why participants always detected the illusion even with a mix of two different frequencies, as each tactile receptor respond to a different range of frequencies. In fact, perception of frequency improves with signal integration through various mechanoreceptor pathways and distinct body locations. Kuroki, Watanabe & Nishida (2017) claim that different types of receptors located within the body could be why humans perceive tactile stimulations. It might be why variation frequency in two actuators do not affect the success rate of direction detection.

CONCLUSION AND RECOMMENDATIONS

This work investigated the effect of using two different vibratory frequencies on the perception of apparent tactile motion in two different body parts. We wanted to know whether a vibratory frequency mismatch affects the perception of the illusion. The most critical parameter in our work was the frequency of vibration, which we studied in a range from 50 to 300 Hz. We aimed to focus on only the effect of frequency, and therefore completely isolated the vibratory frequency. We normalized the amplitude of vibrations for each frequency so that all vibration pulses had the same perceived intensity.

In all conditions, we found that the success rate of direction detection was more than 60%, which suggests that the tactile illusion was generally perceived correctly. After analyzing the data, we found that the difference in frequency between the two actuators did not affect apparent tactile motion detection. Similar conclusions were obtained when analysing the results as as a function of the Reference Frequencies.

Based on previous studies, we can conclude that illusion detection is more related to other parameters such as timing, body part, or the fact that vibratory perception is integrated from different mechanoreceptors at the same time. A similar study on the fingers (Kwon *et al.*, 2021) found that apparent tactile motion is felt in both high and low frequencies, and combinations of the two. They indicated that although different stimulation was felt with different mechanoreceptors, the stimulation was interpreted as a single motion.

Our results did not confirm our hypothesis. We assumed that a vibratory frequency mismatch would affect the perception of apparent tactile motion. Based on our findings, a vibratory mismatch frequency does not affect the perception of apparent tactile motion and the illusion can be felt despite a vibratory frequency mismatch. In practice, this result means that as long as two actuators are matched in perceived intensity, it is possible to produce the illusion even with mismatched vibratory frequencies.

This work was motivated by the need to improve the experience of illusions when using multiple haptic devices, for example, the movement of a vibration between a smartwatch and a handheld controller. As these devices are manufactured by different companies, the illusions might not be perceive well due to differences in the range of vibratory frequency or perceived amplitude of these devices. It can be concluded from our experiments that it is possible to perceive apparent tactile illusion with a combination of different devices that produce a different range of vibratory frequencies as long as they produced the same perceived intensity.

Future work could include the investigation of the effect of other parts of the body, such as the wrist and palm, or of tactile motion speed, such as faster or slower apparent tactile motion. The variation in mechanoreceptors density on different parts of the body and different timing parameters might affect illusion detection.

Another topic suggested for future work is a comparison of the subjective sensation produced by apparent tactile motion with mismatched vibratory frequency. Indeed, our preliminary results suggest that while perceptible, the apparent tactile motion may be qualitatively different when frequencies are mismatched.

We also want to know what is the effect of a mismatch in perceived intensity. What will happen if the perceived intensity is not the same for the two actuators? What if both the perceived intensity and frequency vary? It may for example not be possible to feel apparent tactile motion when one actuator is much stronger than the other.

We hope that the findings of this research and the proposed future work will help inform the design of tactile devices so that they can better present apparent tactile motion when used together.

APPENDIX I

EXPERIMENTAL SETUP SPECIFICATION

1. Specification of Interface Device components

From the figure I-1 the Interface Device or keypad was made from different electronic pieces: 38-mm 8*8 SQUARE MATRIX LED MATCH, ROTARY ENCODER MECHANICAL 24 PPR, GROVE - OLED DISPLAY 0.96 (SSD1), ARDUINO NANO ATMEGA 328 EVAL BRD and simple calculator pad and also a frame to hold and shaped the keypad.

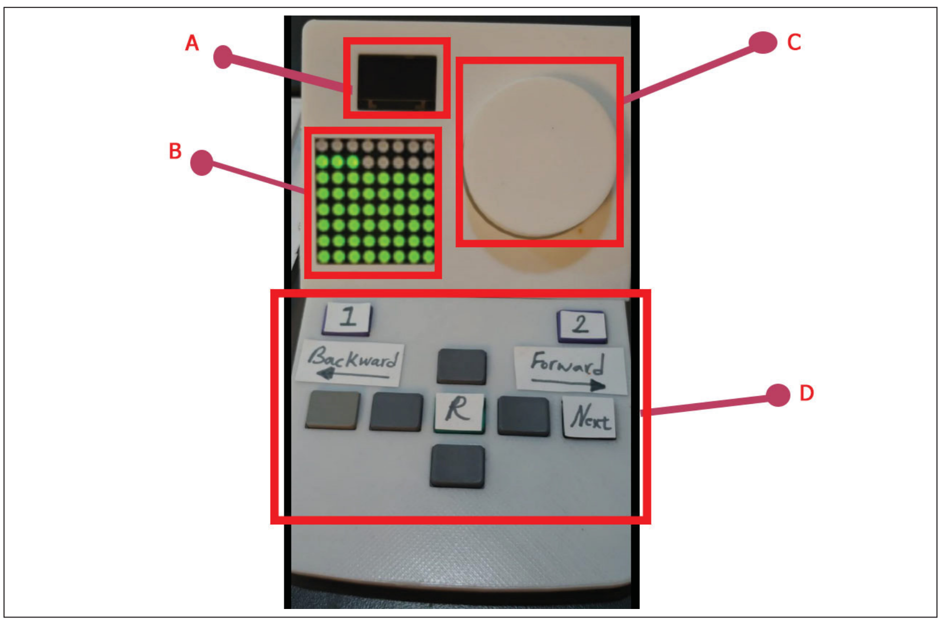

Figure-A I-1 The different components of Interface Device or keypad. A) GROVE-OLED DISPLAY. B) 38-mm 8*8 SQUARE MATRIX LED MATCH. C) ROTARY ENCODER MECHANICAL. D) Simple pad

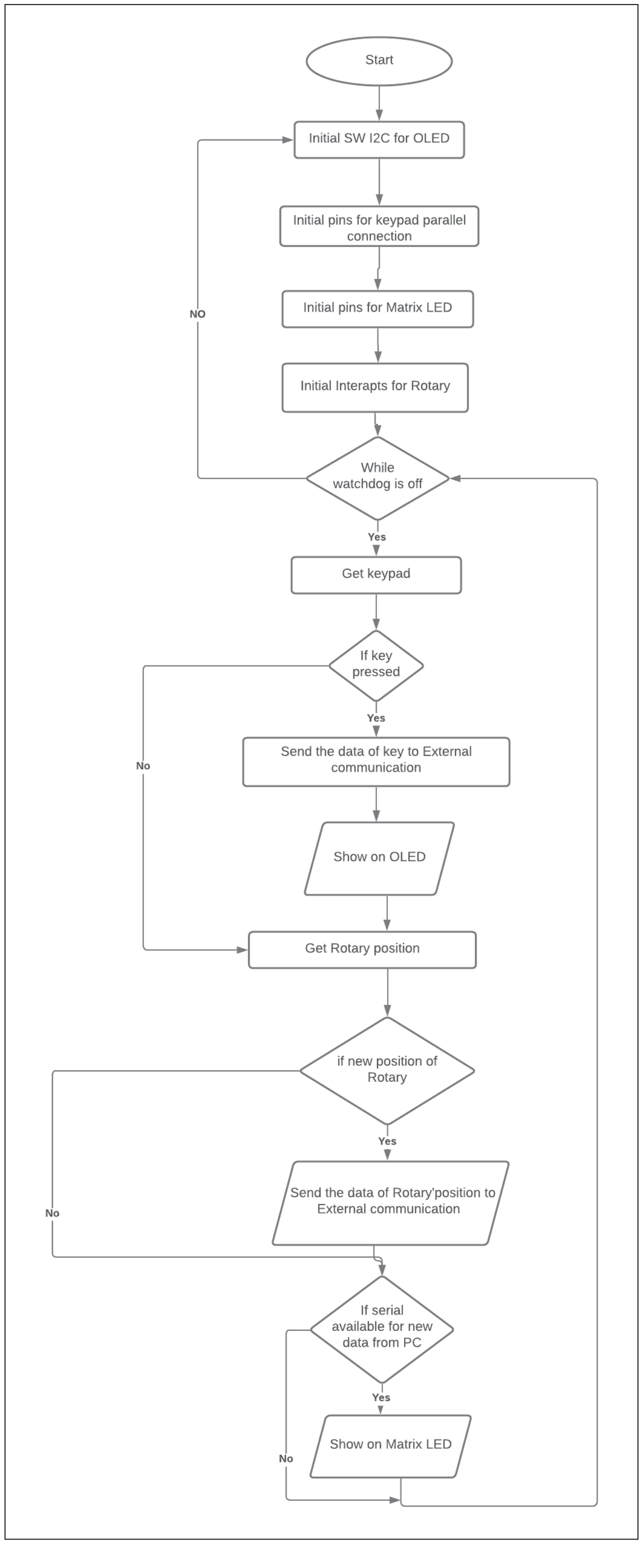

Figure-A I-2 Different blocks of C++ code

APPENDIX II

TABLES AND GRAPHS OF PARTICIPANTS RESPONSES

Table-A II-1 Selected amplitude for each participant and the mean of all participants on the forearm (Pilot 1)

Frequency(Hz)	P1	P2	P3	P4	P5	Average
50	11%	25%	27%	27%	14%	21%
75	5%	13%	14%	9%	5%	9%
100	6%	13%	11%	6%	5%	8%
125	5%	9%	11%	8%	6%	8%
150	6%	13%	9%	13%	6%	9%
175	9%	13%	16%	11%	14%	13%
200	16%	31%	16%	20%	16%	20%
225	19%	75%	20%	25%	44%	37%
250	77%	31%	19%	36%	100%	53%
275	52%	63%	73%	100%	100%	78%
300	100%	100%	100%	100%	100%	100%

Table-A II-2 Selected amplitude for each participant and the mean of all participants on the wrist (Pilot 1)

Frequency(Hz)	P1	P2	P3	P4	P5	Average
50	5%	16%	9%	11%	3%	9%
75	2%	9%	5%	6%	2%	5%
100	2%	6%	5%	6%	2%	4%
125	2%	13%	6%	8%	2%	6%
150	3%	13%	5%	9%	2%	6%
175	3%	25%	5%	13%	3%	10%
200	8%	38%	9%	17%	2%	15%
225	6%	38%	8%	22%	6%	16%
250	14%	100%	13%	100%	8%	47%
275	17%	50%	13%	97%	5%	36%
300	34%	100%	22%	100%	5%	52%

Table-A II-3 The actuator's frequencies for each trial
Pilot Study 1

Forward Direction		**Backward Direction**	
Frequency on the forearm (Hz)	**Frequency on the Wrist (Hz)**	**Frequency on the forearm (Hz)**	**Frequency on the Wrist (Hz)**
50	50	50	50
50	75	75	50
50	100	100	50
50	125	125	50
50	150	150	50
50	175	175	50
50	200	200	50
50	225	225	50
50	250	250	50
50	275	275	50
50	300	300	50
125	50	50	125
125	75	75	125
125	100	100	125
125	125	125	125
125	150	150	125
125	175	175	125
125	200	200	125
125	225	225	125
125	250	250	125
125	275	275	125
125	300	300	125
300	50	50	300
300	75	75	300
300	100	100	300
300	125	125	300
300	150	150	300
300	175	175	300
300	200	200	300
300	225	225	300
300	250	250	300
300	275	275	300
300	300	300	300

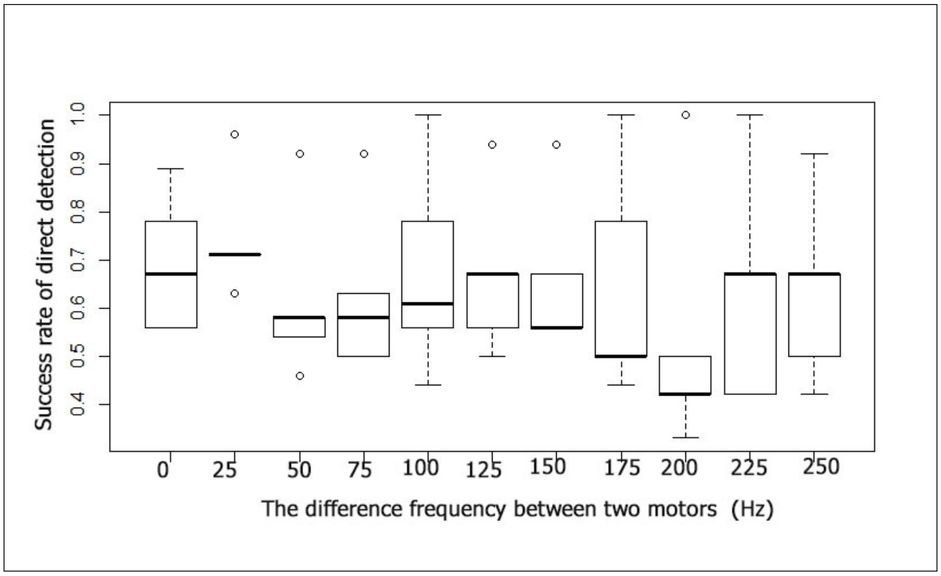

Figure-A II-1 The mean success rate of direct detection for each participant based on the difference frequency between two actuators Pilot Study 1

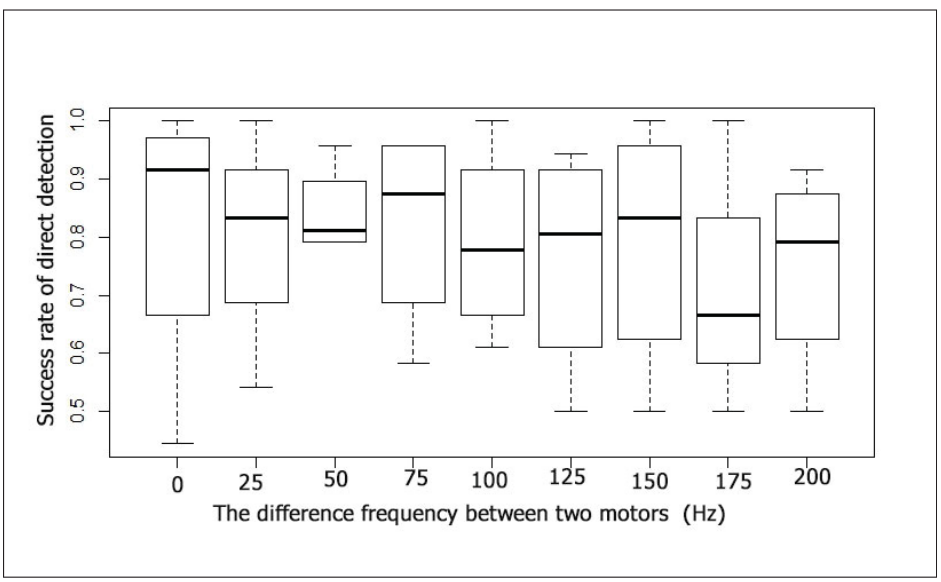

Figure-A II-2 The mean success rate of direct detection for each participant based on the difference frequency between two actuators Pilot Study 2

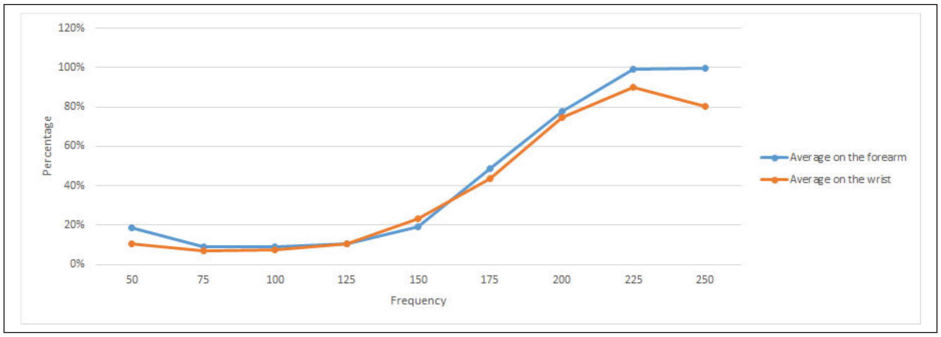

Figure-A II-3 The mean of selected amplitude of all participants on the forearm and the wrist (Experiment 1)

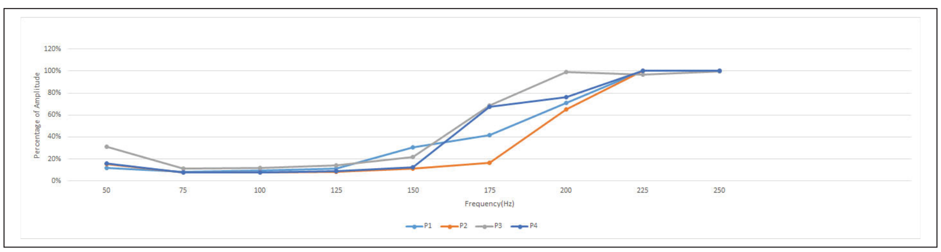

Figure-A II-4 Selected amplitude for each participant on the forearm (Experiment 1)

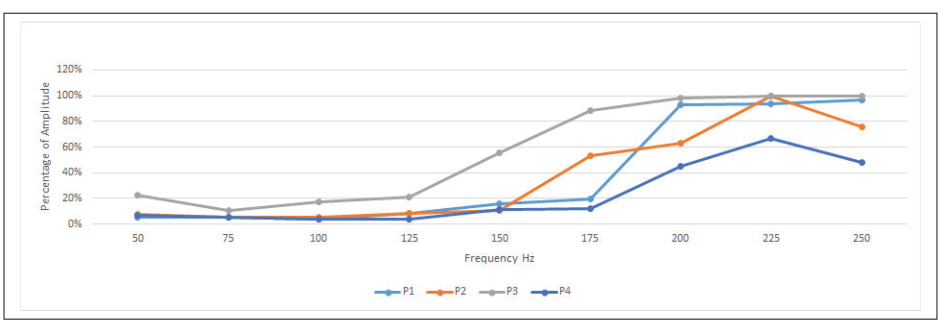

Figure-A II-5 Selected amplitude for each participant on the wrist (Experiment 1)

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