Navigation Using the Haptic Feedback of a Mobile Phone and a Smartwatch

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This thesis was written in memory of the victims of Flight PS752. Their gentle souls will never be forgotten.

Navigation à l'aide du retour haptique d'un téléphone portable et d'une montre intelligente

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RÉSUMÉ

L'apport des applications de navigation est clair. Cependant, il est encore possible d'améliorer l'Expérience Utilisateur de ces applications. Un problème principal de ces applications de navigation est la nécessité de regarder l'écran de l'appareil pour suivre une direction sur la carte. Cependant, utiliser le sens de la vue pour trouver son chemin peut causer certains problèmes et difficultés, particulièrement pour les personnes malvoyantes. Actuellement, plusieurs solutions existent pour résoudre ce problème comme utiliser les sens du toucher ou de l'ouïe. Utiliser les sons pour montrer une direction peut cependant être problématique, particulièrement dans les lieux bondés. Le retour haptique utilisé couramment n'est pas non plus la meilleure solution. En effet, les différentes directions sont montrées avec un seul appareil avec plusieurs rythmes et motifs et l'utilisateur a besoin de les mémoriser. La surcharge mentale, le temps de réaction et des erreurs dans distinction des directions peuvent être certains inconvénients.

Dans cette étude, nous proposons de nouvelles idées pour montrer les directions avec un retour haptique qui n'a pas les mêmes inconvénients que les solutions actuelles. Au lieu d'utiliser un seul appareil, nous avons combiné plusieurs appareils haptiques pour concevoir des indices directionnels plus faciles à distinguer et comprendre. À cette fin, nous avons utilisé une montre intelligente comme appareil additionel au téléphone mobile. Les utilisateurs peuvent sentir les vibrations dans chacun des appareils. Nous avons utilisé deux tacteurs C-2 au lieu de véritables appareils afin de développer et valider notre solution. Un des tactors était placé sur la poche du participant et l'autre était placé sur son poignet.

Nous avions deux stratégies pour montrer les directions aux utilisateurs. La première stratégie est appelée Implicite. Dans cette stratégie, les participants ressentent une vibration uniquement sur un côté du corps (gauche ou droit). La vibration a lieu dans la partie du corps correspondant à la direction que les utilisateurs devraient suivre. La seconde stratégie est appelée Explicite. Dans cette stratégie, une séquence de vibrations commence dans un appareil et se déplace vers l'autre appareil. La direction de ce mouvement indique la direction que les utilisateurs devraient suivre. Nous avons aussi comparé ces deux stratégies avec une troisième stratégie, appelé Symbolique, qui est inspirée du retour haptique directionnel d'une montre intelligente commerciale.

Nous avons réalisé 3 expériences. Dans chacune de ces expériences, nous avons changé certaines variables. Dans la première expérience, l'objectif était de voir quel indice directionnel fonctionnait le mieux sans entrainement. Dans la second expérience, nous avons entrainé les participants et avons comparé les indices directionnels Symboliques avec ceux Explicites et Implicites. Dans la troisième expérience, nous avons ajouté certaines variables pour rendre la situation plus proche du monde réel.

Les expériences ont montré que nos indices directionnels utilisant deux appareils fonctionnent mieux que ceux qui sont Symboliques. De plus, les indices directionnels Explicites rendent les directions plus distinguables par rapport aux notifications. Bien que nos indices soient faciles à comprendre, l'entrainement reste nécessaire.

Mots-clés: Retour haptique, navigation

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ABSTRACT

The value of using navigation applications is clear. However there is room for improvement in the User Experience of these applications. One main problem is the necessity of looking at a device's screen to follow directions. Using vision to find a path causes problems and difficulties, especially for people who are visually impaired or blind. Currently, there are other ways to tackle this problem, such as using touch and audition. Using sounds to show directions, however, can be problematic, especially in crowded places. Current touch feedback is not the best solution either because different directions are shown on one device with rhythms and patterns that users need to memorize. Cognitive overload, a long time to react, and more mistakes in distinguishing the directions are possible downsides.

In this study, we propose new ideas for showing directions with haptic feedback that do not have the same problems as current solutions. Instead of using only one device, we combined multiple haptic devices to design haptic directional cues that are easier to understand and distinguish. More specifically, we used a smartwatch as an additional device to a mobile phone. Users could feel vibrations from each or both devices. We used two C-2 tactors instead of the actual devices to develop and validate the solution. One of the tactors was placed in the participant's pocket, and the other one was placed on their wrist.

We had two main strategies to show directions. The first strategy is called Implicit. In this strategy, only one of the two devices vibrates simultaneously. The direction is indicated by the device's position relative to the other one. The second strategy is called Explicit. In this strategy, a sequence of vibrations starts from one device and moves to the other. The direction of this movement indicates in which direction they should go. We also compared these two strategies with another one that is inspired by the directional haptic feedback used in a commercial smartwatch, which we will call Symbolic.

We ran 3 experiments. In each experiment, we changed some variables. In the first experiment, the goal was to see which of the suggested directional cues are easier to understand when there is no training. In the second experiment, we trained participants and compared Symbolic directional cues with Explicit and Implicit cues. In the last experiment, we added variables to make the situation closer to the real world, such as distractions and haptic notifications.

The experiments showed that our suggested directional designs using two devices work better than Symbolic cues. Also, the Explicit directional cues work best to make the directions distinguishable from other typical notifications. Although the suggested designs are easy to understand, instructions are still necessary to make sense of them.

Keywords: Haptic Feedback, Navigation

TABLE OF CONTENTS

Page

INTRODUCTION 1

CHAPTER 1 BACKGROUND 3
1.1 Haptic Physiology and Perception 3
1.2 Haptic Technology 5
1.3 Multi-Device Haptics 7
1.4 Haptic Device Placement 9
1.5 Haptic and Navigation 10
1.6 UX and HX 15

CHAPTER 2 EXPERIMENTAL SETUP 17
2.1 Vibrotactile Effect Design 18
2.1.1 Implicit Effects 21
2.1.2 Explicit Effects 25
2.1.3 Symbolic Effect 31
2.1.4 Notification Effect 32
2.2 Vibrotactile Hardware 33
2.2.1 Vibrotactile Actuators 33
2.2.2 Actuator Mounting 34
2.2.3 Digital to Analog Conversion 37
2.3 Experimental Software 38
2.3.1 Communication 43
2.3.2 Distractor Game 43

CHAPTER 3 EXPERIMENTS 47
3.1 Experiment 1 48
3.1.1 Participants 49
3.1.2 Experimental Procedure 50
3.1.3 Experiment Design 52
3.1.4 Quantitative Results 52
3.1.4.1 Error Count 53
3.1.4.2 Clarity 55
3.1.4.3 Reaction Time 56
3.1.5 Qualitative Results 57
3.1.6 Discussion 58
3.2 Experiment 2 59
3.2.1 Participants 59
3.2.2 Experimental Procedure 60
3.2.3 Experiment Design 61
3.2.4 Quantitative Results 62

3.2.4.1 Error Count 62
3.2.4.2 Clarity 63
3.2.4.3 Reaction Time 63
3.2.5 Qualitative Results 65
3.2.6 Discussion 65
3.3 Experiment 3 66
3.3.1 Participants 67
3.3.2 Experimental Procedure 68
3.3.3 Experiment Design 70
3.3.4 Quantitative Results 70
3.3.4.1 Error Count 70
3.3.4.2 Clarity 73
3.3.4.3 Reaction Time 75
3.3.5 Qualitative Results 76
3.3.6 Discussion 77

CONCLUSION AND RECOMMENDATIONS 79

APPENDIX I DEMOGRAPHIC SURVEY FOR ALL 3 EXPERIMENTS: 81

APPENDIX II FACILITATORS GUIDE 83

APPENDIX III INTERVIEW QUESTIONS 87

APPENDIX IV SUMMARY OF QUALITATIVE DATA 89

BIBLIOGRAPHY 101

LIST OF FIGURES

Page

Figure 1.1 Major categories of haptic systems 7

Figure 1.2 Nine spatial and temporal tactile patterns using two sources of vibrations: a tablet (green) and a smartwatch (gray). For each box (from a to i), the X-axis is the time, and the Y-axis is the strength of the vibration 9

Figure 1.3 The arrangement of the 8 actuators around the belt 13

Figure 1.4 The arrangement of 8 actuators and GPS direction sensor around the Activebelt 14

Figure 2.1 Block diagram of the experimental setup 17

Figure 2.2 Bilateral Condition 18

Figure 2.3 Unilateral Condition 19

Figure 2.4 Two Implicit effects with different characteristics 20

Figure 2.5 Six Explicit effects with different characteristics 21

Figure 2.6 Bilateral Implicit effects for (1) left and (2) right directions 22

Figure 2.7 Unilateral Implicit effects for (1) left and (2) right directions 23

Figure 2.8 Implicit 1: 45-ms, 275-Hz vibration pulse at maximum amplitude 24

Figure 2.9 Implicit 2: 45-ms, 75-275-Hz at maximum amplitude 24

Figure 2.10 Bilateral Explicit effects for (1) left and (2) right directions 25

Figure 2.11 Unilateral Explicit effects for (1) left and (2) right directions 26

Figure 2.12 Explicit 1: 95 ms, 275 Hz and maximum amplitude. A sequence of vibration from one device to the other 27

Figure 2.13 Explicit 2: 95 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency 28

Figure 2.14 Explicit 2: 95 ms, 275 Hz and 50% - 100% amplitude. A sequence of vibration from one device to the other to see the effect of amplitude 29

Figure 2.15 Explicit 4: 47 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency and time ... 29

Figure 2.16 Explicit 5: 145 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency and time ... 30

Figure 2.17 Explicit 6: 145 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to evaluate different patterns ... 31

Figure 2.18 Symbolic effect: a steady series of 12 taps indicates the right direction ... 32

Figure 2.19 Symbolic effect: 3 pairs of two taps indicates the left direction ... 32

Figure 2.20 Picture of the experimental setup ... 33

Figure 2.21 Transfer function of C-2 tactors ... 36

Figure 2.22 The bands used to fix the actuators on the thigh and the wrist ... 36

Figure 2.23 Picture of the Sound Blaster E5 ... 38

Figure 2.24 Screen flow of Experiment 1 ... 40

Figure 2.25 Screen flow of Experiment 2 ... 41

Figure 2.26 Screen flow of Experiment 3 ... 42

Figure 2.27 The game when it starts ... 44

Figure 2.28 The game over condition ... 44

Figure 3.1 Methodology in all experiments ... 47

Figure 3.2 Demographic data in Experiment 1: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker ... 50

Figure 3.3 The total number of Error Count for each effect. The lines on the bar chart shows the significant differences between two effects and the number above each line, shows the p-value ... 53

Figure 3.4 The cumulative number of errors based on vibration numbers ... 54

Figure 3.5 Clarity of each effect based on participants' opinion. The line that divides the box is the median (average value). The lower quartile is the point where one-quarter of the values are below it. Likewise, the upper quartile is where one-quarter of the values are above it. The lines and numbers on the chart show the significant differences between the effects and the p-value 55

Figure 3.6 Reaction Time of each effect 56

Figure 3.7 Demographic data in Experiment 2: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker 60

Figure 3.8 The Error Count of each effect 62

Figure 3.9 Clarity of each effect based on participant's opinion. The lines on top of the box plot show the significant differences and the numbers on them show the p-values 64

Figure 3.10 Reaction Time of each effect 64

Figure 3.11 Demographic data in Experiment 3: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker 68

Figure 3.12 The bar chart for (a) Total Error Count, (b) Directional Error Count and (c) Notification Error Count 71

Figure 3.13 The bar chart of total errors based on 3 different effects and their Conditions (Unilateral and Bilateral) 72

Figure 3.14 Clarity of each effect with two Conditions (Unilateral/Bilateral) in showing directions 74

Figure 3.15 Clarity of each effect with two Conditions (Unilateral/Bilateral) in distinguishing with notification. The lines on top of the box plot show the significant differences between effects and the numbers show the p-values 75

Figure 3.16 Reaction Time of each effect with two Conditions (Unilateral/Bilateral) 76

LIST OF ABBREVIATIONS

ETS	École de Technologie Supérieure
ASC	Agence Spatiale Canadienne
UX	User Experience
HX	Haptic User Experience
LRA	Linear Resonant Actuator
DC	Direct Current
ERM	Eccentric Rotating Mass
EAP	Electroactive Polymer
SMA	Shape Memory Alloy

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

A	Ampere
mA	Milliampere
I	Current measured in amps
R	Resistance measured in ohms
V	Electric potential difference (voltage)
mm	Millimetre
Hz	Hertz
ms	millisecond
dB	decibel [rms] root-mean-square [DC] Direct current

INTRODUCTION

We often see people on the street looking at their mobile phones and trying to find a direction. A significant challenge for users is the need to look at a map on the screen of their devices to find their direction. In special weather conditions or while doing intense activities such as cycling, looking at a device's screen can be difficult for users. Similarly, people who are blind or visually impaired are unable to use such applications. They can use audible cues; however, this can bring other problems such as cognitive overload or the need to use headphones in crowded places, which can lead to a disconnection with their surroundings.

This research aims to address this problem by using the sense of touch instead of vision or hearing. Prior work has tried to use haptic feedback to guide users. For example, Rosenthal *et al.* (2011) designed a vibrotactile belt with 8 actuators. Vibrating some actuators together indicates a forward movement, while other patterns indicate a movement backward or to the left and right. In another vibrotactile belt, Tsukada & Yasumura (2004) showed the direction by the actuators activated and the distance by controlling the pulse intervals of vibrations. While this prior work required special-purpose devices to be implemented, we propose ideas that can show directions using devices that users carry in their everyday lives, such as a mobile phone and a smartwatch.

Currently, commercially-available smartwatches provide directions using different rhythms and patterns. However, we decided to use two devices instead of one in order to show direction cues that are easier and faster to interpret. We used one actuator with the role of a mobile phone and one with the role of a smartwatch. We placed the mobile phone over the pant pockets and the smartwatch on the left wrist. We proposed two groups of directional vibrotactile patterns. The first group is called Implicit. In this group, only one of the two devices vibrates to indicate a direction. If the vibration is located on the left side relative to the center of the body (or relative to the other device), the vibration indicates left and vice versa. The other group is called Explicit, and produces a sequence of vibrations. The users should feel that something is jumping from one device to the other. The direction of this movement indicates where to turn. We varied many factors such as amplitude, frequency, and timing to create different sequences of vibrations.

In Experiment 1, we aimed to see which of these vibrotactile patterns shows the directions better without any training. More precisely, we wanted to compare the Implicit and Explicit patterns and understand which factors (frequency, amplitude, etc.) are more beneficial in showing directions. In Experiment 2, we trained participants and compared our directional vibrotactile patterns with those of commercially-available solutions. In Experiment 3, we added different variables to make the situation closer to the real world. For example, we distracted participants by asking them to play a game. We also added a vibration similar to the notifications that participants can receive from a text message in a daily life. The goal was to see if they could distinguish the notification from directional vibrations. We also changed the mobile phone's location and compared when both devices are on one side of the body versus on different sides.

The thesis structure is as follows: Chapter 1 reviews basic concepts related to the sense of touch and haptic feedback, as well as relevant prior work on topics such as haptic navigation guidance. Chapter 2 describes the experimental setup, including the design directional haptic effects and the hardware and software used in the experiments. Chapter 3 describes the experiments that we ran, the results, and their analysis. Finally, we discuss our conclusions and future work.

CHAPTER 1

BACKGROUND

In this Chapter we will understand the physiology of the sense of touch, haptic systems and how we can use them for navigation purposes. We separate this Chapter into six sections. Section 1.1 covers the general understanding of touch and haptic perception and the terminologies used in different studies. Section 1.2 introduces different actuators and haptic systems. Section 1.3 describes how we can combine different haptic devices to produce richer haptic feedback. Section 1.4 describes why it is important to know the place of a haptic device and how we can understand it. Section 1.5 gives examples of some studies that used haptic feedback to guide users. Finally Section 1.6 describes the differences between User Experience and Haptics User Experience.

1.1 Haptic Physiology and Perception

An important difference between the sense of touch and the four other senses (sight, hearing, taste, and smell) is that the sense of touch is distributed across the entire body and that it is not localized to only a specific region or body part (Borhade & Shelkar, 2019).

Looking at the biological side of touch sensation, four types of receptors distributed throughout the skin or in muscles, tendons, and joints receive touch information and transmit it to the brain for interpretation and perception (Lederman & Klatzky, 2009).

The sense of touch is divided into two modalities (Culbertson, Schorr & Okamura, 2018):

Tactile: This modality provides awareness of stimulation of the skin, which consists of touch, pressure, vibration, temperature, and nociception (pain) (Felten, O'Banion & Maida, 2016).

Kinesthetic: This modality provides an awareness of body movements, force and torques. It is sensed in the muscles, tendons, and joints (Culbertson *et al.*, 2018).

Human beings can experience the world through passive or active touch. Passive touch happens when the individual does not move their body and the stimulation is imposed on the skin without any control. Vibrating ringtones or notifications on a phone or smartwatch are two examples of passive touch. On the other hand, active touch is when the individual moves their body to initiate the touch. Vibrotactile feedback produced when a user touches a touchscreen is a good example of active touch (Choi & Kuchenbecker, 2012).

Now we will define some terms that are commonly used in the study of human touch sensing.

Haptics: The word "haptics" is believed to come from the Greek word haptesthai, which refers to the sense of touch. In psychology and neuroscience, haptics is the study of human touch, mainly via kinesthetic and cutaneous receptors (Hannaford & Okamura, 2008).

Vibrotactile Perception: Vibrotactile sensation is defined as the perception of oscillating objects in contact with the skin (Hayward, Astley, Cruz-Hernandez, Grant & Robles-De-La-Torre, 2004).

Tactile detection threshold: The weakest stimulus intensity that humans are able to detect (Bruce Goldstein, 2013).

Just Noticeable Difference (JND): The smallest difference between two stimuli that leads to reliable discrimination (Choi & Kuchenbecker, 2012).

Masking effect: Interference in the perception of one stimulus when another stimulus is present at the same time (Zook, Fleck & O'Malley, 2021).

Tactile Reaction Time: The amount of time that it takes for sensory receptors to initiate a tactile stimuli.

1.2 Haptic Technology

Actuator: An actuator is a device that converts input energy into useful mechanical energy (Poole & Booker, 2011). These mechanical signals stimulate human kinesthetic and touch channels in contact with the skin. One or multiple actuators can be implemented in a haptic device to produce haptic feedback. For example, most mobile phones have actuators that convert electrical energy into vibration, which is a representative example of vibrotactile feedback.

Many elements are important in choosing an actuator, such as its size, shape, cost, availability, robustness, speed of response, input requirements, power consumption, and potential interference with other system components (Choi & Kuchenbecker, 2012).

Choi & Kuchenbecker (2012) reviewed the most commercially available and popular actuators:

- **Linear electromagnetic actuators:** This type of actuator uses electromagnetics to create a physical phenomenon that results in vibrotactile stimuli. A linear electromagnetic actuator is made by coiling an electrically conductive wire around a cylindrical tube. Inside the tube is a ferromagnetic material (such as steel) that is free to move. By passing a constant electrical current through the coiled wire, a steady magnetic field is created. When the current is on, this ferromagnetic material moves towards the electromagnetic field, and when the current is turned off, it comes back to its resting position. This produces a mechanical movement that can stimulate human touch channels (Choi & Kuchenbecker, 2012).

  A C2 tactor (EAI, Casselberry, FL) is an example of a linear electromagnetic actuator with a moving magnet pre-loaded against the skin. By passing an electrical signal, the moving magnet oscillates against the skin. The surrounding skin area is shielded by the passive housing. This design provides a strong and localized sensation, unlike other actuators in this group that shake the whole device.

  A linear resonant actuators (LRA) is another popular actuator in this category that directly transfers the force produced by the voice coil to the skin. Many mobile phones use a linear resonant actuator since they use less power than other actuators.

- **Rotary electromagnetic actuators:** These actuators are made of rotary direct current (DC) motors which use electromagnetism to produce vibrotactile stimuli. When a constant voltage or current is applied, these motors rotate continuously. Rotary electromagnetic actuators have a more complex internal structure than linear electromagnetic actuators because of the difference in their movement.

  An eccentric rotating mass (ERM) actuator is an example of this category of actuators. They consist of a DC motor with an offset mass attached to the shaft. Their sizes range from very small (e.g., for use in mobile phones) to very large (e.g., for use in massaging or manufacturing) (Choi & Kuchenbecker, 2012).
- **Nonelectromagnetic actuators:** These types of actuators use technologies other than electromagnetics. One of the main approaches is to use the piezoelectric effect to produce vibrotactile sensations. These actuators are made of a particular solid material that can change shape and produce a mechanical signal when an electrical voltage is applied to them. Electroactive polymer (EAP) actuators use the piezoelectric effect and are an example of a non-electromagnetic actuator. The other approach is to use the shape memory alloy effect (SMA). These actuators are made of metals that remember their original shapes and produce a mechanical signal with temperature changes (Choi & Kuchenbecker, 2012).

There are three main categories of haptic systems (Culbertson *et al.*, 2018):

- **Graspable:** which needs to be grasped by the users, like some types of surgical devices;
- **Touchable:** which needs the movement of user's fingers, like mobile phones;
- **Wearable:** which needs to be worn by users, like smartwatches.

After understanding different actuators and haptic systems. We need to better understand the factors that affect the haptic perception.

Signal characteristics, body part, gender, age, skin temperature, physical exertion, and the presence of other masking stimuli have effects on the detection threshold and reaction time.

For example, Pakkanen *et al.* (2008) investigated the effect of amplitude on haptic perception and reaction time. The test was conducted in conditions where participants experienced low

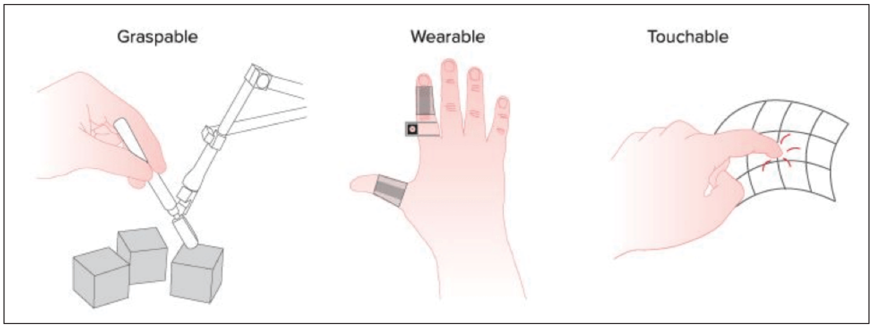

Figure 1.1 Major categories of haptic systems
Taken from Culbertson *et al.* (2018)

or medium physical exertion (biking). Two stimulus durations (1 s and 2 s) were applied to 4 different body locations (wrist, leg, chest and back) while participants were cycling. The results showed that participant's movement had a significant effect on perception rate and reaction time on all body parts when low-amplitude stimuli was applied. However, the stimuli duration did not have a significant effect on perception rate and reaction time, although much lower and higher duration were not examined in this study. They conclude that, in mobile users with a medium to high exertions, the amplitude factor need to be taken into account and it is suggested to use slightly higher amplitudes for mobile users than immobile.

Increasing our knowledge of actuators and perceptual limits can help to design the most efficient haptic devices and systems. However, we need to take note that vibrotactile perception is complicated, and it is hard to know ahead of time how our design will work in practice. It is a good practice to iterate by designing rapid prototypes and running experiments with potential users before finalizing a design (Choi & Kuchenbecker, 2012).

1.3 Multi-Device Haptics

Each of the haptic systems can transfer useful information to the users with only one actuator. However, the accuracy and realism of haptic sensations can be increased by adding arrays of actuators to devices. Adding multiple actuators is especially efficient for devices with larger interfaces or ones that contact the user's body on a large surface such as theatre or driving seats (Karuei *et al.*, 2011). These techniques, however, require that a completely new device be created from scratch. To avoid this, some studies combine two or more available tactile devices that people use on a daily basis to produce rich tactile sensations and user experiences.

Harmonious Haptics (Hwang, Song & Gim, 2015) considers smartwatches as additional tactile displays for smartphones. By harmonizing these two tactile devices, users perceive rich tactile feedback from their wrist and fingertip at the same time. The smartwatch and mobile phone are connected with Bluetooth, and users receive vibration patterns from both their wrist and their fingertip while touching the mobile phone. The different vibration patterns used are shown in Figure 1.2. Among these patterns, some used tactile illusions, which occur when "the perception of a quality of an object through the sense of touch does not seem to be in agreement with the physical stimulus." (Hayward, 2015). Figures 1.2 a-b used phantom sensations, which happen when two stimuli are presented simultaneously on the skin. Users feel a sensation midway between the two stimulators. Figures 1.2 d-e used sensory saltation, another tactile illusion. When a sequence of taps are generated at two separate skin locations, users feel a tapping sensation in the successive locations of the skin as well.

Harmonious Haptics used and tested these tactile patterns in 3 different applications:

- **Feeling an image:** They used phantom sensations. When the user touches the screen of the tablet, it generates a vibration with a strength in proportion to the luminance of the touched area, while the smartwatch emits a vibration in the inverse proportion. This technique provides tactile feedback that has perceptual depth.
- **Transferring a file:** They used sensory saltation to create a tapping feeling that a file is moving from the mobile phone to the smartwatch, or the reverse.
- **Controlling UI components:**
  They used tactile patterns to add feedback to UI components such as sliders, buttons, toggles, etc. For example, when the user moves a slider from left to right, vibrations decrease in the tablet and increase in the smartwatch.

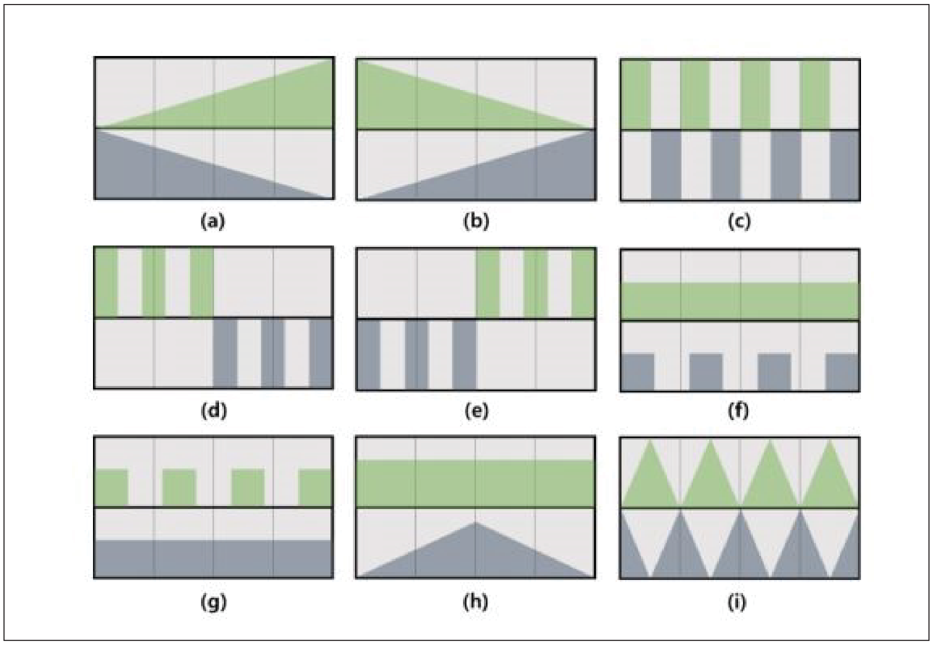

Figure 1.2 Nine spatial and temporal tactile patterns using two sources of vibrations: a tablet (green) and a smartwatch (gray). For each box (from a to i), the X-axis is the time, and the Y-axis is the strength of the vibration
Taken from Hwang *et al.* (2015)

Surround Haptics (Israr, Kim, Stec & Poupyrev, 2012) uses some low-resolution and inexpensive actuators to produce a high-resolution, moving and continuous tactile sensation instead of some separated vibration pulses on the skin. To generate this feeling, they use tactile illusions by creating virtual actuators in the grid of actual actuators.

1.4 Haptic Device Placement

Karuei *et al.* (2011) studied the impact of the body part on detection rate and response time in different conditions. They examined whether visual workload and user's movement have any effect on tactile perception. The experiment was conducted in a lab environment. They chose seven body parts (foot, wrist, stomach, thigh, chest, arm, spine) and five vibration intensities. Participants were asked to press a button when they perceived tactile stimuli. The results showed that the thighs and the feet are the worst in detecting vibrations. The stomach, chest, and arms are slightly better. The wrist and the spine are the best. Also, movement (e.g., walking) can significantly decrease the detection rate. The visual workload does not significantly affect the detection rate, but it increases the reaction time. Increasing intensity of the vibrations, increases the perception rate and decreases the reaction time.

After understanding the importance of the body part on detection rate of a stimuli we will discuss how we can understand the context and the place of the haptic devices.

Darbar & Samanta (2015) mention that knowing the context of a phone or other devices could have advantages, such as making it possible to adjust the intensity of haptic feedback. In other words, different intensities would be needed if a user holds a mobile phone in the hands or keep it in the backpack or in the pocket. In this way, the haptic feedback would not be annoying in the hands and neither missed in the bag or pocket.

The approach Darbar & Samanta (2015) used in this study is simple and inexpensive. When a change in mobile phone placement is detected, the phone vibrates for 4 seconds. During this time, the accelerometer and gyroscope record motion data, the magnetometer records magnetic field strength, the proximity sensor measures the presence of nearby objects at different distances, and the microphone captures phones vibration echoes. Once sensor data collection is completed, the data are processed, and the place of the haptic device is recognized.

1.5 Haptic and Navigation

Navigation applications are common in our day to day life. However, users might face some problems interacting with these applications. For example, a significant problem is the need to look at the map to find a direction, which can distract users from the activity they are doing. Some activities even do not allow looking at a mobile phone, such as running or riding a bicycle. Similarly, people who are blind or visually impaired are not able to use such applications either. Understanding the directions through audio is a possible solution. However, people with visually impairment will face challenges using it. The reason is that, the sense of hearing is their main sense to be aware of their environment. Using that to transfer directional information can cause cognitive overload through that sense. An alternate channel to deliver some information would be helpful (Rosenthal *et al.*, 2011).

In a study, Kern, Marshall, Hornecker, Rogers & Schmidt (2009) compared three human senses (vision, audition, and touch) and their combinations in terms of pleasantness and distraction rate in transferring directional information. The results showed that users preferred the combination of visual and tactile as the most pleasant and the least annoying type of feedback, and audio alone as the least pleasant and most annoying type (Kern *et al.*, 2009). Another experiment measuring the rate of distraction revealed that visual guidance distracted users the most and a combination of visual and tactile distracted them the least (Kern *et al.*, 2009). Overall, adding tactile feedback to visual guidance could successfully improve the rate of pleasantness and decreased the distraction rate.

As we discussed in Section 1.1, haptic feedback is divided into two modalities: kinesthetic and tactile. These modalities of haptic feedback have been used in navigation applications to transfer directional information.
One form of haptic display in applications is haptic icons. Bliss (1974) defines an icon as "an image, picture or symbol representing a concept."

- **Haptic icons, or Hapticons:** "[B]rief computer-generated signals, displayed to a user through force or tactile feedback to convey information such as event notification, identity, content or state." (Enriquez & MacLean, 2003)
- **Vibrotactile icons:** "[S]tructured vibrotactile messages for presenting multidimensional information non-visually" (Brewster & Brown, 2004). In fact, it is one form of haptic icons that uses vibration to convey information.

Rosenthal *et al.* (2011) propose ways to map meaning to haptic icons. The two most common mappings are:

- **Symbolic:** Each feedback represents a meaning. Users need to understand the relationship between the haptic feedback they perceive and the actual meaning they have. This way of mapping needs training and memorizing. For example, two short pulses could be representative of the left direction and three long pulses could be representative of the right direction.

- **Literal:** Rosenthal *et al.* (2011) defines it as "[a]ssigning vibrotactile cues to intuitive somatosensory signals that humans are already acquainted with". It is an intuitive approach that users do not need to be trained for. For example, a shoulder tap to obtain attention is a literal mapping.

Now we will make some examples of studies that use haptic in navigation.

Kinesthetic, literal guidance

Amemiya & Sugiyama (2009) designed a haptic direction indicator to help blind pedestrians safely find their way using kinesthetic haptic feedback. In a laboratory experiment, they asked participants to hold the haptic directional indicator in their hands and start walking based on the perceived haptic cues. First, the force display gave a sensation of pushing forward. In the turning points, a force feedback displayed a sensation of left or right. If users mistakenly turned the opposite direction, the indicator displayed a force feedback to show users to return to the predefined route.

The results showed that 91% of the participants could successfully find the way. Some of them could not perceive the direction at first and made a mistake in turning the corners, but they could recover the route with the force display in the end (Amemiya & Sugiyama, 2009).

As it is understood from the results, kinesthetic feedback is easy to understand for users. However, this form of feedback is not available in our everyday devices such as a mobile phone, smartwatch, etc. To implement this form of feedback, a new device should be designed and built.

Tactile, symbolic guidance

Rosenthal *et al.* (2011) designed a vibrotactile display that is worn around the waist and called a vibrotactile belt. They used the belt in an experiment to guide towards specific dance movements. The aim of the research was to evaluate the usability of the belt. They asked participants to use the belt to do some dance movements and, after the experiment, to complete a questionnaire.

In the design, 8 actuators are mounted around the belt (Figure 1.3). The researchers designed some patterns that delivered the cues for the dance movements.

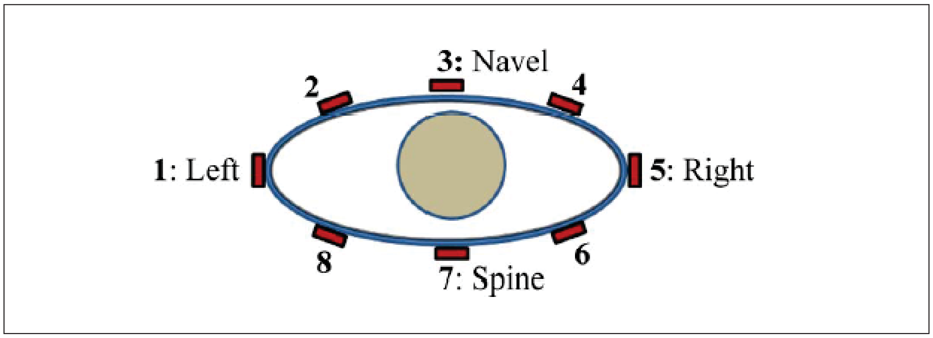

Figure 1.3 The arrangement of the 8 actuators around the belt
Taken from Rosenthal *et al.* (2011)

Vibrating some tactors together creates a pattern that delivers the meaning of a dance movement. You can see the movements and the mapped vibrotactile patterns in Table 1.1.

Table 1.1 Mapping a movement to a vibrotactile pattern
Taken from Rosenthal *et al.* (2011)

ID	Movement	Vibrotactile Pattern
A	Left foot forward (small step)	1-2-3
B	Right foot forward (small step)	5-4-3
C	Left foot forward (long step)	7-8-1-2-3
D	Right foot forward (long step)	7-6-5-4-3
E	Left foot back (small step)	1-8-7
F	Right foot back (small step)	5-6-7
G	Left foot back (long step)	3-2-1-8-7
H	Right foot back (long step)	3-4-5-6-7
I	Left foot forward	1-2-3-4-5
J	Right foot forward	3-4-5
K	Left foot forward	3-2-1
L	Right foot forward	5-4-3-2-1

The recognition accuracy of vibrotactile patterns, averaged across participants, was 97%. This shows that they did not have much difficulty recognizing the patterns (Rosenthal *et al.*, 2011).

Tactile, literal guidance

In another study, Tsukada & Yasumura (2004) designed a similar vibrotactile belt (Figure 1.4). The aim was to show a direction by activating a specific vibrator, without the use of patterns or the activation of a group of vibration motors together. They also wanted to show the distance by controlling the pulse intervals of vibration. They examined experimentally if users can understand changes of direction as well as distances. They considered two conditions: standing and walking. The results showed that in the standing state, all users could understand all changes. However, in the walking condition, the behavior of the users was different. In the short pulse intervals, the users could not recognize the change in direction. However, for the long intervals, they understood the changes in the direction and after one or two steps they stopped and changed the direction. From the results, it is revealed that the condition of the user is one of the most important factors of haptic stimuli perception (Rosenthal *et al.*, 2011).

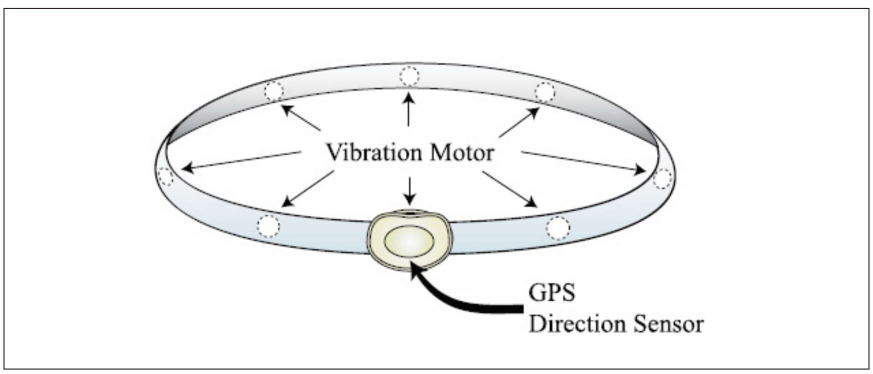

Figure 1.4 The arrangement of 8 actuators and GPS direction sensor around the Activebelt
Taken from Rosenthal *et al.* (2011)

In (Floréen, Krüger & Spasojevic, 2010), a vibrotactile belt was designed again with 12 actuators that were distributed equally around torso when the belt was worn. The goal of the study was to show two informations: the current and subsequent way points so that the user will understand where to turn now and anticipate how the route will continue. The body location encodes the direction and the rhythm encodes the type. To show the direction, the actuator which points most accurately into the waypoint's direction starts vibrating. To show the waypoint type, different rythms were used. For example, the current waypoint is encoded by a heartbeat-like vibration which is repeated five times. The next waypoint is showed with a single pulse vibration.

1.6 UX and HX

User experience (UX) includes all the aspects of the interaction between the end user with a company, its services, and its products (Norman & Nielsen, 2016).

As haptic technologies are developped and made available to designers, they will likely become a bigger part of UX. Despite their similarities, there are differences between the definitions of UX (User Experience) and HX (Haptic User Experience). Kim & Schneider (2020) believe that designers and researchers will benefit from a specific definition of HX instead of using the current definitions of UX. For instance, UX and HX are different in their time frames. For UX, the time before, after, and during an interaction is important while for HX, only the moment at which the user is interacting is important. Kim and Schneider's aim was to measure the HX and, to this end, they defined a specific definition of HX and developed a theoretical model of the factors that constitute a good HX. This model helps designers and researchers to have the same language around haptics and provides the basis for evaluative instruments like heuristics and questionnaires. They proposed design parameters of Timeliness, Density, Intensity, and Timbre; usability requirements of Utility, Causality, Consistency, and Saliency; experiential factors of Harmony, Expressivity, Autotelics, Immersion, and Realism; and the cross-cutting concern of Personalization.

In this Chapter, first, we learned about haptic physiology and the most common terms that are used in the haptic study. Then we discussed different actuators and haptic systems. In Section 1.3 we discussed the combination of some actuators or haptic devices to produce richer tactile feedback. In Section 1.4 we reviewed why the context of a haptic device is important and how we can understand it using the sensors of the device. In the end, we discussed using haptic feedback in navigation and reviewed related works and studies about that.

CHAPTER 2

EXPERIMENTAL SETUP

In this Chapter, we will describe the setup we used for all of our experiments. We separate this Chapter into three sections. Section 2.1 covers the detail of each vibrotactile effect design that includes Explicit, Implicit, Symbolic, and notification effects. Section 2.2 describes the vibrotactile hardware we used. Section 2.3 describes the experimental software that is implemented for the tablet to play the effects and interact with participants and the facilitator.

Figures 2.1 shows the main core. The tablet was connected to actuators wirelessly through a Bluetooth audio amplifier. Software developed for the tablet made it possible to play the directional effects on actuators and to ask information from participants.

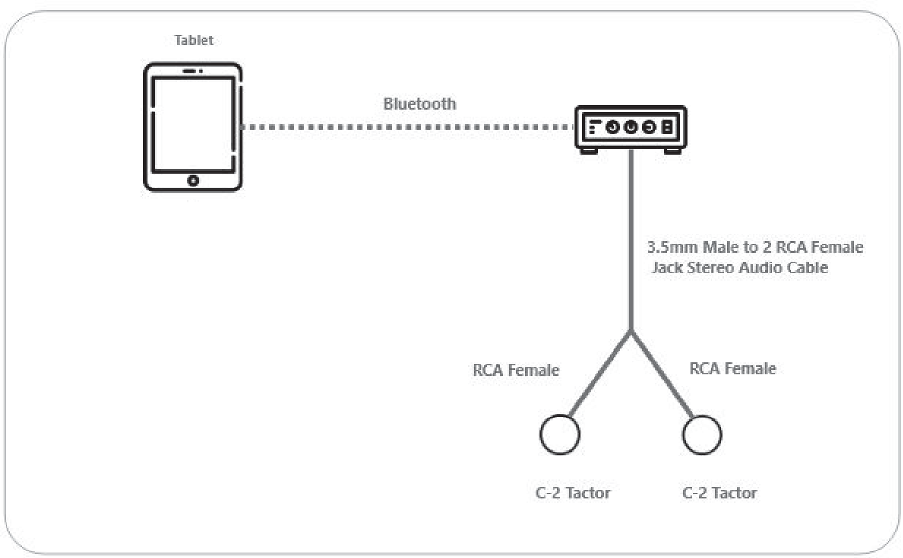

Figure 2.1   Block diagram of the experimental setup

2.1 Vibrotactile Effect Design

We designed directional vibration patterns that make use of two actuators playing the role of a smartwatch and a mobile phone, respectively. The directional patterns were designed to indicate left and right directions, and be referred to as directional effects throughout this thesis.

An important consideration was the placement of the smartwatch (left or right wrist) and smartphone (left or right pocket, or other location on the body). Since prior work has shown that most people prefer to wear a watch on their left wrist[1], we chose to have one actuator at that location in all three experiments. We chose the front pocket for the mobile phone as it is one of the most common places to keep the device when not in use. The challenge was to decide in which pocket (left or right) we place this actuator. As further explained in Section 3.3, we hypothesized that the placement of the devices on one or two sides of the body would affect how the directional feedback is interpreted. So the placement of the other actuator created two conditions:

- **Bilateral:**
  Devices are on different sides of the body. The smartwatch is on the left wrist, and the mobile phone is in the right pocket. Figure 2.2 shows the Bilateral condition.

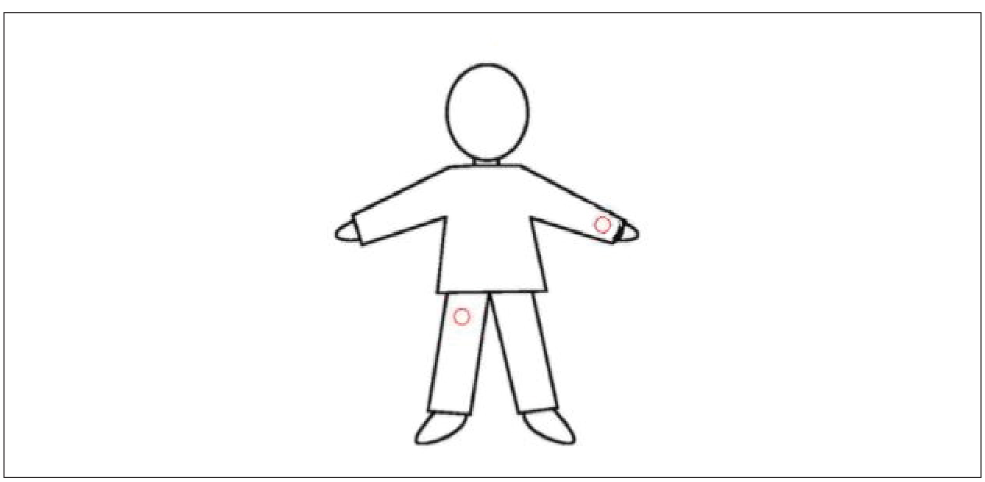

Figure 2.2 Bilateral Condition

[1] http://manyfaces.armitron.com/why-people-wear-watches-on-left-hand/

- **Unilateral:**

  Both the smartwatch and the mobile phone are on the left side of the body. The smartwatch is on the left wrist, and the mobile phone is in the left pocket. Figure 2.3 shows the Unilateral condition.

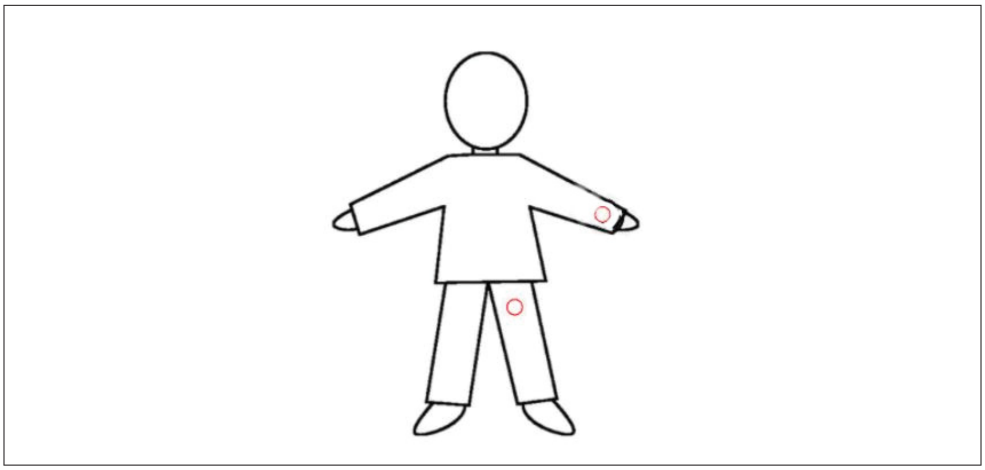

Figure 2.3 Unilateral Condition

After brainstorming, we chose two main strategies to show the directions: Implicit (2.1.1) and Explicit (2.1.2) effects. In Implicit effects, only one actuator vibrates in the same time. A vibration from the smart watch means left and from the mobile phone means right. In Explicit effects, users feel something is jumping from one device to the other. The direction of this movement shows the left and right to the users. Refer to Sections 2.1.1 and 2.1.2 for more detail.

We designed the effects using Audacity[2], a free and open-source digital audio editor and recording application software. The audio signals were exported as WAV files. The C-2 tactors (EAI, Casselberry, FL) work like speakers with audio files and vibrates.

We started designing some effects by changing different parameters such as frequency, amplitude, time, and waveform. We came up with 109 effects (Implicit and Explicit) in the first step, and in each effect, we changed one or a combination of these parameters. Among them, we picked two Implicit effects and 6 Explicit based on informal pilots within the research team. Figure 2.4

[2] https://www.audacityteam.org/

shows the two Implicit effects we chose. Implicit 1 was a simple buzz with a fixed frequency (275 Hz) and amplitude (100%). In Implicit 2, the frequency ramped up. (started from 75 Hz and ended in 275 Hz) but the amplitude was fixed (100%).

The duration of both Implicit effects was 45 ms which is not too short neither too long, and it feels close to a notification duration.

We used different amplitudes for the thigh and the wrist. Because the wrist is more sensitive to vibration than the thigh (Karuei *et al.*, 2011) also the wrist has skin contact with the actuator, but the thigh does not. There is a material (pants) between the thigh and the actuator. So we reduced the intensity of the wrist to have a balanced intensity on both sides of the body. We used 100% of the maximum amplitude for the thigh. However, for the wrist, we used 30% for Experiment 1 and 2 based on our pilot test comments, but in Experiment 3, we chose it based on each participant's preference. It means that participants feel almost the same vibration intensity with 100% of maximum on their thigh and 30% of maximum on their wrist. To simplify everything, we will refer to 100% through the thesis for both.

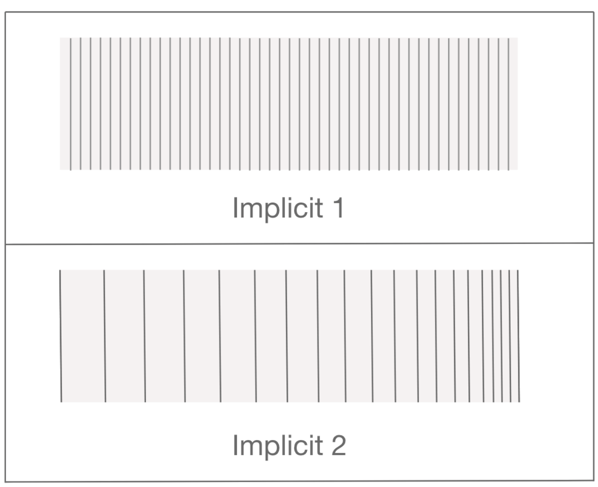

Figure 2.4 Two Implicit effects with different characteristics

Figure 2.5 shows the Explicit effects we picked. Explicit 1 was two buzzes of vibrations with a fixed frequency (275 Hz) and amplitude (100%). In Explicit 2, the frequency ramped up (started from 75 Hz ended in 275 Hz), the amplitude was fixed (100%). Explicit 3 had different amplitudes. It started from a lower amplitude and ramped up (started from 50% ended in 100%). Explicit 4 was the shorter form of Explicit 2, and in reverse Explicit 5 was a longer form of Explicit 2. In Explicit 6 we added some gaps to have a feeling of tapping, and it followed the same frequency of Explicit 2.

In all effects we have a short overlap between two actuators. The reason was to make the feeling of connection between them.

Like Implicit effects, the thigh had 100% of amplitude and the wrist had 30% of amplitude to have a balanced feeling on the wrist and thigh. We chose 30% based on our pilot test comments.

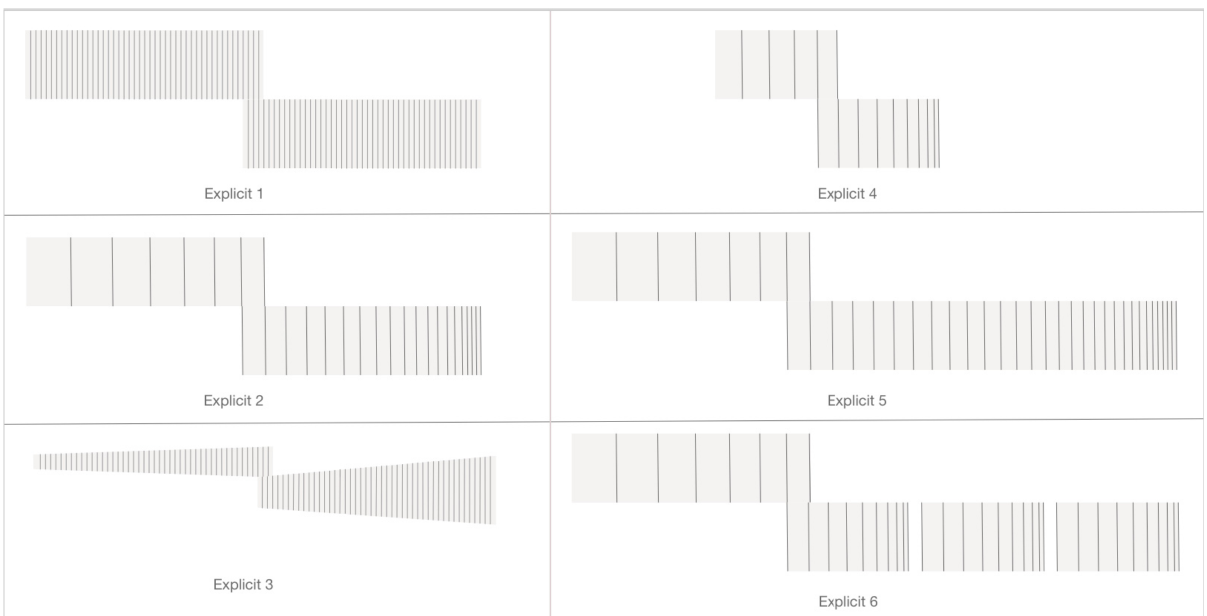

Figure 2.5   Six Explicit effects with different characteristics

2.1.1   Implicit Effects

In this strategy, only one actuator vibrates for each direction. Receiving a vibration on the smartwatch means left and on the mobile phone means right. In the Unilateral condition, this is supported by the fact that the watch is always on the left of the phone. In the Bilateral condition, there are two interpretations: again, the watch is always on the left of the phone, but also the watch is on the left of the body, and the phone is on the right of the body. In the Unilateral condition, only the relative position of the devices can be used. In the Bilateral case, either their relative position or the position relative to the center of the body can be used. We call these patterns Implicit because the meaning of the effects is not clear from the vibrations alone. We need to interpret them based on the position relative to the center of the body or the other device. Here you can find the pictures describing the conditions and the directions for the Implicit effects.

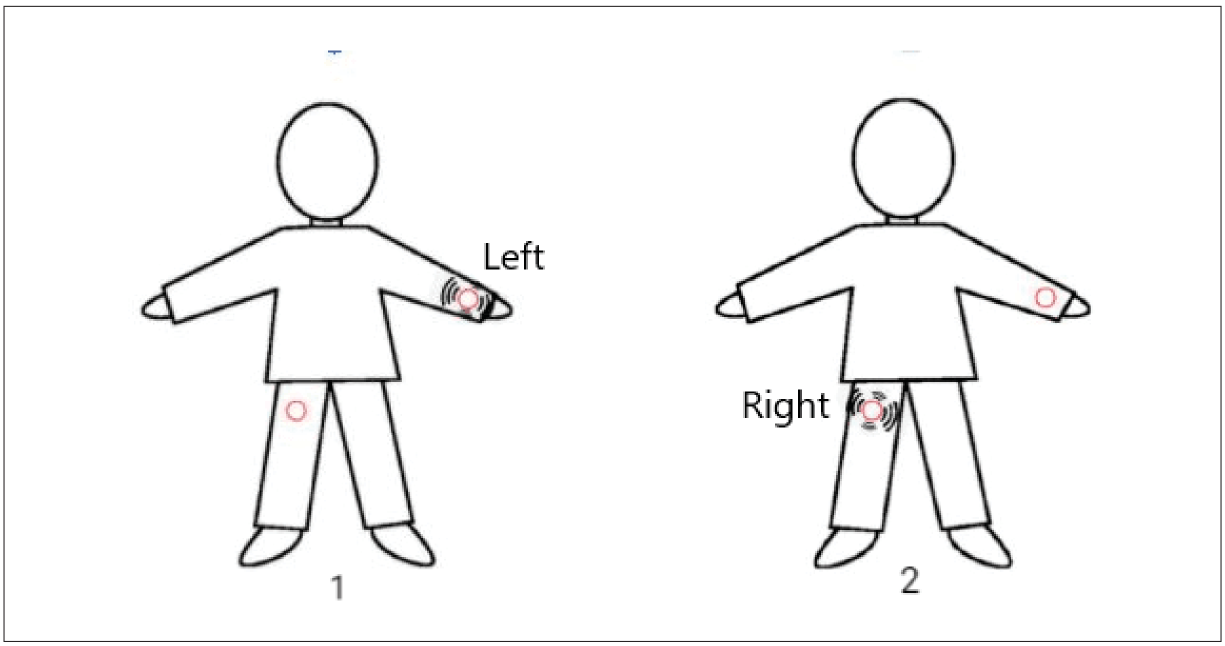

Figure 2.6 Bilateral Implicit effects for (1) left and (2) right directions

Figure 2.6 shows the Implicit effects in the Bilateral condition. (1) shows the left direction because the smartwatch vibrates and it is in the left side of the body relative to the center of the body or relative to the mobile phone. (2) shows the right direction because the mobile phone vibrates and it is in the right side of the body relative to the center or to the smartwatch.

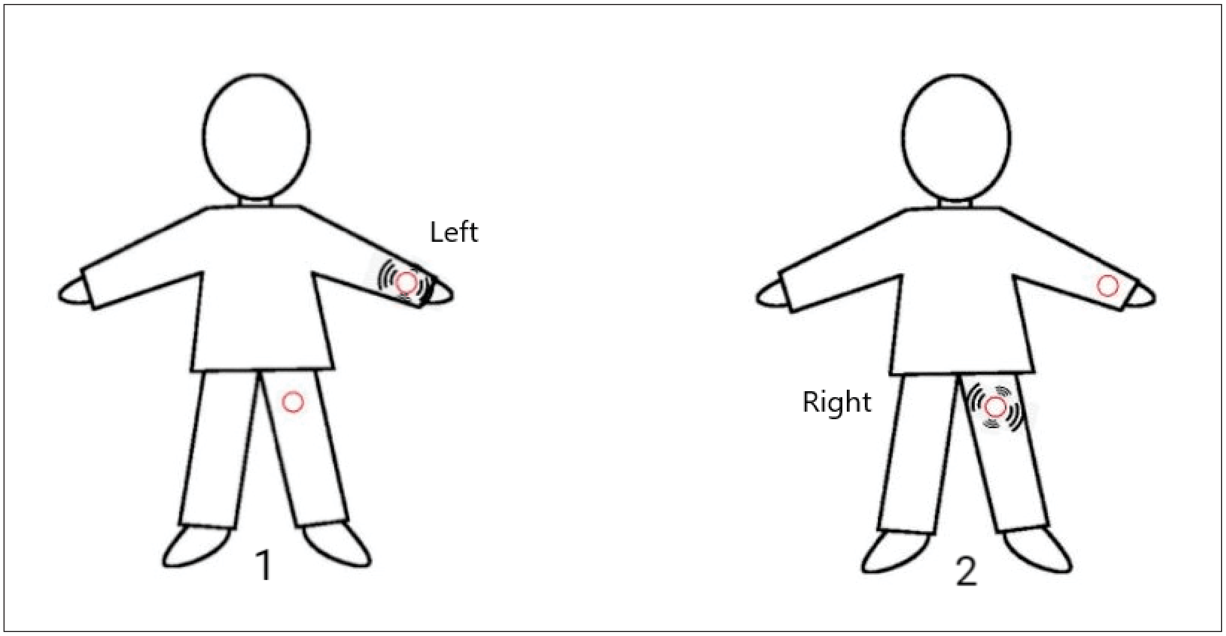

Figure 2.7 Unilateral Implicit effects for (1) left and (2) right directions

Figure 2.7 shows the Implicit effect in the Unilateral condition. (1) shows the left direction because the smartwatch vibrates and it is in the left side relative to the mobile phone. (2) shows the right direction because in this case, the mobile phone vibrates and it is in the right side relative to the smartwatch.

Implicit 1:

Frequency: 275 Hz

Amplitude: 100%

Duration: 45 ms

It's a pulse of vibration with a fixed frequency and amplitude. We used this frequency as it was the most efficient frequency for the C-2 tactors (EAI, Casselberry, FL). The goal of this effect was to see if participants could guess the direction and differentiate this directional signal from notifications. (refer to Section 2.1.4 for more detail).

Figure 2.8, shows the Implicit 1 right directional effect.

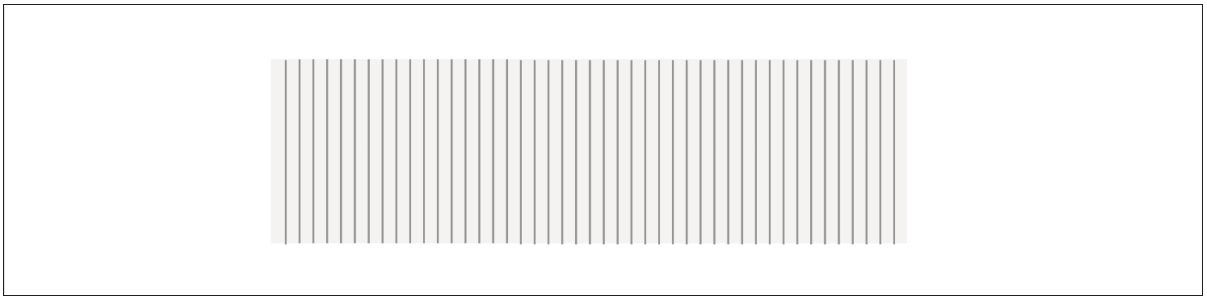

Figure 2.8 Implicit 1: 45-ms, 275-Hz vibration pulse at maximum amplitude

Implicit 2

Frequency: 75 - 275 Hz

Amplitude: 100%

Duration: 45 milliseconds

In this effect, the frequency starts from 75 Hz and goes up to 275 Hz. We used this pattern to facilitate differentiation from a typical notification. Other factors, such as amplitude and duration, were identical to Implicit 1.

Figure 2.9, shows the Implicit 2 right directional effect.

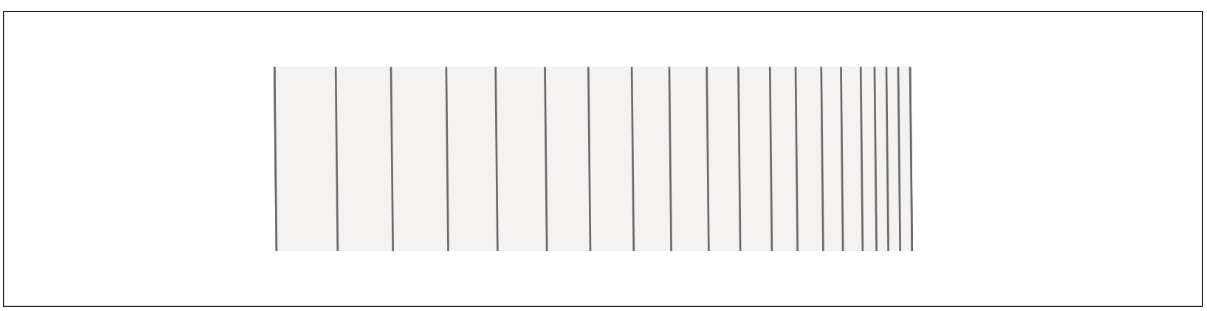

Figure 2.9 Implicit 2: 45-ms, 75-275-Hz at maximum amplitude

2.1.2 Explicit Effects

The second strategy is a sequence of vibrations. We designed directional effects that users feel like something is jumping from one device to the other to show them the direction. We called it Explicit because the vibration pattern alone is enough to show the direction since both actuators are involved.

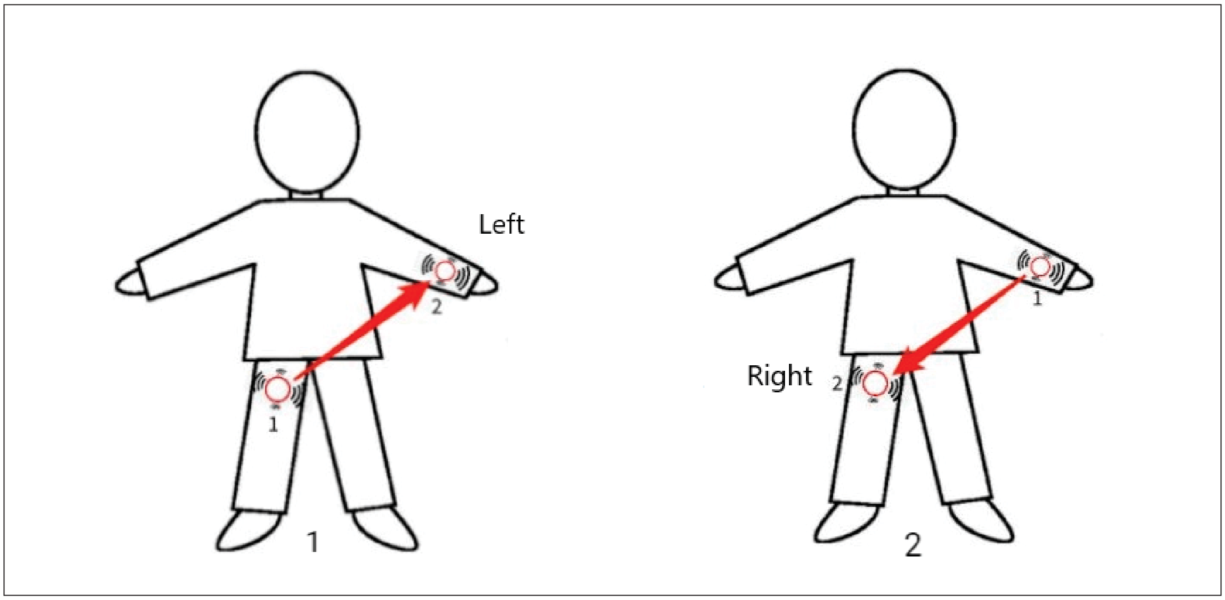

Figure 2.10 Bilateral Explicit effects for (1) left and (2) right directions

Figure 2.10 represents the Bilateral condition of the Explicit effects. The vibration starts from one device and moves to the other device. We changed many factors (such as timing, frequency, amplitude, etc.) to create the feeling of a vibration jumping from one device to the other. In Figure 2.10 (1) , the vibration starts from the mobile phone and moves to the smartwatch on the left side of the body, and this movement indicates the left direction. In Figure 2.10 (2), the vibration moves from the smartwatch to the mobile phone that is on the right side of the body relative to the center of the body or to the other device and this movement indicates the right direction.

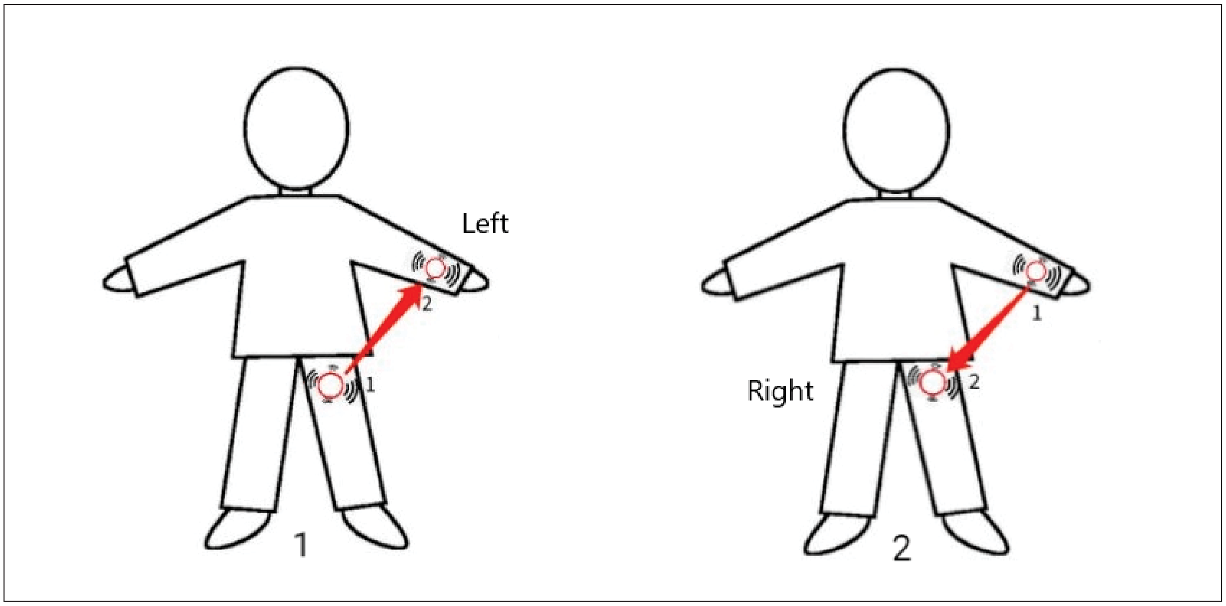

Figure 2.11 Unilateral Explicit effects for (1) left and (2) right directions

Figure 2.11 shows the Unilateral condition for the Explicit effects. In Figure 2.11 (1) the vibration starts from the smartwatch on the left side relative to the mobile phone and moves to the mobile phone that is on the right side of the smartwatch. This movement indicates the right direction. Reversely, in Figure 2.11 (2), the vibration starts from the mobile phone, which is on the right side relative to the smartwatch, and moves to the smartwatch, which is on the left side relative to the mobile phone. This movement indicates the left direction.

Explicit 1

Frequency: 275 Hz

Amplitude: 100%

Duration: 95 milliseconds with five milliseconds overlap between the actuators.

This effect was the base as we did not change the frequency, amplitude and time factors. We used 275 Hz for frequency and 95 ms for the duration which comes to be 50 ms for each actuator that is close to the duration of a notification. 5 ms is the overlap between the actuators.

Figure 2.12 shows the Explicit 1 effect. The vibration starts from the left side, and after 50 ms, the right side with a short overlap with the left starts vibrating. This transition from left to right indicates the right direction.

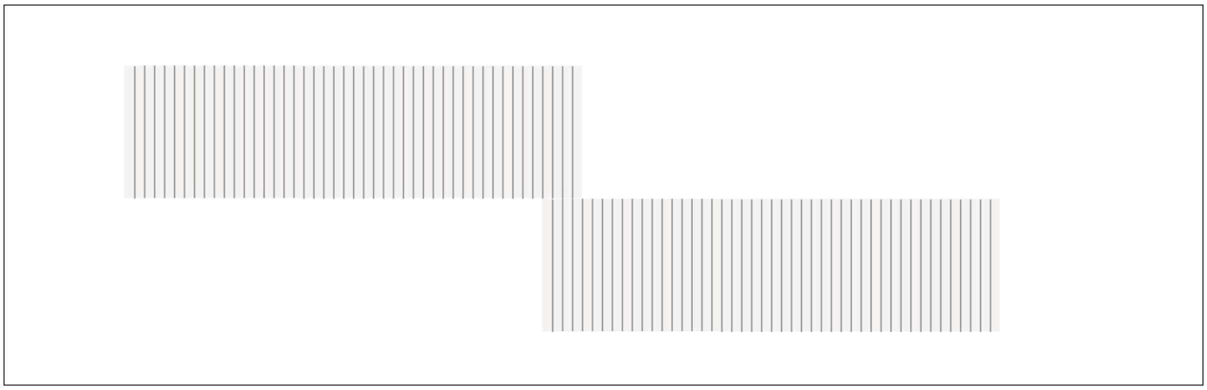

Figure 2.12 Explicit 1: 95 ms, 275 Hz and maximum amplitude. A sequence of vibration from one device to the other

Explicit 2

Frequency: 75-275 Hz

Amplitude: 100%

Duration: 95 milliseconds with five milliseconds overlap between the actuators.

In this directional effect, we want to evaluate the impact of the frequency factor on showing the direction. In this regard, we did not change the amplitude. However, we changed the frequency on both actuators. The frequency starts from 75 Hz and goes up to 175 Hz on one actuator, and then the second actuator, with a short overlap with the first one, starts the frequency from 170 Hz and goes up to 275 Hz. The goal is to make the feeling of movement on the body by changing the frequency factor.

In Figure 2.13, the vibration that starts from the left and goes to the right indicates the right direction.

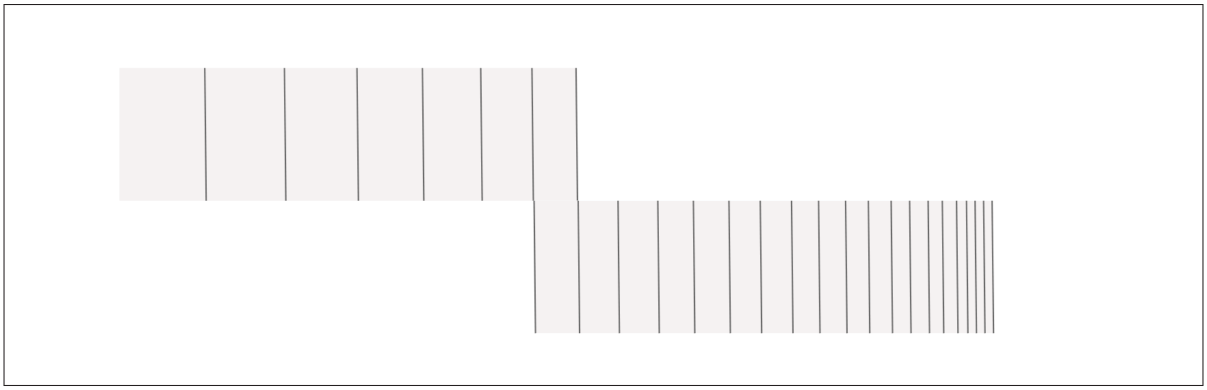

Figure 2.13 Explicit 2: 95 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency

Explicit 3

Frequency: 275 Hz

Amplitude: 50% -100%

Duration: 95 milliseconds with five milliseconds overlap between the actuators.

In this effect, we want to evaluate the impact of the amplitude factor on showing the direction. In this regard, we did not change the frequency, and we used 275 Hz for both actuators. However, we changed the amplitude. The amplitude starts from 50% and goes up to 70% on one actuator, and then the second actuator, with a short overlap with the first one, starts the amplitude from 70% and goes up to 100%. the relative side that the effect ends shows the direction. The goal is to make the feeling of movement on the body by changing the amplitude factor.

As you see in Figure 2.14, the vibration that starts from the left and moves to the right indicates the right direction.

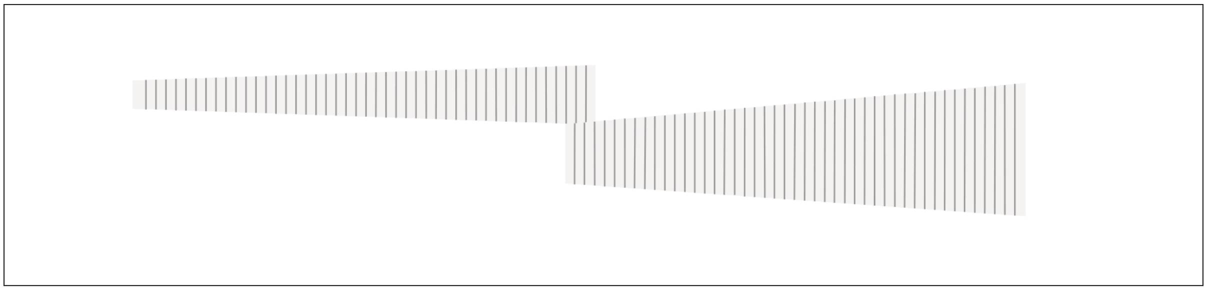

Figure 2.14 Explicit 2: 95 ms, 275 Hz and 50% - 100% amplitude. A sequence of vibration from one device to the other to see the effect of amplitude

Explicit 4

Frequency: 75-275 Hz

Amplitude: 100%

Duration: 47 milliseconds with three milliseconds overlap between the actuators. We reduced the total duration and the overlap period.

In this effect, the base is Explicit 3; however, we shortened that for Explicit 4. The reason was that we found the frequency factor interesting in our informal pilot tests, so we changed other factors to create more effects based on it. The goal in this effect is to make the feeling of movement on the body by changing the frequency and timing factors.
As you see in Figure 2.15, it is the shorter version of the Explicit 3 to see the impact of the time.

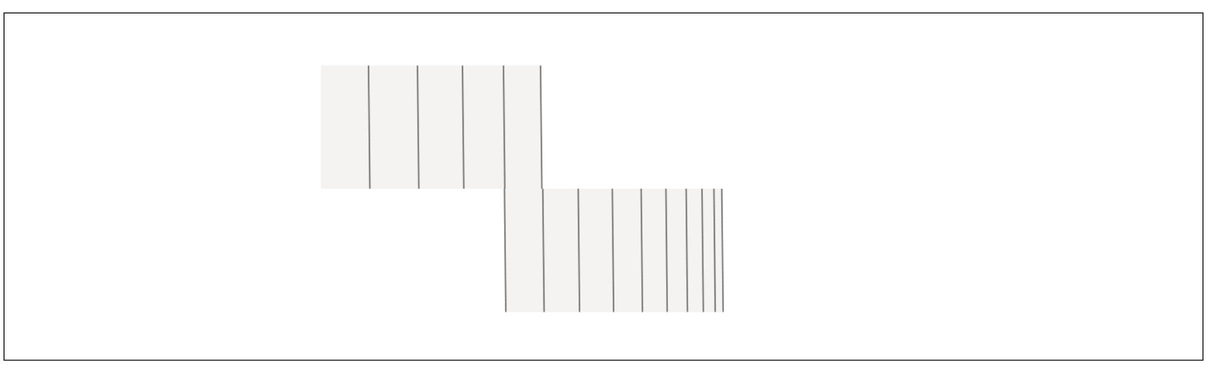

Figure 2.15 Explicit 4: 47 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency and time

Explicit 5

Frequency: 75-275 Hz

Amplitude: 100%

Duration: 145 milliseconds with five milliseconds overlap between the actuators.

In this effect, we changed the Explicit 3. We wanted to see the impact of time on showing the direction. We increased the duration of the Explicit 3. The goal is to make the feeling of movement on the body by changing the frequency and timing factors with a focus on the side that indicates the direction.

As you see in Figure 2.16, the vibration starts from the left and goes to the right with a longer duration on the right side, indicates the direction.

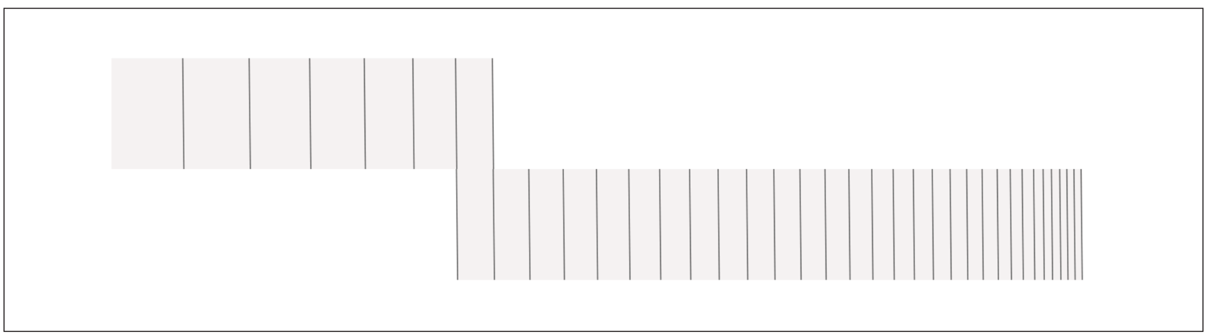

Figure 2.16 Explicit 5: 145 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to see the effect of frequency and time

Explicit 6

Frequency: 75-275 Hz

Amplitude: 100%

Duration: 145 milliseconds with five milliseconds overlap between the actuators.

In this effect, we changed the Explicit 3. We wanted to see the impact of a different pattern, such as tapping on showing the direction. In this effect, we increased the duration and designed the tapping pattern on the side that indicates the direction. The goal is to make the feeling of movement on the body with a focus on the side that shows the direction by changing the frequency and timing factors.

Figure 2.17 shows the Explicit 6, the vibration starts from left and continues to the right with a repetition that creates a tapping feeling on the side that indicates the direction.

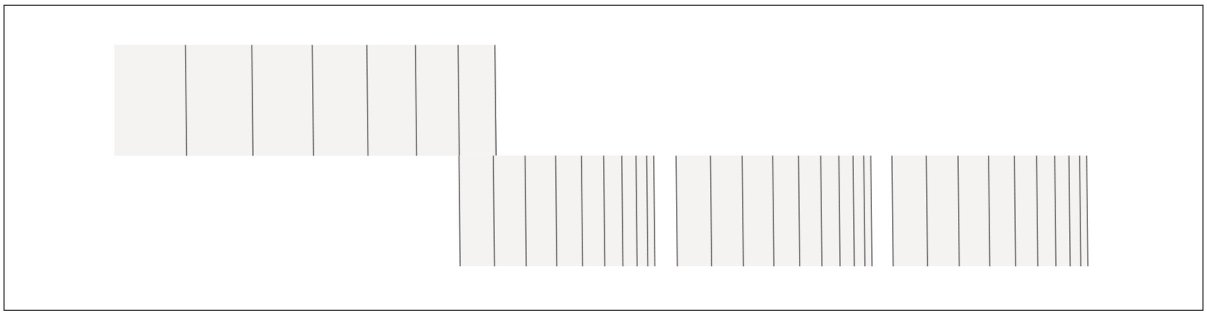

Figure 2.17 Explicit 6: 145 ms, 75-275 Hz and maximum amplitude. A sequence of vibration from one device to the other to evaluate different patterns

2.1.3 Symbolic Effect

We were interested in comparing the Implicit and Explicit effects with the haptic feedback used in commercial smartwatches to guide users. We designed an effect that is inspired by the Apple Watch strategy to show the left or right directions on the smartwatch. The strategy is based on different haptic patterns. A steady series of 12 taps indicates a turn to the right, and 3 pairs of two taps indicate a turn to left[3]. Refer to the Figures 2.18 and 2.19.

[3] https://www.cultofmac.com/320234/how-to-navigate-using-only-your-apple-watch/

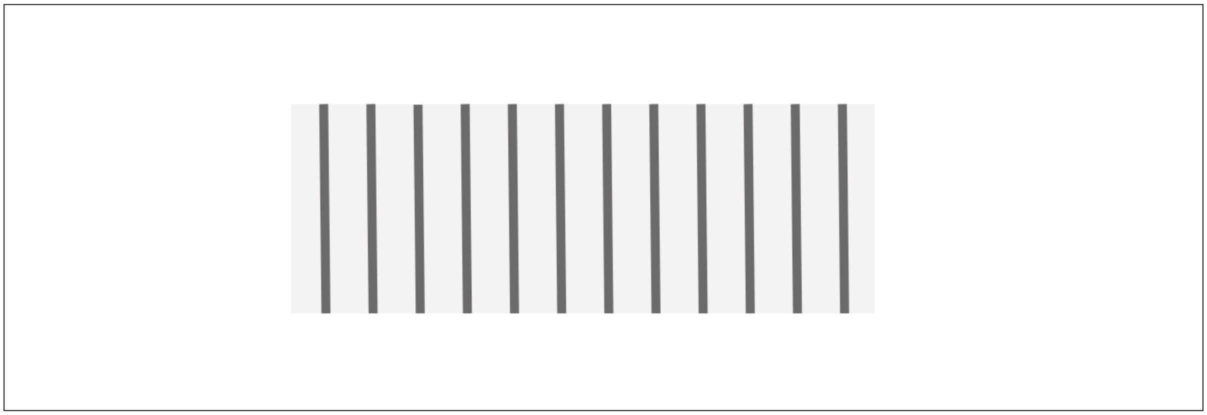

Figure 2.18 Symbolic effect: a steady series of 12 taps indicates the right direction

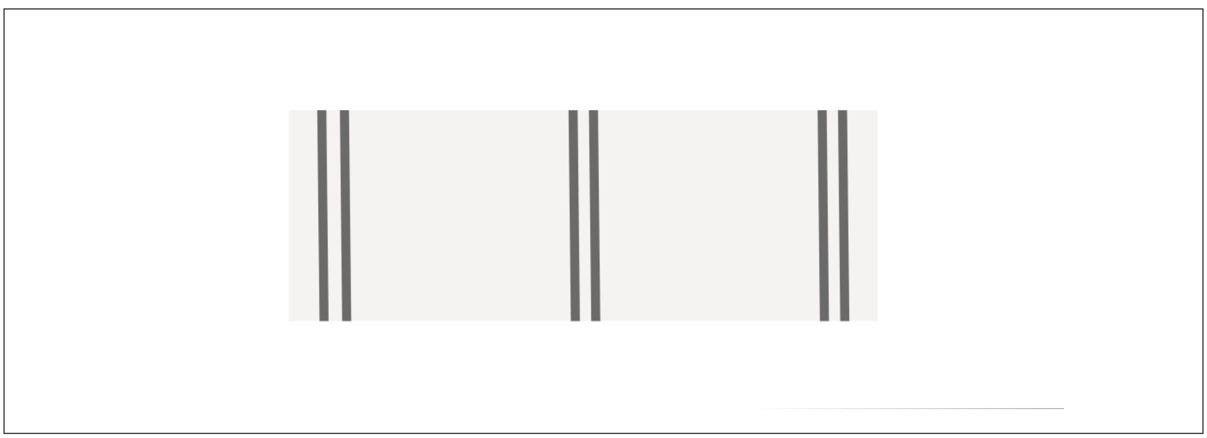

Figure 2.19 Symbolic effect: 3 pairs of two taps indicates the left direction

2.1.4 Notification Effect

Typically people receive vibrations on their devices, such as vibrations from a notification of a text message. One of the goals was to see if participants could distinguish the directional effects from a typical notification. In this regard, we designed the notification that was inspired by the Apple Watch notification on Audacity. The question was which devices (smartwatch or mobile phone) vibrate with a notification. Based on the Apple website[4], if the iPhone is locked

[4] https://support.apple.com/en-ca/HT204791

or asleep, notifications will appear on the Apple Watch. The mobile phone is always in the pocket in our conditions, so we considered notification only on the watch.

2.2 Vibrotactile Hardware

In this section, we will discuss the hardware and equipment we used in all 3 experiments. As you see in Figure 2.20 the hardware consists of two actuators, two straps to mount the actuators, an amplifier, and a tablet.

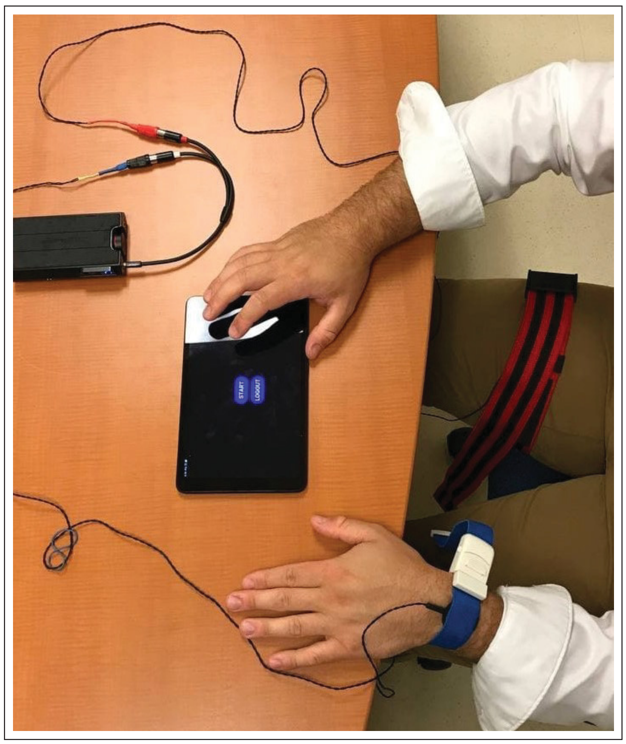

Figure 2.20 Picture of the experimental setup

2.2.1 Vibrotactile Actuators

The goal was to choose two actuators that can play the role of a mobile phone and a smartwatch and place them on the wrist and the thigh over the pants. We chose actuators instead of actual devices because we did not want to be restricted by the limitations of current technology, such as the latency introduced by wireless communications and the limited expressivity of mobile actuators. After reviewing different actuators, we chose C-2 tactors (EAI, Casselberry, FL), which are a type of linear electromagnetic actuators (refer to Section 1.2 for more details). We chose these because we needed vibrotactile actuators that could be placed easily on the body and felt even through a layer of material, like pants. The C-2's high force and their small, flat rounded shape gives them the advantage that they can be placed on all parts of the body (Choi & Kuchenbecker, 2012) and be felt even through layers of clothing[5]. Another advantage is that this actuator works like a speaker and can produce vibrations easily using audio signals. We could therefore design our directional effects using audio editing software. Table 2.1 and Figure 2.21 show the characteristics of this actuator, which we used for the best performance in our directional effect designs (2.1). Figure 2.21 shows that this actuator is maximally responsive from 265 Hz to 285 Hz, but still responsive over a wide range of frequencies. Considering the recommended drive nominal current (I = 250 mA) and the nominal resistance of the actuator (R = 9 ohms), using the Ohm's law (V = IR), we can understand the recommended voltage is (V = 2.25 V).

2.2.2 Actuator Mounting

We needed to fix one actuator on the wrist to play the role of a smartwatch and one actuator on the thigh over the pants to play the role of a mobile phone. The main reason we did not place the actuator in the participants' pocket was that we did not expect all participants to wear pants with pockets. The other reason was that we wanted to tighten the actuator on the body to reduce the risk of missing any vibrations. So, we chose two bands with an elastic material that can easily be loosened and tightened based on the size of each participant. The actuators were placed under these bands. For the wrist, we chose an elastic tourniquet as it was easy to change the size only by one hand, and the band's size was sufficient to keep the actuator under. For the thigh, we chose an elastic sports band that is meant to restrict the blood flow. We used this band because the size was designed for the leg and thigh; also, it was easy to adjust the size. The two

[5] https://www.eaiinfo.com/product/c2/

Table 2.1 Specifications of C-2 tactors
Taken from
https://www.eaiinfo.com/product/c2/

Physical Description:	1.2" (30.5 mm) diameter by 0.31" (7.9 mm) high
weight:	17 grams
Exposed materials:	Anodized aluminum, polyurethane
Electrical Wiring:	5ft flexible, insulated, #24 AWG tinsel *
Body Contactor:	0.31" (7.87 mm) diameter, pre-loaded on skin
Tactile Pulse Characteristics:	200-300 Hz, <2 ms rise time
Electrical Characteristics:	6 ohms nominal without wire;9 ohms nominal with wire
Transducer Linearity:	+/- 1 dB from sensory threshold to 0.02" (0.5 mm) peak displacement
Recommended Drive:	Sine wave tone bursts 250Hz at 250 mA rms nominal, <10% duty cycle, 500 mA rms max for short durations.
Recommended Controller:	EAI Universal Controller and all distributed series controllers

bands were similar in terms of the material; however, they were different in size, and each was designed for a different body part.

Participants could adjust the bands alone; however, if they asked for help, the facilitator could provide additional explanations or help them fix it on the body. Refer to Figure 2.22 for the bands we used for the thigh (left image) and the wrist (right image).

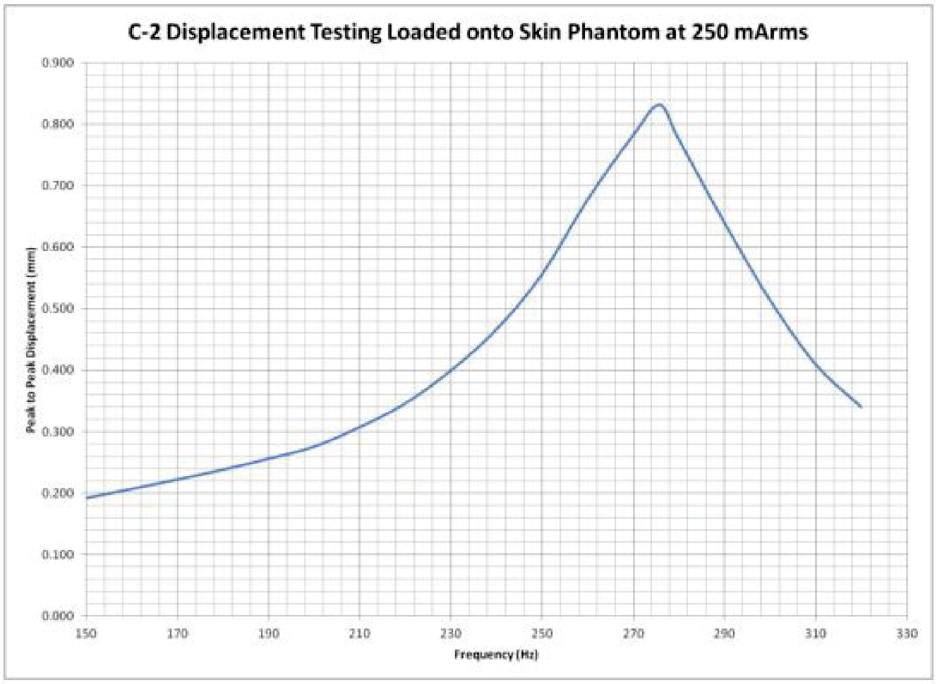

Figure 2.21 Transfer function of C-2 tactors
Taken from
https://www.eaiinfo.com/product/c2/

Figure 2.22 The bands used to fix the actuators on the thigh and the wrist

2.2.3 Digital to Analog Conversion

We had to convert effects saved as digital audio files into analog audio signal. In order to have the maximum vibration amplitude, the actuators required the maximum voltage (2.25V) (refer to Section 2.2.1).

We created the digital audio files using 100% of the amplitude in Audacity. We tested the effects on 3 different devices: an iPhone 7 plus, a laptop Dell Latitude 5500, and a Xiaomi Mi Pad 4 tablet. We tested them standalone and with an amplifier. The reason was to boost the intensity of the effects.

We used a Sound Blaster E5 amplifier (Creative Technology Ltd). It is small and battery operated and could therefore be moved easily with the tablet (refer to Figure 2.23). We connected the devices through Bluetooth to the amplifier. The Bluetooth connection was consistent and did not introduce any significant delays. The amplifier was wired to two actuators. We set the volume of the amplifier and the device to the maximum. (Refer to Figure 2.1)

Only iPhone 7 plus standalone and Xiaomi Mi pad 4 Tablet with the amplifier were able to produce a signal voltage between 2V and 2.25V (the maximum).

As discussed in next Section 2.3, participant needs to interact with this device. To have a better interaction, we selected the device with the biggest screen: the Xiaomi Mi Pad 4.

With this setup, the effects could be felt on actuators as vibrations.

Figure 2.23 Picture of the Sound Blaster E5

2.3 Experimental Software

This Section consists of three main parts. First, we will discuss the software that was developed to interact with participants and the facilitator. Then we will discuss how the software communicates with Google Drive to load the effects (refer to 2.3.1), and in the end, we will introduce a game that we used as a distractor to make the situation closer to the real world (refer to 2.3.2).

We developed a website application instead of an android software because it uses basic technologies like HTML and JavaScript, which coding with them is relatively easier than android application development. We also decided to implement a web application instead of a website because of some advantages. First of all, if the internet disconnects, the web app does not show a "No Internet" web page, and it can keep working. Also, we can have a more fluid UX with a web app because it works faster than a website, and participants do not need to wait to refresh a page or go to another page. The web application was also developed a full screen to make it more immersive. The web application is hosted on GitHub because rather than being free, the application updates in a real-time after pushing the code on GitHub.

Now we will discuss the user interface for both the participants and the facilitator. The design of the software changed based on the goal of each experiment.

In the first experiment, to access the effects, the facilitator needed to copy the Google Drive File ID where the whole directional effects were uploaded there. Also, the participant ID and repetition number should be added by the facilitator.

- **Google Drive File ID:** A unique identifier of the file on Google Drive.
- **Participant ID:** A unique identifier that can be used in experiments instead of the name of the participant for ethical purposes.
- **Repetition Number:** To achieve more accurate results, each effect is repeated many times during the experiment.

After filling in the information by the facilitator, the tablet was given to participants. They were feeling several effects, and after each effect, two questions were shown on the tablet regarding the direction of the effect. Refer to Section 3.1 to read more in detail.

The second experiment was separated into nine blocks (2 Implicit, 6 Explicit, and one Symbolic). Instead of a pool of effects, the experiment grouped based on the effect types. The facilitator needed to choose the effect type in each block. Refer to Figure 2.25 for the screen flow. The two questions were asked after each type of effects. The rest of the steps were similar to the first experiment. Please read more on Section 3.2.

The last experiment was quite different. We designed a game, and participants were receiving the effects while playing the game. Refer to Section 2.3.2 for more details about the game. Two more steps were added for the facilitator. The first was a page with options to balance the actuators. In previous experiments, the wrist had a lower and fixed intensity than the thigh because the wrist is generally more sensitive. We chose the intensities based on our pilot tests. In this experiment, we gave options to participants to choose the most balanced vibrations based on their feelings. We also added the Unilateral/Bilateral conditions that you can read more on 2.1. For Participants, we added another effect to directional effects that were considered as a notification. They needed to distinguish the difference between a direction and notification effect. Read more on Section 2.1. We added one more question regarding the difference between notification and directional effects in this experiment. The order looked like Experiment 2, and questions were being asked after each type of effects. Read more about that in Section 3.3.

Figure 2.24 Screen flow of Experiment 1

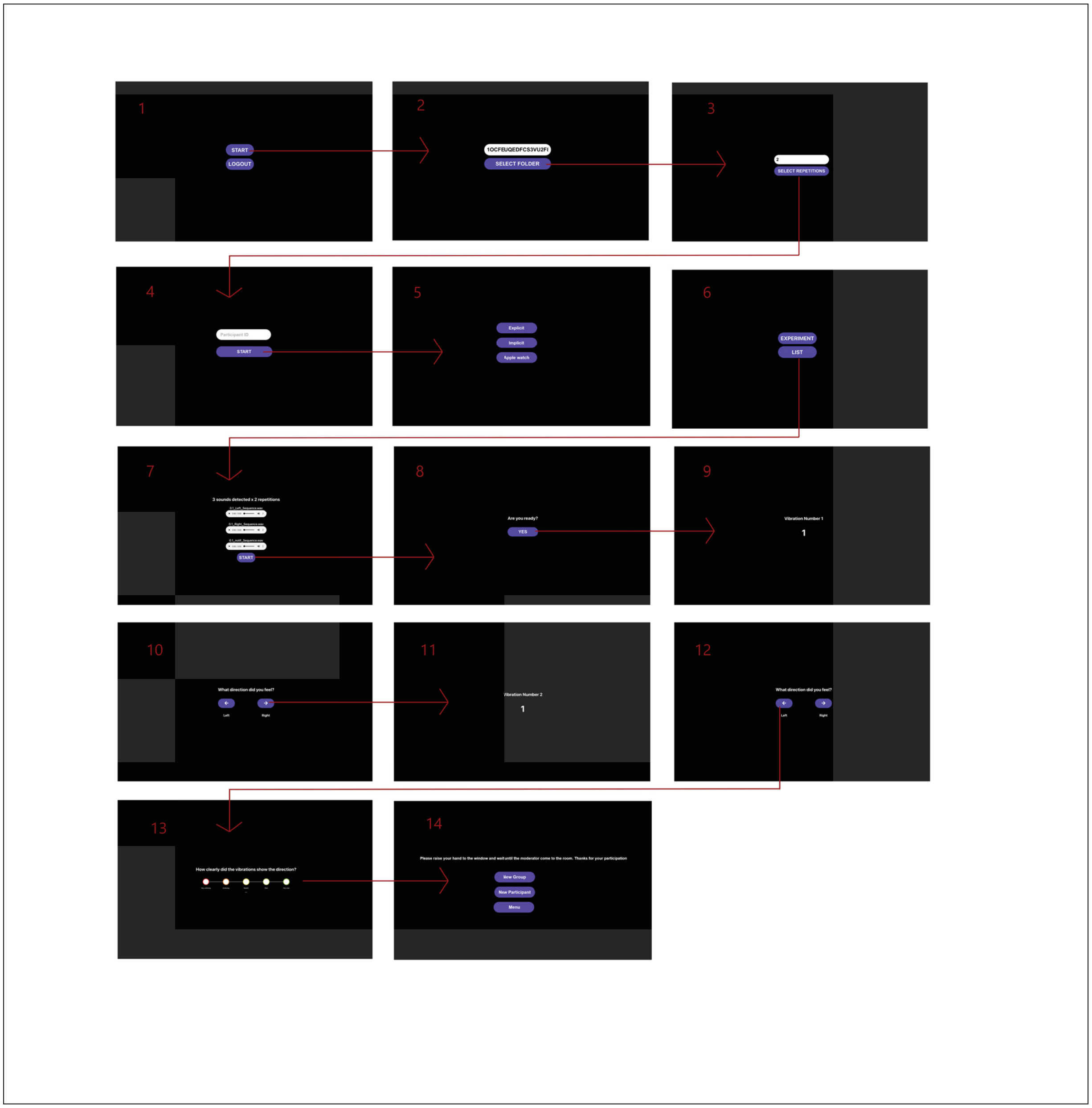

Figure 2.25 Screen flow of Experiment 2

Figure 2.26 Screen flow of Experiment 3

2.3.1 Communication

As we discussed before, we generated the directional effects using Audacity software and exported them as WAV files which is a standard audio file format. We needed to upload them in storage so that we could load them for participants during the experiment. We decided to use Google Drive as our storage for some reasons:

- Loading the effects from Google Drive allowed us to have access to the file through any other device. In this way, we could make any changes live without the need to plug in the tablet.
- We stored the data collected from participants in the Google Drive file, allowing us to observe the participants' answers simultaneously from any other rooms during the experiment.

In this regard, we used Google Drive as well as the Google Sheet APIs for the communication. We needed to copy the Google Folder ID in the web application to be able to read the Audio files.

2.3.2 Distractor Game

In Experiment 3, we added a game to distract participants during the experiment. The reason is that in real life, people would use the haptic navigation feature while doing other activities such as walking, running, driving, etc. Adding the game resulted in less attention to the directional effects and made the environment much closer to the real world. We decided to implement the dinosaur game that appears on the Chrome browser when it is offline. During the game, a dinosaur starts running. It will jump by tapping on the screen. There are some cactus on the ground. The player should avoid oncoming cactus by jumping over them. Two elements determine the game's difficulty, the number of the cactus and the dinosaur's speed while running. As the game progress, the speed of the dinosaur and the number of cactus increase. However, we simplified the game and kept these two elements consistent. The reason is that participants were receiving the directional effects during the game, and we wanted to have the same level of cognitive load coming from the game for all the effects. The effects were randomly distributed during the game. Two questions were asked from participants after each effect, and again the game was played until the participant felt the following effect. We chose this game because, first of all, it was easy to implement. Also, we wanted a game that was not too complicated to make participants tired to play for 1 hour nor too easy that is boring to play. Participants could play that using only one finger to tap on the screen.

We implemented the game from scratch and did not use a third-party game.

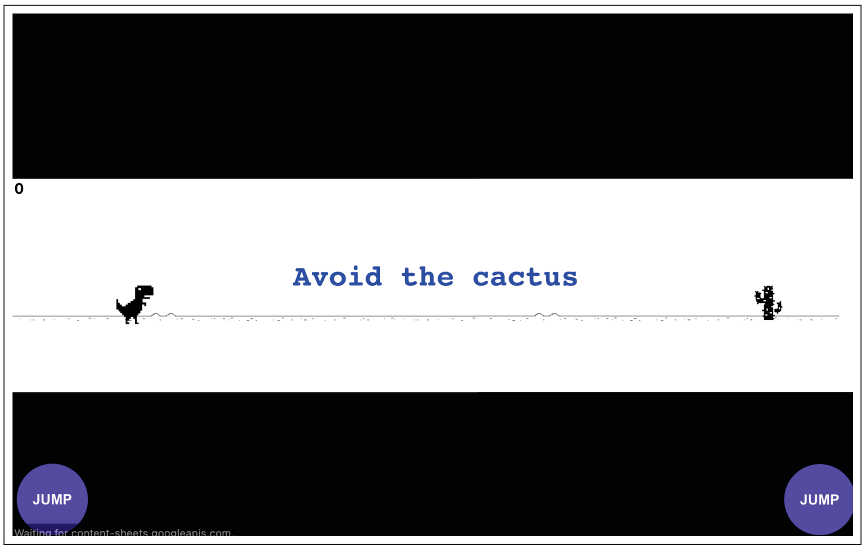

Figure 2.27 The game when it starts

Figure 2.28 The game over condition

Figures 2.27 and 2.28 show the game in two conditions. The time when the player starts the game and once it hits the cactus.

CHAPTER 3

EXPERIMENTS

We ran 3 experiments to understand if using two actuators would work better in showing the directions compared to one actuator, also we wanted to see which directional effects would work better in Implicit and Explicit effects. In each experiment, we changed or added some variables to get closer to real-world conditions. In this section, we will specifically talk about the experiments, their variables, and the results obtained.

In all experiments, participants were asked to imagine that they had a mobile phone in their pocket and a smartwatch on their wrist. Instead of a real mobile phone and smartwatch, an actuator was attached to their leg, near their pocket, and another to their wrist. The phone and the smartwatch were working together to guide participants towards a destination. They felt some vibrations from the phone, the smartwatch, or both. These vibrations are the effects that we designed as described in Section 2.1. After feeling each effect, participants were asked questions regarding the direction indicated and its clarity. At the end, additional questions were asked as part of a semi-structured interview to better understand the participants' feelings and points of view. Figure 3.1 shows the methodology we used for all 3 experiment.

Figure 3.1   Methodology in all experiments

In Experiment 1, we hypothesized that Explicit effects would be easier to interpret than Implicit effects without any training. You can find the list of effects and their characteristics in Section 2.1.

In Experiment 2, we were interested to see how the results would change if we trained the participants. We also were able to add the Symbolic effect discussed in Section 2.1, which could not be included in Experiment 1 since it is meaningless without training. We hypothesized that our suggested directional effects would work better than the Symbolic.

In Experiment 3, we added variables to make the experiment closer to the real world. First, we added a game as a distraction because users will normally get distracted while using this feature outside. This distraction might be some noise from the street, their movement, etc. Also, in the real world, users might receive other vibrations on their devices, such as a notification from a text message. We wanted to see if practically these directional effects are distinguishable from a typical notification. The last variable is the location of the mobile phone. In the first two experiments, the mobile phone was always in the right-front pocket. We wanted to see the results if it was moved to the left-front pocket, on the same side of the body as the smartwatch. For more details, please see Section 2.1.

The experiments were approved by the Ethics Committee of École de technologie supérieure (ÉTS). For each experiment, we recruited participants from the students of ÉTS. They were given an Amazon gift card (CA$ 20) for their 60 minutes of participation in our study. The recruitment poster was published in student social media groups. As the beginning of the experiments, the participants were asked to fill and sign a consent form and a demographic survey.

3.1 Experiment 1

The goal was to identify the most efficient directional effects described in Section 2.1, and more specifically to compare the performance of the Explicit and Implicit effects. In this experiment, 8 types of effects in both left and right directions were played for participants. After each effect, they were asked two questions regarding the direction indicated and its clarity, respectively. At the end, the facilitator asked more questions as part of an interview to understand which effect participants subjectively preferred and why. We hypothesized that Explicit effects would be easier to understand than the Implicit effects without any training.

3.1.1 Participants

12 participants (6 males) were recruited. At the beginning of the experiment, they were asked to complete a survey. The demographic information collected with the survey can be summarized as follows:

- None of the participants had any health issues that cause impairments to the sense of touch.
- Most participants (75%) were in the age group of 25-34. (Figure 3.2a)
- Most participants (75%) preferred to wear a watch on their left wrist and the rest on their right wrist.
- Half of participant (53.9%) reported using a normal watch occasionally. (Figure 3.2b)
- 50% (6 out of 12) of the participants reported that they never used a smartwatch or an activity tracker. (Figure 3.2c).

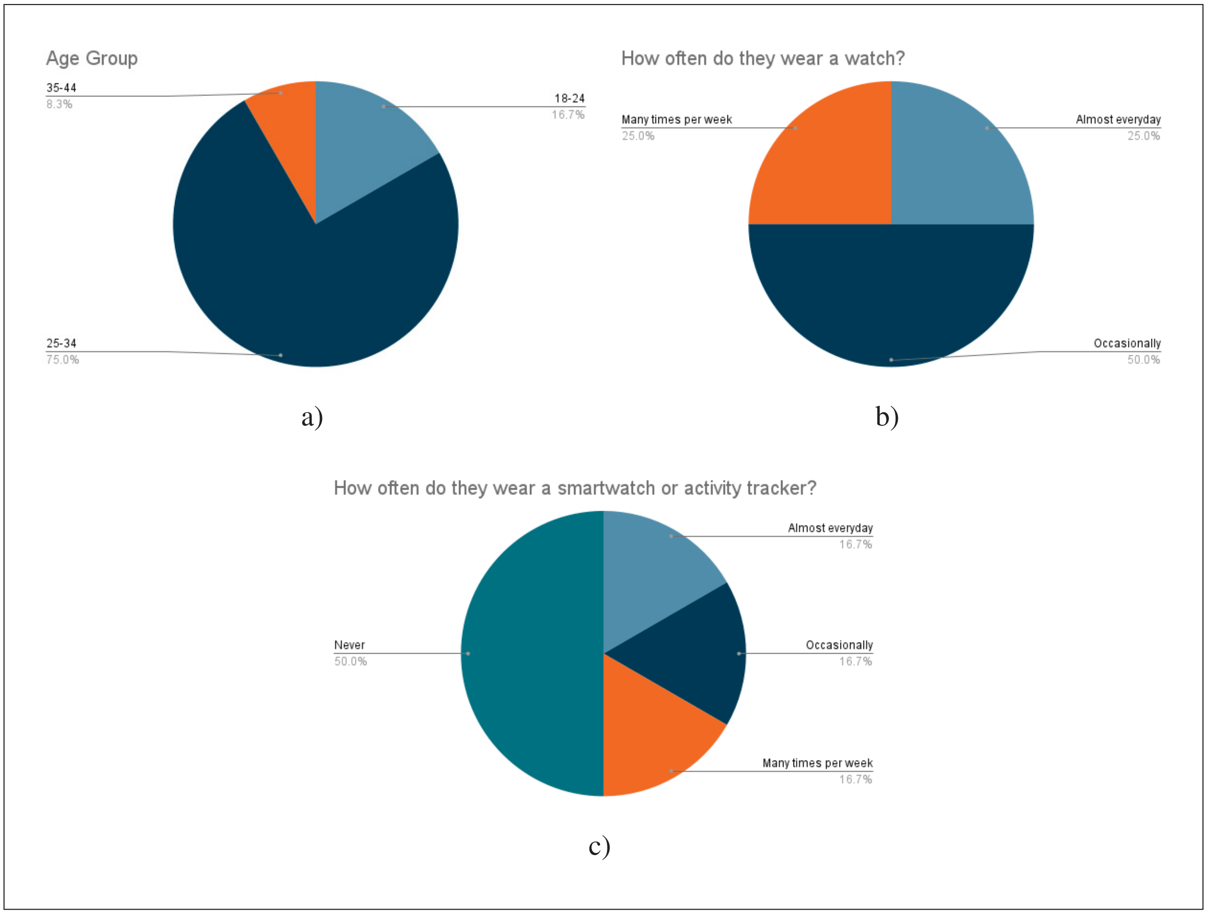

Figure 3.2 Demographic data in Experiment 1: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker

3.1.2 Experimental Procedure

The experiment ran in a laboratory environment. The participants were asked to sit on a chair in front of a table. Using two straps, the facilitator helped them to fix the actuators on their left wrist and on top of their right-front pocket. We played a white noise for all participants during the experiment to reduce the effect of audible vibrations and any possible surrounding noises. The facilitator followed the same guide for all participants to avoid any biases (see Appendix 1 for details). While participants were receiving the effects and answering the questions, the facilitator observed them from another room through a one-way mirror. In this experiment no training was given to the participants.

After starting the experiment, the participants felt the effects one by one. After each effect they had to answer two questions on a tablet on the desk and after a pause of 3 seconds the next effect was played.

Question 1: “What direction did you feel?” The answer was "Left" or "Right".

Question 2: “How clearly did the vibration show the direction?” The answer was in a Likert scale: "Very confusing", "Confusing", "Neutral", "Clear", "Very clear".

The experiment evaluated 6 Explicit and 2 Implicit effects. Each effect had two directions (left and right), and each direction was repeated 6 times. In total, 96 effects were played for each participant. The order of the effects was fully randomized to avoid biases.

For the last step, an interview was conducted. 8 pairs of effects were played, as fully described in Appendix 1. Each pair consisted of two effects with only one factor changed. For example, the first pair consisted of Explicit 1 and Explicit 3, which differed in their amplitude profile. The comparison helped us understand participants’ opinions on this factor. These questions were asked after each pair:

Question 3: "Can you explain what your strategy is to guess the direction?"

Question 4: "Which one showed the direction more clearly? Why?"

Question 5: "Imagine yourself receiving notifications as well on your watch or smartphone. Would they be confusing for you to distinguish from notifications?"

Question 6: "In real life, have you ever been in a situation where you could not look at your phone to follow the map? When do you think it would be useful to have this feature in your daily life?"

After the comparison of the effects, the Symbolic effects for both left and right directions were played and the following instructions were given: "There are also other solutions to guide users by only the sense of touch. For example, some watches use two different effects only on smartwatches to show left and right. I will play them for you, and then we will discuss more in detail." Participants were then asked this question:

Question 7: "What do you think of the Symbolic effect compared to what you already felt? Which one do you think is more clear for you in real life?"

3.1.3 Experiment Design

To measure the efficiency of each effect, we measured the error count, the reaction time, and participants' opinions on the clarity. We will explain each variable here:

Error Count: The number of times the direction of an effect had been incorrectly identified (Question 1).

Clarity: The participant's rating of the clarity of the direction indicated by an effect (Question 2).

Reaction Time: The time between the end of the effect and when the participant presses the button to answer Question 1.

The independent variable is the Effect, with 8 possible values: Explicit 1-6 and Implicit 1-2. The dependent variables are the Error Count, Reaction Time, and Clarity. Moreover, it was interesting to see if participants would develop a strategy and improve their performance during the experiment. We therefore consider exposure to different effects as a moderating variable because it can affect the Error Count and decrease it.

We chose a within-subject design in which all participants were exposed to every effects, and all participants followed the same methods and process.

3.1.4 Quantitative Results

The quantitative results were analysed based on Error Counts, Claritys and Reaction Time.

3.1.4.1 Error Count

In total, the direction of 27.2% of the effects was identified incorrectly. The bar chart in Figure 3.8 shows the number of errors for each effect. A one-way repeated measures ANOVA was conducted to see the impact of the effect type on the Error Count. The results show a significant impact of the effect type on the Error Count ($F = 14.64$, $p = 2e - 16$). We ran a post-hoc analysis using Bonferroni. The results show that there are no significant differences between Explicit 2, Explicit 5, Explicit 6, Implicit 1 and Implicit 2 and that they have the lowest Error Count. Most errors come from Explicit 1 and Explicit 3 and Explicit 4.

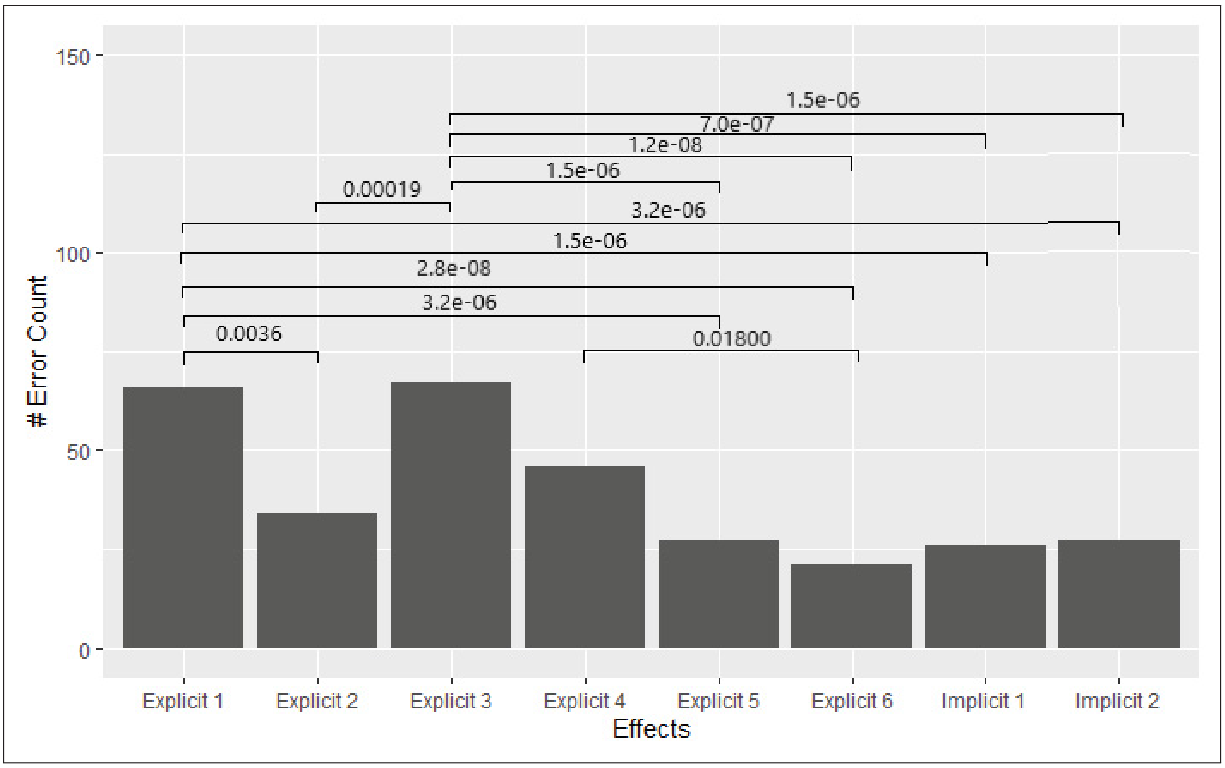

Figure 3.3 The total number of Error Count for each effect. The lines on the bar chart shows the significant differences between two effects and the number above each line, shows the p-value

It was also interesting for us to analyze if, over time and by exposure to repetitive effects, participants would learn a strategy and make fewer mistakes. Looking at Figure 3.4, the X-axis shows the sequence of effects numbered from 1 to 96 for each participant. The Y-axis shows the cumulative number of errors. Each line belongs to one participant. The graph slope shows the Error Count. If the graph slope is 0, it means that no errors have occured among those vibration numbers. For example, Participant 13 (black line) had 0 error from vibration number 18 until vibration number 49 as the slope of the line is 0.

By analyzing this data, we could not find any consistent evidence that participants were learning. The slope decreases over time for some participants, but not for others. For example, Participant 8 started with a sharp slope, but the slope decreased after vibration number 25. This suggests that this participant learned the effects during the experiment. In reverse, the slope for Participants 11 and 12 did not decrease over time. We can therefore not generalize that there is any learning strategy among all participants.

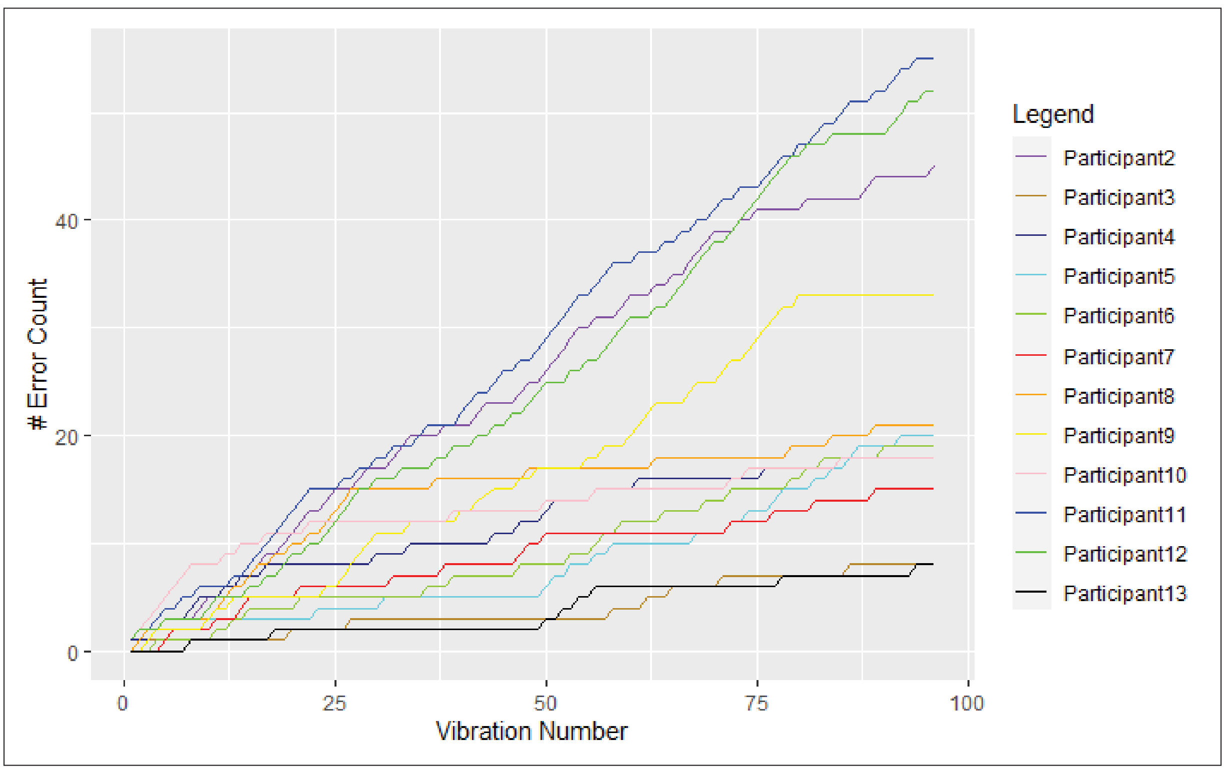

Figure 3.4 The cumulative number of errors based on vibration numbers

3.1.4.2 Clarity

After receiving each effect, the participants were asked how clearly it showed them the direction, and participants answered on a Likert scale from very confusing to very clear. In our analysis, we converted the data into numbers: very confusing mapped to 1, confusing mapped to 2, neutral to 3, clear to 4, and very clear to 5.

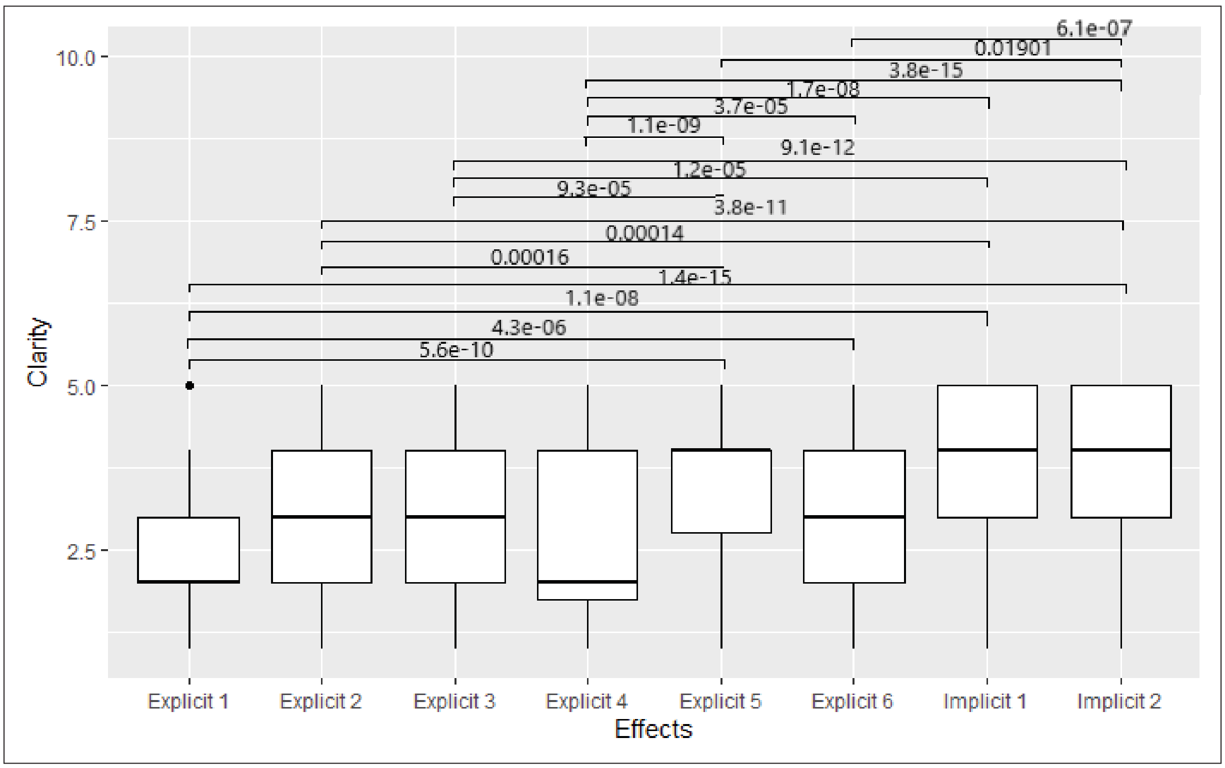

Figure 3.5 Clarity of each effect based on participants' opinion. The line that divides the box is the median (average value). The lower quartile is the point where one-quarter of the values are below it. Likewise, the upper quartile is where one-quarter of the values are above it. The lines and numbers on the chart show the significant differences between the effects and the p-value

A one-way repeated measures ANOVA was conducted to see the impact of each effect on the Clarity. The results show a significant impact of effect type on the Clarity ($F = 29.96$, $p = 2e{-}16$). We ran a post-hoc analysis using Bonferroni. You can find which effects had significant differences on Figure 3.5.

Implicit 1, Implicit 2 are not significantly different and they received the highest Clarity. On the other hand, Explicit 1 and Explicit 4 received the lowest Clarity from participants and are not significantly different.

3.1.4.3 Reaction Time

The difference between the time when an effect ends and when participants press the button to answer the first question (Question 1) corresponds to the time they need to think, and it shows how intuitive each effect is in showing the direction.

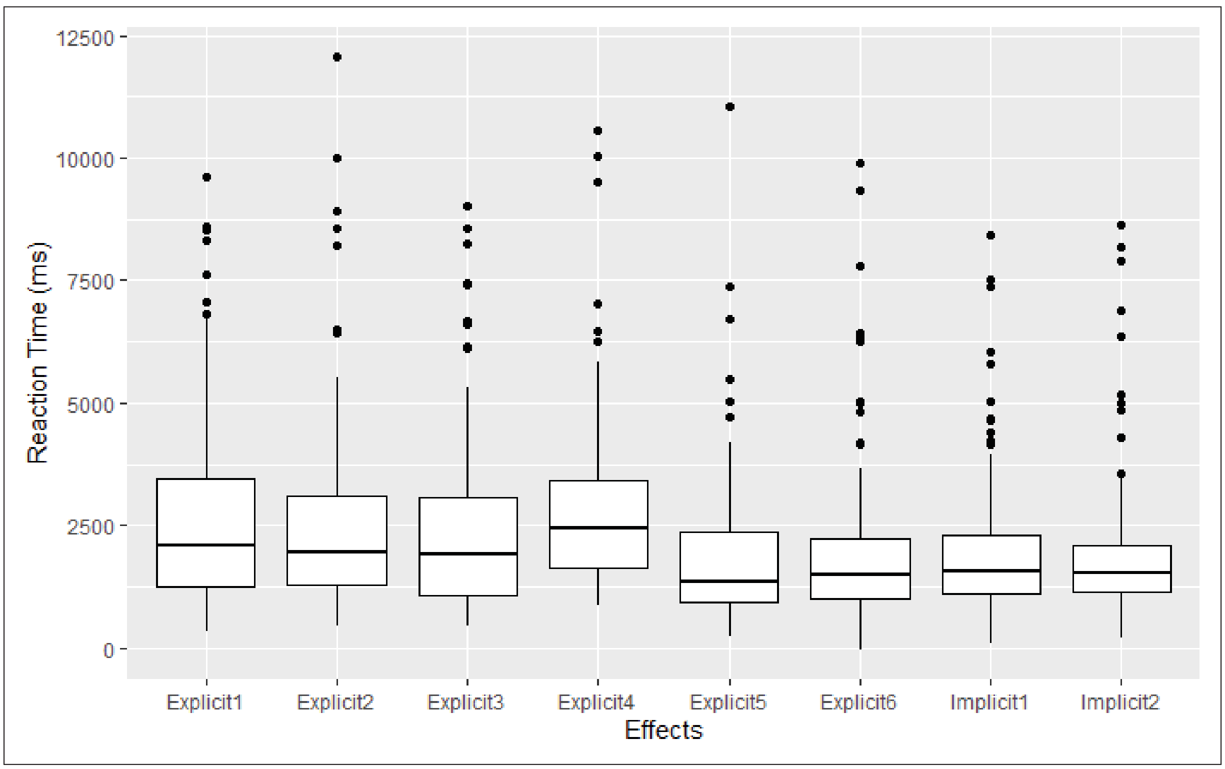

Figure 3.6 Reaction Time of each effect

We decided not to remove the outliers. The box plot in Figure 3.6 shows the results. A one-way repeated measures ANOVA was conducted to analyze the impact of the effect type on the Reaction Time. We could not find any significant impact of effect type on the reaction time (F = 1.764, p = 0.0909).

3.1.5 Qualitative Results

In summary, participants had different strategies in guessing the direction.

Explicit effects:

- 4 out of 12 participants guessed the direction based on the side of the body where they were feeling a stronger or longer pattern. For example, Participant 4 said: "It starts the leg and transfers to the wrist and gets stronger; that's why I choose left."
- 1 out of 12 participants felt an arrow shape in their mind: "The first one what I really like is that it is not powerful on the leg and gets powerful on the wrist. In my brain, it's like drawing a line. For me, it really draws a line to the left."
- 5 out of 12 participants were feeling either on the wrist or leg a sliding sensation that moves from one side of the wrist/leg to the other side.
- 2 out of 12 participants were choosing the direction based on the body side where the directional effects end

Implicit effects:

- 8 out of 12 people guessed the direction based on the side of the body. For example, Participant 2 said: "It was very clear because I just felt on one side." However, some mentioned their concern in distinguishing that from a typical notification. For example, Participant 3 said: "I don't think it's a good way to show the direction. It really can be a notification. Maybe you can use a special signal that is not used on other apps."
- 4 out of 12 participants chose direction based on a sliding sensation to the left/right.

They found the feature useful in bad weather such as cold winters, riding a bicycle or driving, doing activities such as running, and for disabled people.

Most of them could understand the Symbolic effect. However, they preferred the other two types of effects and found them easier to understand and follow. Participant 3 said, "This one (Symbolic) maybe you can learn, but if you don't learn, you can't understand." Participant 5 said, "I like the first strategy (Implicit), especially when you have high tension activities like riding a bicycle." Participant 9 said, "It's hard (Symbolic). The numbers were different, and I could distinguish. I prefer the first method (Implicit) because I like it. I don't like the tapping thing. sliding feels better." Participant 10 said, "Because they are both on your left hand, it might take a long time to figure out okay, it's this pattern, and sometimes you might say was it fast or slow, so you don't want to go back and check (Symbolic)." Participant 11 said, "I am not sure. Because if I am using an online map, it means that I have a surface. Although I think it's very good for people who have disabilities. I prefer sound rather than vibration. I can't trust the vibrations because they were confusing." Participant 12 said, "I need to focus on guessing (Symbolic) maybe I am busy doing other things maybe I am running." Participant 13 said, "The thing is that if I need to think and analyze (Symbolic), I don't need a new challenge on my daily basis.Technology supposed to simplify my life."

3.1.6 Discussion

We conclude that participants made fewer mistakes for Implicit 1, Implicit 2, Explicit 2, Explicit 5, and Explicit 6. This means that among Explicit effects the repetition pattern or a longer vibration on the side that indicates the direction is helpful (Explicit 6 and Explicit 5). Frequency ramp-up was also beneficial in showing the direction (Explicit 2). We also found that, effect type had a significant impact on the Clarity, and participants gave higher ratings to both the Implicit effects.

We hypothesized that by exposure to more effects, participants would start to learn a strategy, and the number of errors would decrease. However, we did not find any consistent learning effect. We aslo could not find any significant impact of effect type on the Reaction Time.

In conclusion, Implicit effects and some Explicit effects work well and are rated well. The error count, however, is somewhat high for all effects, which indicates that even Explicit effects are not obvious without training. The qualitative results supports this by showing different strategies and interpretations. Therefore, we learned from this experiment that instructions are necessary and that some effects work better than others.

3.2 Experiment 2

The main goal of Experiment 2 was to see the impact of training. We separated the experiment into several iterations, each testing one of the 9 effects. These 9 effects are what we used in Experiment 1 and one Symbolic. At the beginning of each iteration, we trained participants by describing the strategy of each effect and playing it once (see Section 3.2.2 for more details).

We also could add the Symbolic effect to compare with our existing directional effects in this experiment because the Symbolic effect needs memorizing the pattern and training. We hypothesized that Explicit and Implicit effects would work better and participants will make lower mistakes in these two groups than the Symbolic.

During the experiment, two questions were asked on the tablet from participants. The questions were exactly like Experiment 1. Question 1 was asked after each effect and Question 2 was asked after each iteration. As the last step, the facilitator collected qualitative data about the directional effects in an interview (see Appendix 1 for details).

3.2.1 Participants

8 participants were recruited (4 males). The demographic information collected with a survey can be summarized as follows:

- None of the participants had any health issues that caused impairments to their sense of touch.
- Most participants (75%) were in the age group of 25-34.(Figure 3.7a).
- Most participants (62.5%) preferred to wear a watch on their left wrist.
- 25% of the participants reported that they never used a normal watch, 37.6% used one occasionally, 12.5% used one many times per month, and 25% used one many times per week (Figure 3.7b).
- Almost half (54%) of the participants reported that they never used a smartwatch or an activity tracker. (Figure 3.7c).

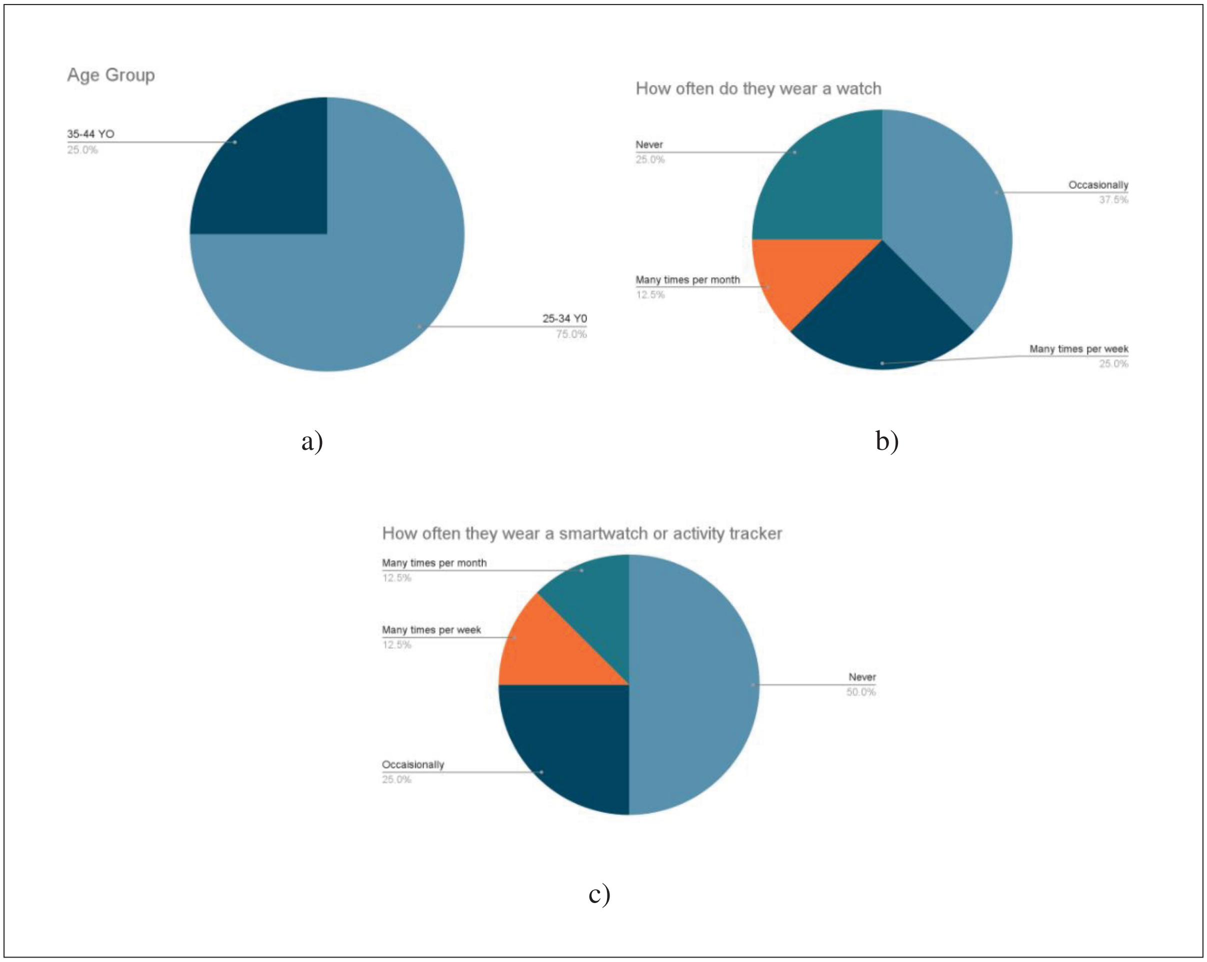

Figure 3.7 Demographic data in Experiment 2: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker

3.2.2 Experimental Procedure

The experiment room and the procedure to fix the actuators and start the experiment was the same as in Experiment 1. The facilitator used the same guide for all participants (see Appendix 2). However, in order to provide training for each effect, the experiment was separated into 9 iterations. In each iteration, instructions were provided for one effect and the effect was then tested. The following instructions were provided:

Symbolic effect: “You will feel vibrations only on your wrist. The difference between left and right is based on their patterns.”

Implicit effects: “This group is based on the body side to find out the direction. If the signal is felt on the right side of the body, it shows turning to the right, and if it is on the left side, it shows to turn left.”

Explicit effects: “This group has vibration on both sides of the body but they are connected together. The vibration starts from one side and moves to the other side of the body. The direction of this movement indicates in which direction you should go.”

The experiment consisted of 6 Explicit effects, 2 Implicit effects, and the Symbolic effect. Each effect was played in two directions (left/right). Each direction was repeated 6 times. In total 108 directional effects were played for each participant.
The order of the 9 iterations was counterbalanced. For each iteration, the order of the 12 directional effects was randomized to avoid biases.

During the experiment, after each directional effect, Question 1, (“What direction did you feel?”), was appeared on the tablet. However, Question 2, (“How clearly did the vibration show the direction?”), was appeared once after each iteration as all the directional effects in an iteration was referred to one effect.

As the last step, the facilitator asked 2 questions in the form of a semi-structured interview. The first question was also used in Experiment 1, while the second was new.

Question 5: "Imagine yourself receiving notifications as well on your watch or smartphone. Would they be confusing for you to distinguish from notifications?"

Question 8: "By receiving all of the effects, which one do you think is more clear and useful in your life?"

3.2.3 Experiment Design

The independent variable is the effect with 9 possible values: Explicit 1-6, Implicit 1-2 and the Symbolic effect (see Section 2.1 for more detail). The dependent variables are the Error Count, Reaction Time and Clarity, as described in Section 3.1.3. Training users before each effect is a moderating variable because it can affect our dependent variables. We chose a within-subject design for this experiment.

3.2.4 Quantitative Results

The quantitative results were analysed based on Error Counts, Claritys and Reaction Time.

3.2.4.1 Error Count

The error decreased to 3.7% from 27.25% in Experiment 1. The errors were limited to only three effects: Symbolic, Explicit 1, and Explicit 3.

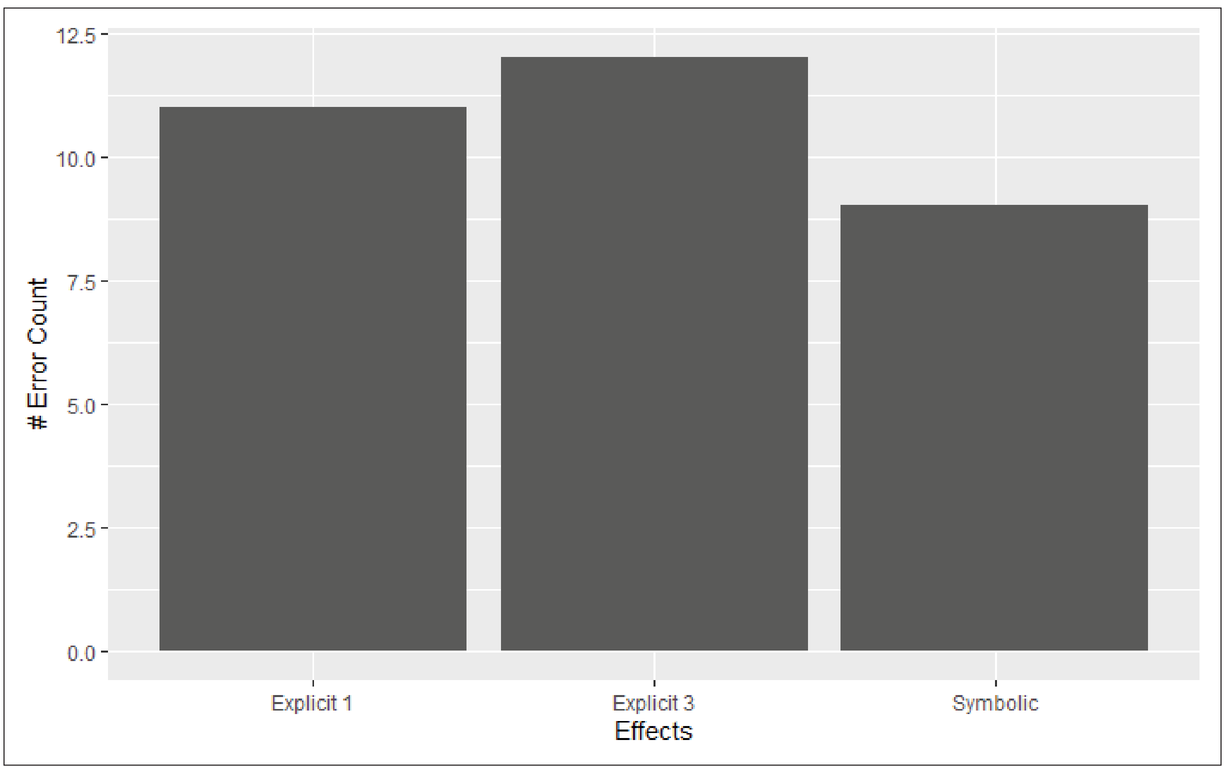

Figure 3.8 The Error Count of each effect

The bar chart in Figure 3.8 shows the number of the errors based on each effect (In total each effect played 96 times). As it is shown, All errors are from Symbolic (9 out of 96), Explicit 1 (11 out of 96), and Explicit 3 (12 out of 96). A one-way repeated measures ANOVA was conducted to analyze the impact of effect type on the Error Count. There was a significant impact of effect type on the Error Count ($F = 9.636$, $p = 7.69e - 13$). We ran a post-hoc analysis using Bonferroni. The Symbolic, Explicit 1 and Explicit 3 are not significantly different. However there are significant differences between these 3 effects and the rest of the effects. In Experiment 1, the highest error was from Explicit 1 (two simple buzzes) and Explicit 3 (amplitude ramp-up).

3.2.4.2 Clarity

After completing the iteration for each effect, the participants were asked how clearly it showed the direction. Participants answered on a Likert scale from very confusing to very clear. In our analysis, we converted the data into numbers. So in the chart, very confusing mapped to 1, confusing mapped to 2, neutral to 3, clear to 4, and very clear to 5.

As shown in Figure 3.9, the Symbolic effect was by far the most confusing type of effect. A one-way repeated measures ANOVA was conducted and the results show a significant impact of the effect type on the Clarity ($F = 6.192$, $p = 1.1e - 05$). We ran a post-hoc analysis using Bonferroni. The results showed there are significant differences between all effects and the Symbolic effect. You can find the p-values on Figure 3.9

3.2.4.3 Reaction Time

As in Experiment 1, we calculated the time participants needed to think after they felt an effect and pushed the button to answer Question 1.

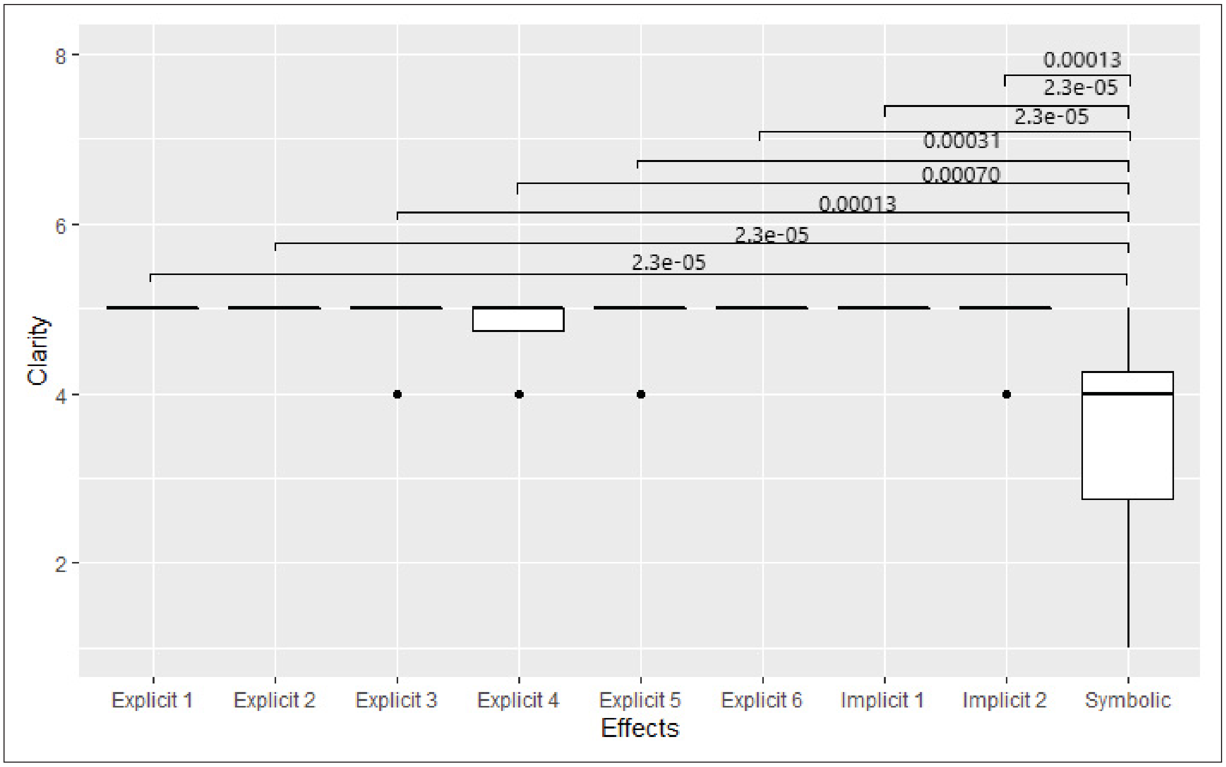

Figure 3.9 Clarity of each effect based on participant's opinion. The lines on top of the box plot show the significant differences and the numbers on them show the p-values

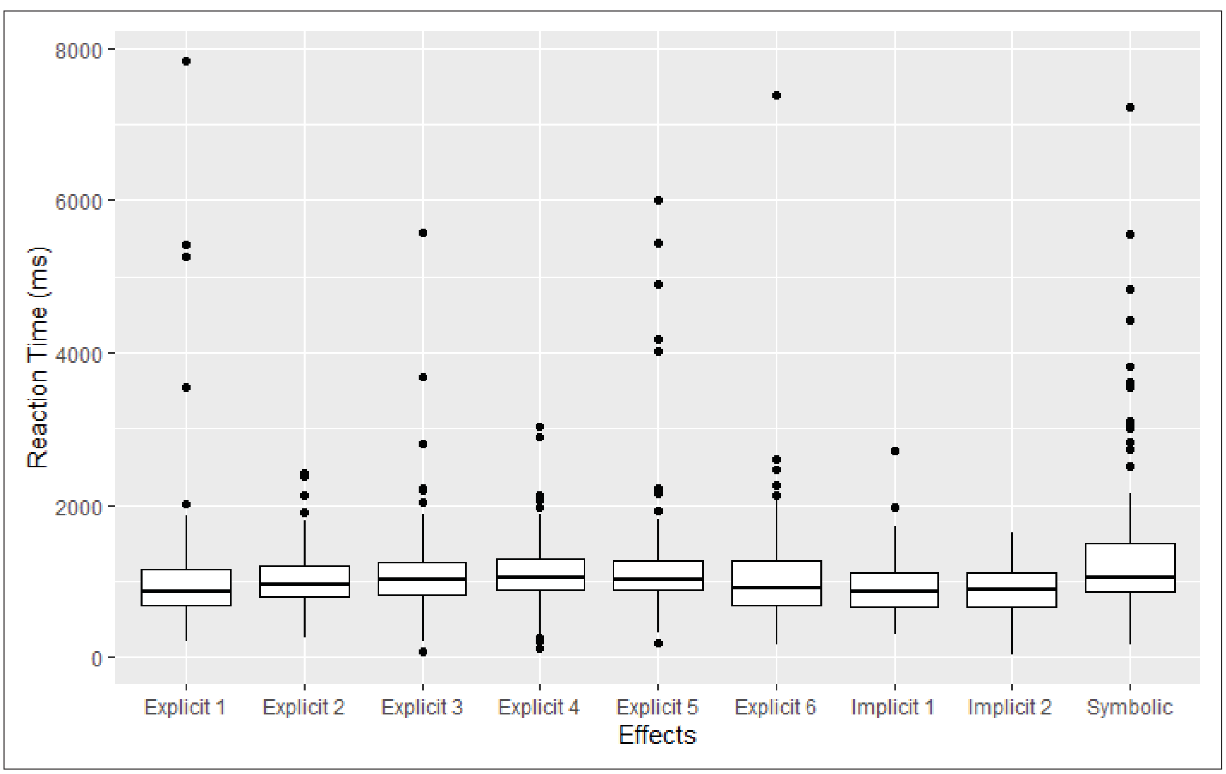

Figure 3.10 Reaction Time of each effect

We decided not to remove the outliers. A one-way repeated measures ANOVA was conducted and no significant impact of effect type on the Reaction Time was found ($F = 1.304$, $p = 0.238$).

3.2.5 Qualitative Results

6 out of 8 participants preferred the Implicit effects because they found them easier and faster to respond. Participant 3 said: “Implicit effect is easier because you don’t need to focus, however for two other effects, when you are walking, you need your concentration so they are not useful.”

To avoid confusion between directional effects and notifications, they preferred to use the Explicit effects or the Symbolic effect. If it is Implicit they said that if the pattern is different from notification it can be helpful. Participant 2 said: “Regarding the notification, having a specific pattern that is different from a typical notification would be helpful.” Participant 1 said: “Yes, that’s the point in this case. The Implicit effect is not helpful and I can make mistakes. At that point starting on one side and going to the other side but the ending is longer is better.”

2 out of 8 participants preferred the Explicit effects. Participant 4 said: “I have no logic, it just takes me to the left or right.” Participant 5 said: “It gives you an image. It’s your mind; it’s like an arrow goes to the left or right.”

3.2.6 Discussion

After training, the errors were limited to only 3 effects: Symbolic, Explicit 1, and Explicit 3. First, this means that showing directions based on patterns and rhythms is not the best solution (Symbolic). Second, the amplitude factor does not work well to show the direction with Explicit effects (Explicit 3). Lastly, a sequence of two simple notifications does not show the direction well (Explicit 1).

We found a significant impact of effect type on the Clarity. Participants found the Symbolic effect to be the most confusing effect. We could not find any significant impact of effect type on the Reaction Time.

In conclusion, we could say that this experiment confirmed that our solutions are better than the Symbolic effect, which was assumed in Experiment 1. Explicit 1 and Explicit 3, which had the highest error in Experiment 1, still performed poorly with training. However, it is still unclear if Implicit or Explicit works better. Implicit works well and is also liked by participants. Explicit is almost as good. However, the comments in interview hint at issues with notification. Participants believed that they might not be able to make differences between the Implicit effects and notification. This might make the Explicit work better than the Implicit. Hence the next experiment was designed to add notification and make the situation closer to the real world by adding other variables as well.

3.3 Experiment 3

The main goal of Experiment 3 was to add variables to make the situation closer to the real world. To simplify the experiment, we decreased the iterations from 9 effects (in Experiment 2) to the 3 most efficient effects based on the results of the previous experiments (Implicit 2, Explicit 2 and Symbolic).

In this experiment, we were interested in analyzing the user's behavior in making a difference between the directional effect and occasional notifications that they might receive on their mobile phone or smart watch such as a notification from a text message in the real life. We asked a question in the end of each iteration regarding the notification: "How clear was the difference between the notification and directional signals?". We hypothesized that, participants would get confused with notification in Implicit effects and Explicit will show better the difference between a notification and directional effects.

We also added a game (Section 2.3.2) as a distraction because people often use navigation applications while doing other activities, such as running or talking. They will not focus entirely on guessing the direction.

The last variable was to see if changing the mobile phone's location could make any difference in the results. In previous experiments, we always kept the mobile phone in the right pocket and the smartwatch on the left wrist (Bilateral condition). We separated Experiment 3 into two main parts (Unilateral and the Bilateral conditions, see Section 2.1). In the Unilateral condition, we changed the mobile phone's location from the right to the left pocket. The reason was that our directional effect designs were based on the side of the body. We hypothesize that having both devices on one side of the body would make guessing the direction more confusing.

We also had training before each iteration like Experiment 2. Refer to Section 3.3.2 for the instructions.

As the last step, the facilitator asked some questions as an interview (see Appendix 3 for details).

3.3.1 Participants

8 participants (4 males) were recruited.The demographic information collected with a survey can be summarized as follows:

- None of the participants had any health issues related to their sense of touch.
- Most participants (75%) were in the age group of 25-34 (Figure 3.11a).
- Most participants (75%) preferred to wear a watch on their left wrist.
- Half of the participants reported using a normal watch almost every day. (Figure 3.11b).
- 62.5% of the participants reported that they never used a smartwatch or an activity tracker. (Figure 3.11c).

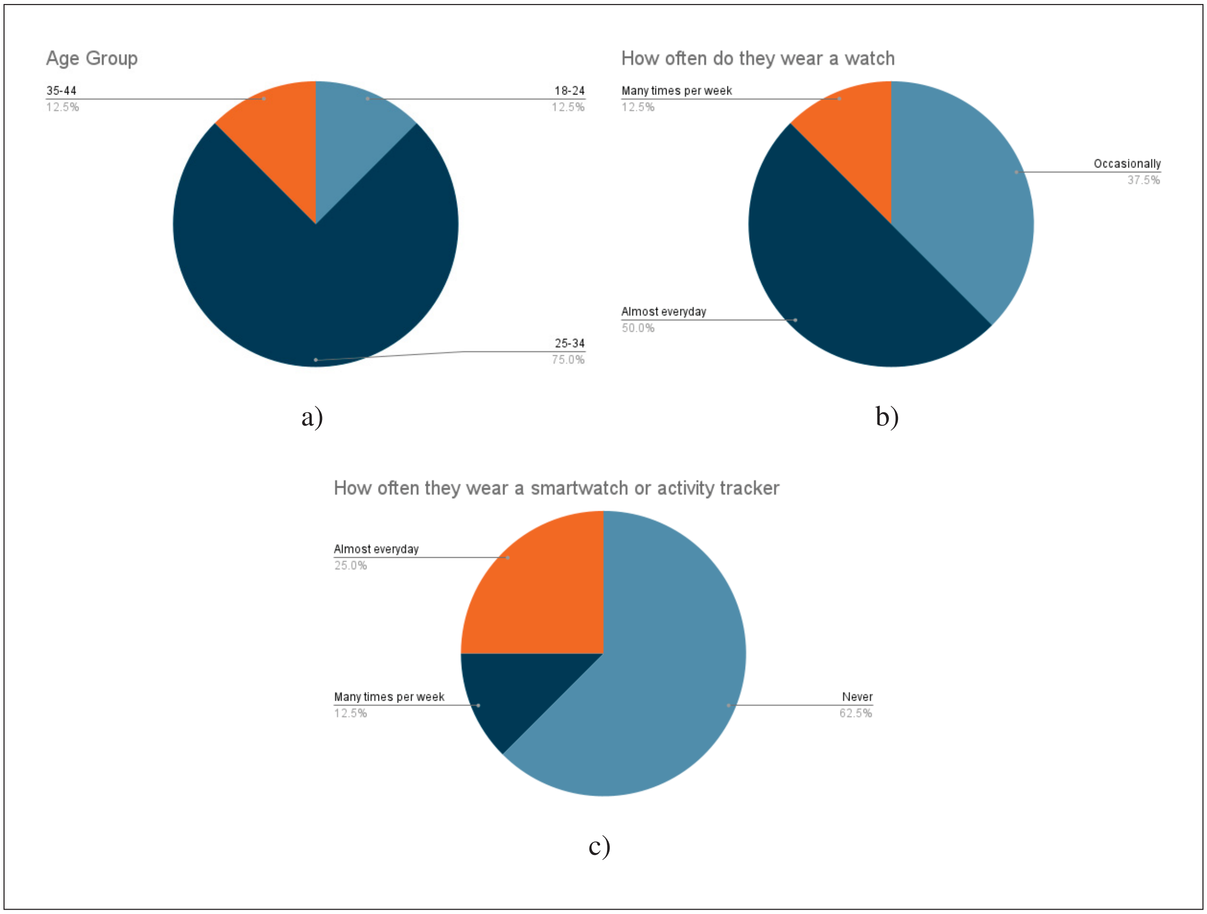

Figure 3.11 Demographic data in Experiment 3: (a) age groups, and frequency of use of (b) a normal watch or (c) a smartwatch or activity tracker

3.3.2 Experimental Procedure

The experiment conducted in the same room as the Experiment 1 and Experiment 2. The same guide was followed for this experiment (see Appendix 3). The experiment was separated into two main conditions: Bilateral and Unilateral (see Section 2.1). Each participant was exposed to both conditions, but the order was counterbalanced so that half of the participants started with the Unilateral condition and the other half with Bilateral condition. In each condition, we ran all 3 effects (Explicit 2, Implicit 2, and Symbolic) in counterbalanced order. Each effect had 2 directions (left/right). As discussed before (refer to Section 2.1.4), a notification effect was also added.

In total, the experiment had 6 iterations. In each iteration there were left and right directions of one effect as well as a notification effect. Each of them were repeated 4 times. In total, each participant was exposed to 72 notification effects and directional effects.

Participants received the effects while playing the game. After each, a question appeared on the tablet:

"What did you feel?" The answer was "Left", "Right" or "Notification".

At the end of each iteration two questions were asked:

“How clearly did the vibration show the direction?”

"How clear was the difference between the notifications and directional signals?"

Before each iteration, the facilitator gave the following instructions, supported by illustrations for the Explicit and Implicit effects. The Symbolic effect did not need any illustration. (Figure 2.10, Figure 2.11, Figure 2.7 and Figure 2.6):

Symbolic effect: "This group is based on different patterns for left/right and notification, and it will only play on your smartwatch."

Implicit effect: "This group is based on the relative position of the devices. Since the watch is on the left side of the phone, its vibration will show you going to the left, and the phone’s vibration will show you going to the right. You will receive a specific vibration only on your wrist for notification."

Explicit effect: "This group has vibration on both sides of your body, but they are connected together. You should feel like something is jumping from one side to the other side of your body to show you the direction. You will receive a specific vibration only on your wrist for notification."

As the last step, the facilitator asked 3 questions in the form of a semi-structured interview. The first question was also used in Experiment 2.

"By receiving all of the effects, which one do you think is more clear and useful in your life?"

"Did you see any differences for understanding the directional signals while both devices were on two sides of your body versus on one side?"
"Could you explain your strategy for choosing the directions on the groups you were receiving vibrations on both motors?"

3.3.3 Experiment Design

One independent variable is the effect with 4 possible values: Implicit 2, Explicit 2, Symbolic and notification. The second independent variable is the place of the devices (Unilateral/Bilateral).

The dependent variables are the Error Count, Reaction Time, and the Clarity. One more dependent variable was added to this experiment:
Notification Clarity: The participant's answer to the Likert scale question ("How clear was the difference between the notifications and directional signals?").

Training users before each effect and a game as a distraction (Section 2.3.2) are moderating variable because they can affect our dependent variables.

We chose a within-subject design for this experiment.

3.3.4 Quantitative Results

The quantitative results were analysed based on Error Counts, Claritys and Reaction Time.

3.3.4.1 Error Count

We would like to look at the Error Count from 3 points of view:
Total Error Count: The number of directional or notification effects incorrectly answered by the participant.
Notification Error Count: The number of notification effects incorrectly answered by the participant.

Directional Error Count: The number of directional effects incorrectly answered by the participant.

Refer to Figure 3.12 for (a) Total Error Count, (b) Directional Error Count and (c) Notification Error Count.

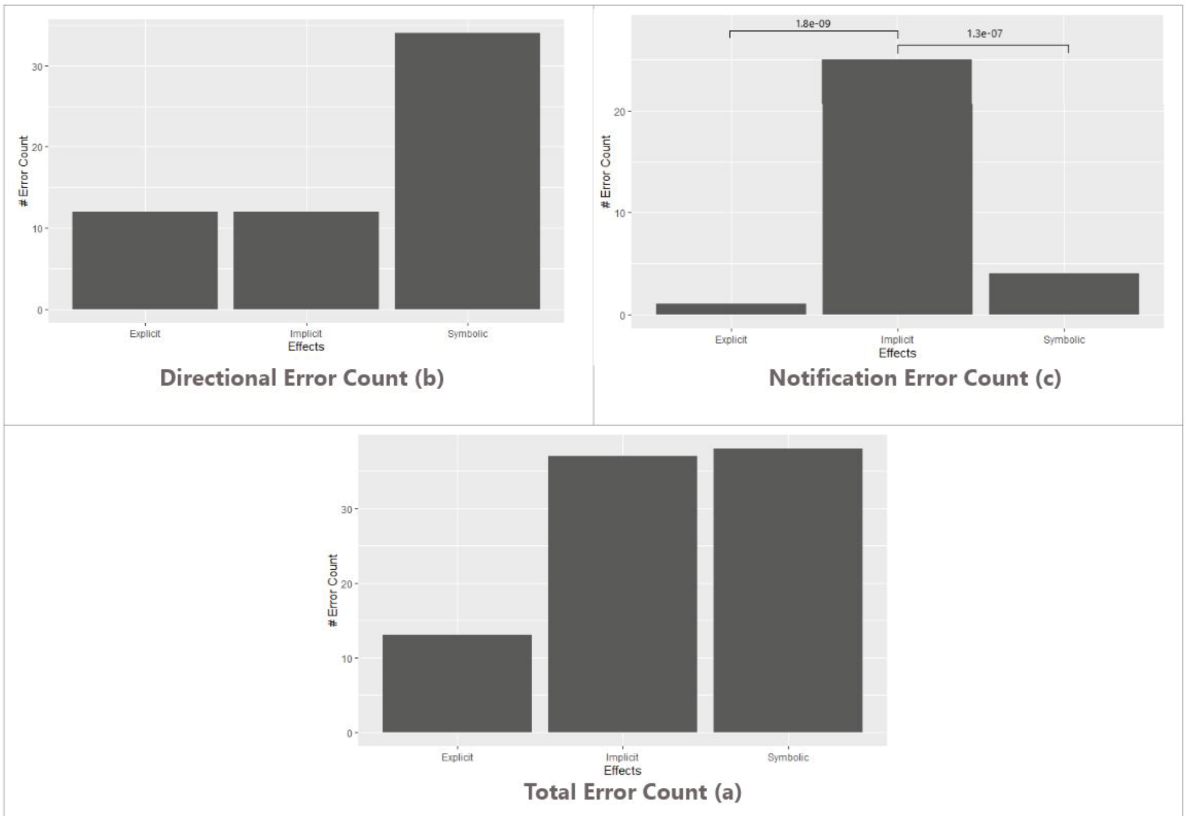

Figure 3.12 The bar chart for (a) Total Error Count, (b) Directional Error Count and (c) Notification Error Count

In total 88 out of 576 (15.2%) effects indicated as errors in this experiment. This amount decreased compared to Experiment 1 which was 314 out of 1152 (27.2%) and increased compared to Experiment 2 which was 32 out of 864 (3.7%). As it is shown in Figure 3.12 (a) only 13 out of 88 errors (15%) come from the Explicit effect, and the rest equally come from the Symbolic or Implicit effects. As shown in Figure 3.12 (c) and Figure 3.12 (b), participants had trouble distinguishing the notification and Implicit directional effect, and understanding the directions indicated by the Symbolic effect.

Firgure 3.13 shows the Total Error Count in both the Unilateral and Bilateral conditions.

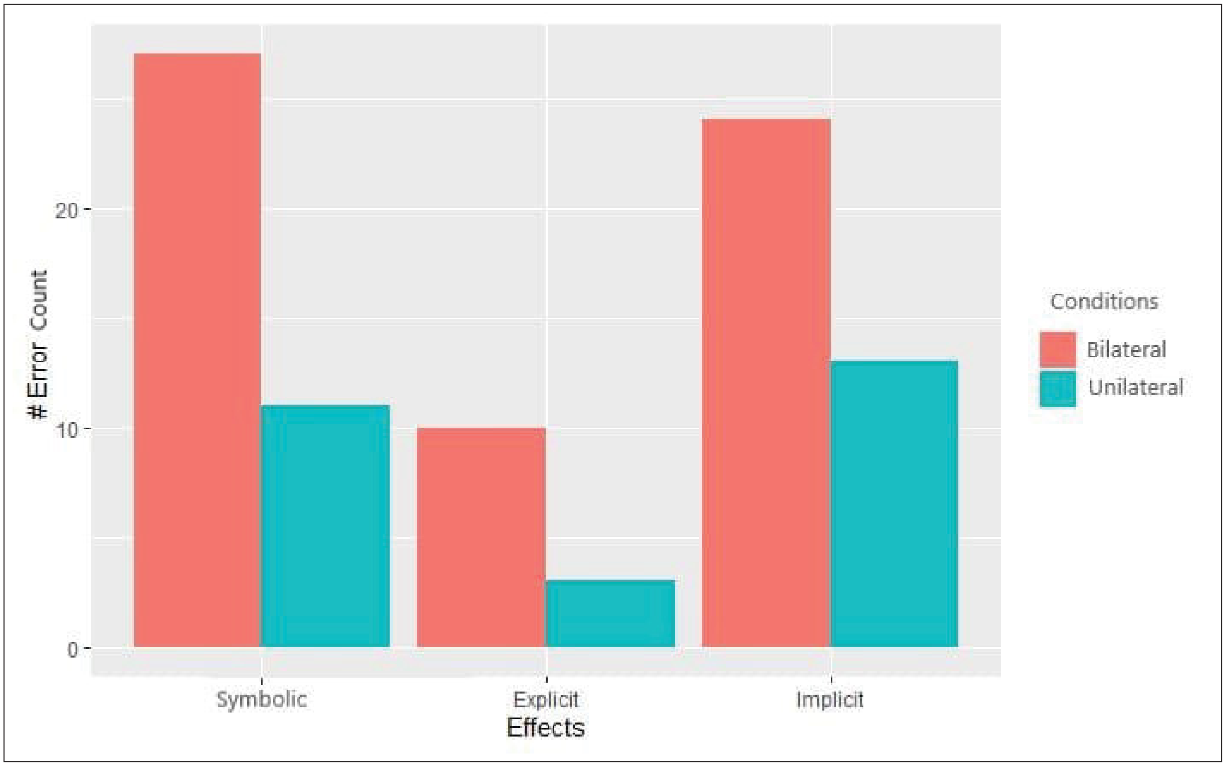

Figure 3.13 The bar chart of total errors based on 3 different effects and their Conditions (Unilateral and Bilateral)

A two-way repeated measures ANOVA was conducted to see the impact of effect type and device location (Unilateral/Bilateral) on the Error Count. The results show that there is a significant impact of device location ($F = 17$, $p = 0.00444$) in Total Error Count and Directional Error Count ($F = 18.05$, $p = 0.0038$). However, we could not find any impact of the effect type neither the interaction of the effect type and device placement (Unilateral, Bilateral) on the Total Error Count and Directional Error Count.

For Notification Error Count, we found a significant impact of effect type on the Error Count ($F = 11.55$, $p = 0.00109$) but not the device location (Unilateral/Bilateral). A post hoc analysis using Bonferroni showed that Implicit is significantly different than Explicit and Symbolic. Explicit and Symbolic are not significantly different. It shows that people made mistakes in distinguishing the notification with Implicit Effect. Refer to Figure 3.12 (c).

3.3.4.2 Clarity

After each effect (Symbolic, Explicit , and Implicit), 2 questions were asked:

- How clearly did the vibrations show the direction?
- How clear was the difference between the notification and directional signals?
  The answers are in a Likert scale of “Very confusing, Confusing, Neutral, Clear, Very Clear”

Figure 3.14 shows the clarity of each effect in showing the direction.

We could not find any significant impact of device location (Unilateral/Bilateral) on the clarify of the direction and neither the effect type.

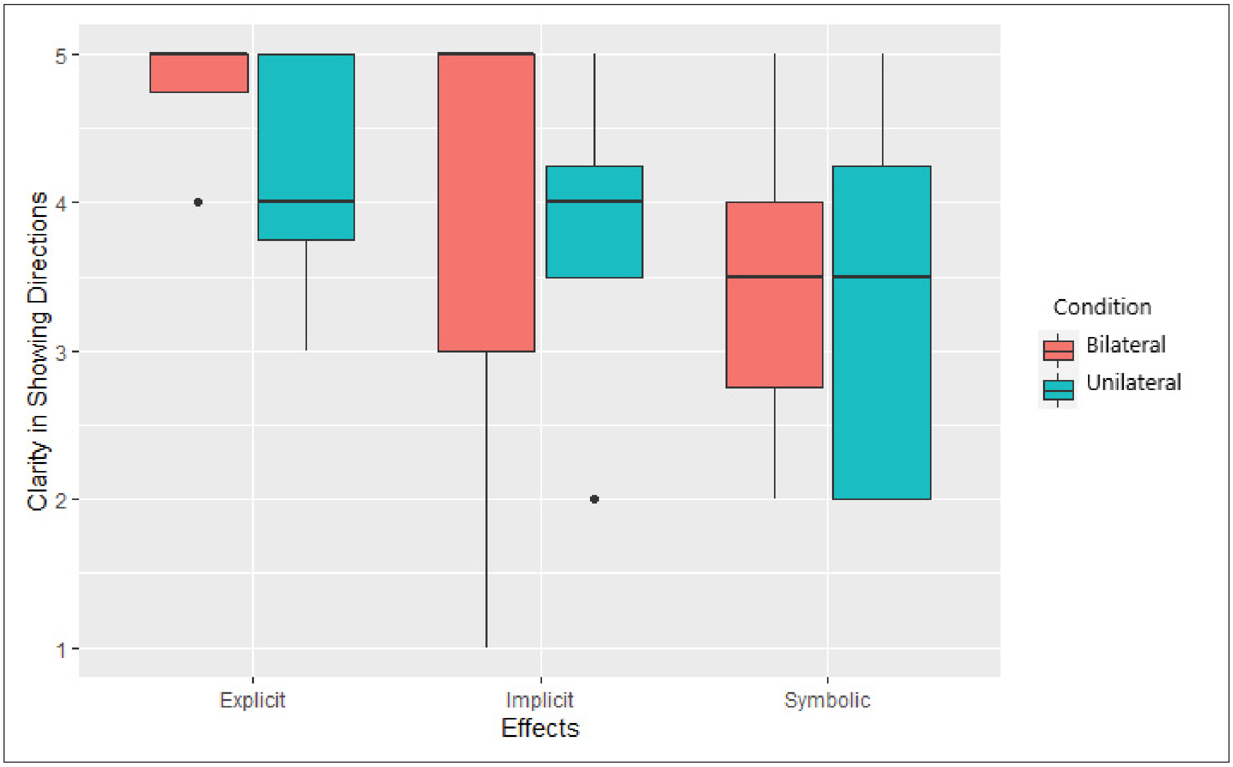

Figure 3.14 Clarity of each effect with two Conditions (Unilateral/Bilateral) in showing directions

Figure 3.15 shows the Clarity of each effect in distinguishing with notification. A two-way repeated measures ANOVA was conducted to see the impact of Condition (Unilateral/Bilateral) and effect type on clarity of notifications. There is a significant impact of the effect on the Clarity ($F = 4.512, p = 0.0307$), but no impact of the Condition (Unilateral/Bilateral) ($F = 0.119, p = 0.741$). A post hoc analysis using Bonferroni showed that the differences between Explicit and Symbolic as well as Explicit and Implicit are significant. People rated higher to Explicit effects in distinguishing better the notification.

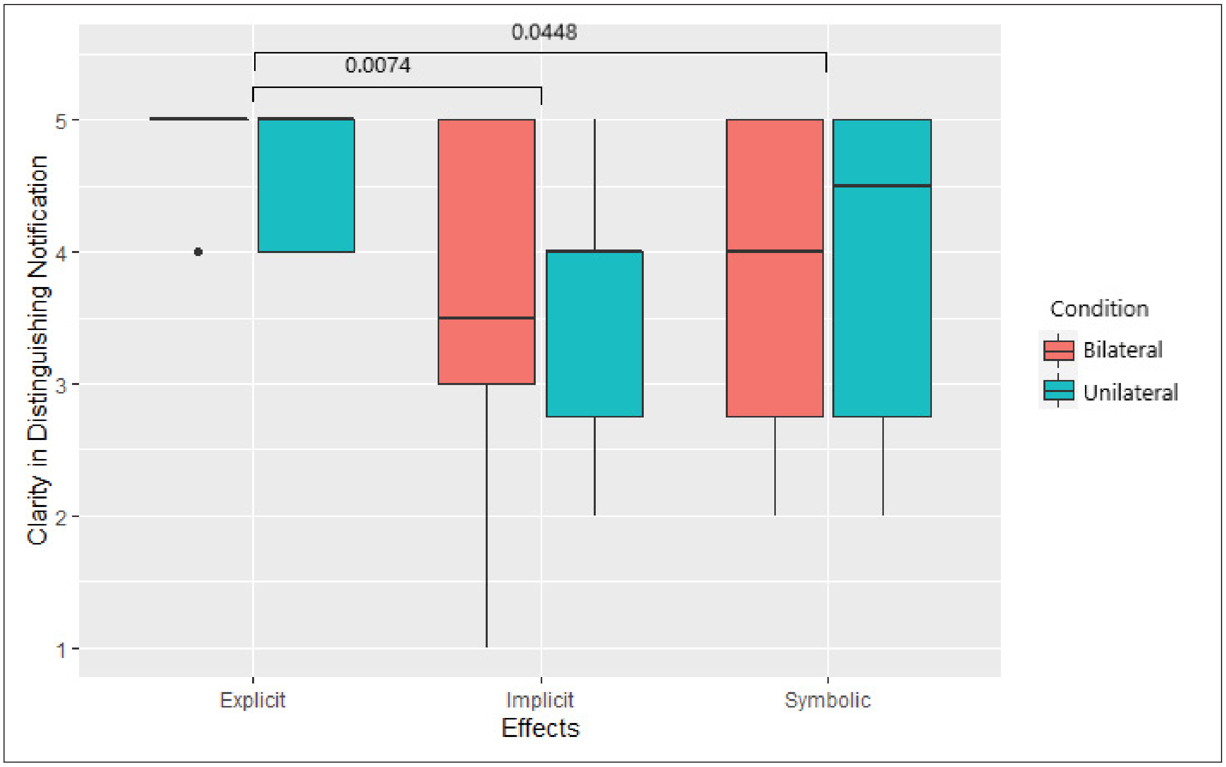

Figure 3.15 Clarity of each effect with two Conditions (Unilateral/Bilateral) in distinguishing with notification. The lines on top of the box plot show the significant differences between effects and the numbers show the p-values

3.3.4.3 Reaction Time

Figure 3.16 shows the reaction time of each effect. We decided not to remove the outliers. A two-way repeated measures ANOVA shows no impact of the effect type ($F = 1.165$, $p = 0.130$) and the Condition (Unilateral/Bilateral) ($F = 1.568$, $p = 0.251$) on Reaction Time.

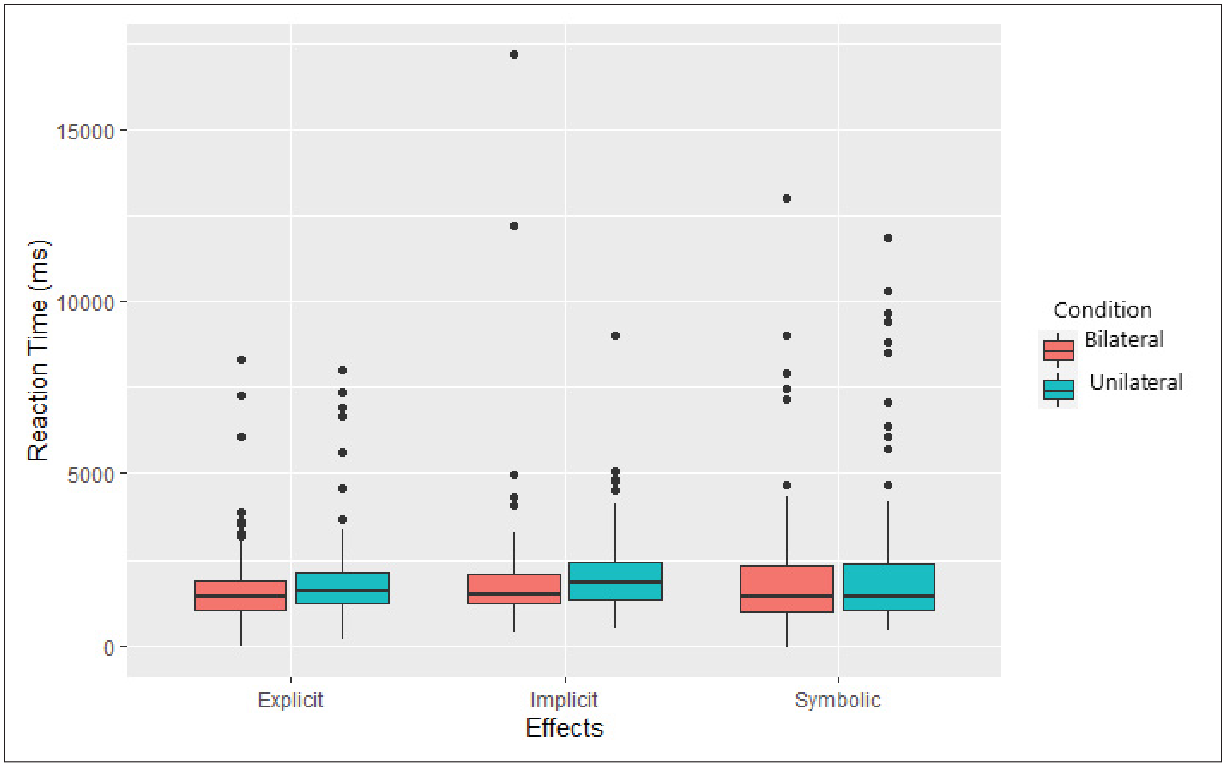

Figure 3.16 Reaction Time of each effect with two Conditions (Unilateral/Bilateral)

3.3.5 Qualitative Results

There was no consensus about the preferred effect or device location. 3 out of 8 participants preferred the Bilateral Implicit effect, 2 preferred the Unilateral Explicit effect, 2 preferred the Bilateral Explicit effect, and 1 preferred the Symbolic effect.

5 out of 8 participants had no specific strategy for choosing the direction with Explicit effect. They reported feeling a jumping vibration or an arrow shape on their body. The rest chose the direction based on the side of the body where the sequence of vibration started or ended.

3.3.6 Discussion

In this experiment, we understood that the Error Count increased by adding distraction compared to Experiment 2. However, the errors are still less than Experiment 1 that we did not have any instructions.

We hypothesized that the Explicit effect is better in the presence of notification than implicit. The results confirmed this statement, and we could find a significant difference in distinguishing the notifications and directional effects between the Explicit and Implicit effects. Participants made more mistakes in Implicit effects to understand the notifications. They also rated significantly higher to Explicit effects in distinguishing better the notifications.

We also hypothesized that having both devices on one side of the body (Unilateral) can confuse participants guessing the directions. The results rejected this statement and we could not find any significant difference between Bilateral and Unilateral conditions.

In the end, we could say that in the real world conditions with the presence of occasional notifications, the Explicit effect works better than the Implicit, and participants liked it better. Changing the place of the devices to one side of the body did not have any significant impact in guessing the directions.

CONCLUSION AND RECOMMENDATIONS

We proposed two strategies to design the directional patterns. The first one is called Implicit. In this strategy, only one device vibrates at a time. Users can guess the direction based on which side is vibrating (relative to the center of the body or to the other device). The second strategy is called Explicit. In this strategy, a sequence of vibrations can make users feel like something is jumping from one device to the other, and this movement indicates the direction. We changed different factors such as frequency, amplitude, and timing to create this feeling.

We ran 3 experiments. In the first experiment, the goal was to see which directional patterns are faster and clearer to understand without any training. We learned that Implicit patterns were easy to understand, and that changing their factors did not alter the results. However, in Explicit patterns, the frequency factor was influential and helped show the directions more clearly. We also could not prove that exposure to more directional patterns can decrease the errors for all participants. Some participants started to learn and made fewer mistakes during the experiment, but some did not. We decided to train the participants for the next experiment.

In the second experiment, we trained participants before each directional pattern. The training decreased the errors significantly. We also could add another haptic pattern, called Symbolic, inspired by a commercial smartwatch directional vibrations. This pattern was based on different rhythms for each direction. It was only on the smartwatch and required training and memorization. The results showed that participants made fewer mistakes in our suggested haptic pattern designs, and they rated them higher in terms of clarity than the symbolic pattern. We decided to add new variables to the next experiment to make the situation closer to reality. We also limited the experiment to one of the best patterns from the Explicit strategy and one from the Implicit strategy.

In the last experiment, we understood that Implicit patterns make participants confuse directional patterns and notification from other applications. The pattern inspired by a commercial smartwatch could not show the direction as clearly as our suggested directional patterns. We conclude that Explicit patterns are showing the direction more clearly in real-life conditions. Also, we changed the mobile phone's location to have both devices on one side of the body, but it did not have a significant impact on the results.

In the end, we could say that the Explicit patterns are easier to understand, in the real world, and that participants can distinguish them from other notifications. Having both devices in one side of the body for the Explicit patterns does not significantly impact the results.

Future work could be done in a more realistic environment to investigate the impact of movement, such as walking and running. Also, it could use an actual mobile phone and a smartwatch to have more realistic vibrations, with all the limitations of these devices.

APPENDIX I

DEMOGRAPHIC SURVEY FOR ALL 3 EXPERIMENTS:

- What is your gender?

  Female

  Male

  Non-binary
- Which wrist do you prefer to wear a watch on?

  Left

  Right
- Do you have any health issues which led to impairments to your sense of touch?

  Yes

  No
- How old are you :

  Under 18

  18 - 24

  25 - 34

  35 - 44

  45 - 54

  55 or older
- Have you ever used any online maps on your phone or smartwatch? If yes please indicate the ones you frequently use.
- How often do you wear a watch?

  Never

  Occasionally

  many times per month

  many times per week

  Almost everyday

- How often do you wear a smartwatch or activity tracker?

  Never

  Occasionally

  many times per month

  many times per week

  Almost everyday

APPENDIX II

FACILITATOR'S GUIDE

1. Experiment 1

Hello, my name is Paria. Thanks for agreeing to participate in our study. The aim of the study is to better understand how users can be given walking directions with only the sense of touch and without looking at a mobile or smartwatch screen. Please read and sign the consent form before starting the experiment.

For the first step I will ask you to complete a survey.

In the first part of the study, you will imagine that you have a mobile phone in your pocket and a smartwatch on your wrist. The phone and the smartwatch will work together to guide you towards a destination as you are walking. You will feel a number of vibrations from the phone, from the smartwatch, or from both. You will then be asked whether these vibrations are telling you to turn left or right, and how clear this directional signal is.

In the second part of the study, I will play some pairs of vibrations and you will be asked to answer some questions regarding them. This session will also be audio recorded so that we can review our discussions. Your responses will remain anonymous. Remember that this is an evaluation of the vibrations and not of your individual performance. Do you have any questions at this point?

During the experiment if you had any concerns or questions just raise your hand and wait. I will be there in a few minutes.

2. Experiment 2

Hello, my name is Paria. Thanks for agreeing to participate in our study. The aim of the study is to better understand how users can be given walking directions with only the sense of touch and without looking at a mobile or smartwatch screen. Please read and sign the consent form before starting the experiment.

For the first step I will ask you to complete a survey.

You will imagine that you have a mobile phone in your pocket and a smartwatch on your wrist. The mobile phone and the smartwatch are connected together and working together to guide you towards a destination as you are walking. The test consists of 9 groups of vibrations and in each group there is one strategy to follow and find the direction whether the signal is showing to turn left or right. Before each group I will train you how it works. After each group finished you will be asked how clearly did the vibrations show the direction? You will be asked to rank in a Likert scale from very confusing to very clear.

This session will also be audio recorded so that we can review our discussions. Your responses will remain anonymous.

Remember that this is an evaluation of the vibrations and not of your individual performance.

Do you have any questions at this point?

During the experiment if you had any concerns or questions just raise your hand and wait. I will be there in a few minutes.

Let's begin the test:

Symbolic: It is based on different patterns only on the smartwatch. I will play left and right for you and then the same vibrations will be played during the test and you have to answer which direction it showed. And in the end you will be asked how clear/useful this signal would be for you in real life.

Implicit: This group is based on your body side to find out the direction. If the signal is felt on your right side of the body it shows you turning to right and if it is on your left side it shows you to turn left. I will play you left and right now.

Explicit: This group has vibration on both sides of your body but they are connected together. The vibration starts from one side and moves to the other side of your body. The direction of this movement indicates in which direction you should go.

3. Experiment 3

Hello, my name is Paria. Thanks for agreeing to participate in our study. The aim of the study is to better understand how users can be given walking directions with only the sense of touch and without looking at a mobile or smartwatch screen. Please read and sign the consent form before starting the experiment.

For the first step I will ask you to complete a survey.

Imagine that you have a mobile phone in your pocket and a smartwatch on your wrist. The mobile phone and the smartwatch are connected together and working together to guide you towards a destination as you are walking. During the test besides the directional signals you will also receive notifications from other applications as well (this notification might be from a text message, Whatsapp message or sth similar). You need to make a distinction between the directional signals and other notifications.

The test consists of 6 groups of vibrations and in each group there is one strategy to follow and find whether the signal indicates a turn to the left or right. Before each group I will explain to you how it works.

There is a dinosaur game that you need to play and during the game you will receive the vibrations and after you need to answer the questions.The questions are : how clearly did the vibrations show the direction? And: how clear was the difference between the notification and directional signals?

This session will also be audio recorded so that we can review our discussions. Your responses will remain anonymous.

Remember that this is an evaluation of the vibrations and not of your individual performance.

Do you have any questions at this point?

During the experiment if you have any concerns or questions just raise your hand and wait. I will be there in a few minutes.

Before starting the test I would like to help you find a balanced vibration on the motors. It means you should receive vibration with almost the same power on your wrist and leg . I will play some vibrations and you should choose which one is the most blanched for you.

Symbolic: This group is based on different patterns and only on the smartwatch. I will play left and right for you and then the same vibrations will be played during the test and you have to answer which direction it showed.

Implicit: This group is based on the relative position of the devices. Since the watch is on the left side of the phone, its vibration will show you going to the left and the phone's vibration will show you going to the right.

Explicit: This group has vibration on both sides of your body but they are connected together. You should feel like something is jumping from one device to the other one to show you the direction.

APPENDIX III

INTERVIEW QUESTIONS

1. Experiment 1

8 pairs of effects (III-1) played for participants and the question below was asked them.

- What did you feel? Can you explain more how you guessed the direction? Which one was more clear for you showing the direction? why?

Explicit 1	Explicit 3	The effect of amplitude factor in Explicit patterns
Explicit 1	Explicit 2	The effect of frequency factor in Explicit patterns
Implicit 1	Explicit 1	The difference between Implicit and Explicit patterns
Implicit 1	Implicit 2	The effect of frequency factor in Implicit patterns
Explicit 6	Explicit 2	The effect of tapping design in Explicit pattern
Explicit 5	Explicit 6	The effect of timing factor in Explicit pattern (longer time)
Explicit 4	Explicit 2	The effect of timing factor in Explicit pattern (shorter time)
Implicit 2	Explicit 4	The difference between Implicit and Explicit patterns

Figure-A III-1 Pairs of effects that were played for each participant to compare in Experiment 1

- Imagine yourself to receive notification as well on your watch or smartphone. Would they be confusing for you to distinguish from notifications?

- In real life, have you ever been in a situation where you could not look at your phone to follow the map? When do you think it would be useful to have this feature in your daily life?

- " There are also other solutions to guide users by only the sense of touch. For Example some watches use two different effects only on smartwatches to show left and right. I will play them for you and then we will discuss more in detail." What do you think of this compared to our work? Which one do you think is more clear for you in real life?

2. Experiment 2

- By receiving all of the effects which one do you think is more clear and useful in your life?

- Imagine yourself to receive notification as well on your watch or smartphone. Would they be confusing for you to distinct from notifications?

3. Experiment 3

- By receiving all of the effects, which one do you think is more clear and useful in your life? why?

- Did you see any differences for understanding the directional signals while both devices were on two sides of your body versus on one side?

- Could you explain your strategy for choosing the directions on the groups you were receiving vibrations on both motors (Explicit)?

APPENDIX IV

SUMMARY OF QUALITATIVE DATA

1. Qualitative data of Experiment1

The summary of the qualitative data is listed below for each participant:

Participant 2:

He had different strategies facing different effects. He understood the Implicit category.

"It was very clear because I just felt on one side."

However, for Explicit effects, he was getting confused. He was relying on which side of the body he receives a longer or stronger vibration. For the Explicit 1 effect, because he was receiving the same vibration on both sides of the body, it was confusing for him to understand. In this situation, the strategy was based on what side of the body the effect starts, and he was ignoring the rest of the effect even if it was moving to the other side of the body.

He did not have any specific idea for notification because he never had vibration for notification on his phone.

He found the feature useful for riding a bicycle or motorcycle.

He could understand the Symbolic strategy. However, he preferred the Implicit effects.

"When you ride a bicycle, there is a motion and making a difference between two effects is hard, so I prefer on one side of my body."

Participant 3:

He did not like the Implicit effects. He said I might get confused and mix it with a typical notification from a text message.

"I don't think it's a good way to show the direction. It really can be a notification. Maybe you can use a special signal that is not used on other apps."

However, for Explicit effects, he had very good comments. He preferred the Short effect among all.

"The first one what I really like is that it is not powerful on the leg and gets powerful on the

wrist. In my brain, it's like drawing a line. For me, it really draws a line to the left."
For the Explicit 1 effect, because he was receiving the same vibration on both sides of the body, it was confusing for him, and he was choosing the direction based on which side of the body the effect ends.
For distinguishing the effects with notification, he preferred the Explicit effect.
He found the feature useful for walking, especially in winters, as well as driving.
"Pretty much every day. I can have my phone in hand, but it's very dangerous crossing the street, especially in winter Canada. I really want something that tells me where to go without looking at it, Maybe while driving, but I don't know if it's risky or not. Yes, in driving, you need your ears. It's kinda better if I have haptics."
He understood the Symbolic strategy, but his opinion on that was not positive.
"This one maybe you can learn, but if you don't learn, you can't understand."

Participant 4:

He understood the Implicit category of effects. However, when it was showing the right, and he was receiving it only on the leg, he was scared to miss that while walking, and in that situation, he preferred the Explicit effect.
For the Explicit effect, he had the same opinion as P1; he chose the direction based on the side of the body he was receiving the more powerful vibration. However, for Explicit 1, it was confusing for him as he received the same vibration on both sides of the body. " It starts on the leg and transfers to the wrist and gets stronger, that's why I choose left"
Regarding the notification, he did not have any specific ideas.
He understood the Strategy idea for directions. However, he did not like the patterns they used. " This one is more like alarm and stressful, but the one during the test (Implicit and Explicit) feels better."

Participant 5:

For the Implicit effect, He had the idea that he would not distinguish that from notification, so he did not like it.

" I don’t know which one is for notification and which one is for direction."
For the Explicit effect, he did not like the Explicit 1 like previous participants as he was receiving the same power of vibration on both sides of the body, but for the rest, he felt he could distinguish that from a notification.
He loved the idea to use it for driving, especially when he needed to concentrate on driving signs.
For Symbolic effect, he understood the strategy. However, he preferred the Explicit effect because he thought the Symbolic effect could be missed or mistaken while doing activities.
"I like the first strategy, especially when you have high tension activities like riding a bicycle."

Participant 6:

He had a very different strategy from previous participants. He was trying to feel a pattern that was like a slide. Sometimes he felt something was moving from right to the left of his wrist, so he chose the left direction and reverse.
He did not find the signals too different from a typical notification.
He found the feature useful for cold weather in Canada.
He did not understand the Symbolic strategy and tried to cope with that again, like the sliding strategy he had for Implicit and Explicit effects.

Participant 7:

He could understand the Implicit effect. However, for the Explicit effect, he was seeing that as two separated vibrations and choosing the direction based on which side of the body is stronger or longer or any different and specific signs, so for Explicit 1, he was so confused as he did not receive a stronger vibration on any sides of the body. And in the end, he preferred an Implicit effect.
He understood the Symbolic strategy. However, he was not positive about that.
"I prefer one side of my body. It’s better than distinguishing between patterns. Because in real life, you can’t focus only on the vibration you might talk, think, or something else, and you might miss the pattern."

Participant 8:

He was very confused about both the Implicit and Explicit effects. He was searching for feeling like sliding on his wrist or leg like Participant 6.

Regarding the notification, he thought if it was a different pattern, he might distinguish that from a typical notification.

He found this feature useful in bad weather, such as in rainy weather.

He understood the Symbolic strategy, but he did not like to be trained before and memorize that.

Participant 9:

He was very confused about both the Implicit and Explicit effects. He was searching for feeling like sliding on his wrist or leg like participants 6 and 8.

When there was a specific pattern he could understand better.

Regarding the notification, he felt he could distinguish that from a typical notification.

He found this feature very useful for driving, riding a bicycle, and any type of sport. "jogging, I put it somewhere that is not reachable, and I can use this feature."

He understood the Symbolic strategy; however, he was not positive about the tapping feeling. "It's hard. The numbers were different, and I could distinguish. I prefer the first method because I like it. I don't like the tapping thing. sliding feels better."

Participant 10:

She liked the Implicit effect but preferred to have a unique pattern for that so that he is able to distinguish it from a typical notification.

For the Explicit effect, he was choosing the direction based on the side of the body that the effect ends or the side of the body that he receives more intense or a specific pattern.

He was a bit scared about what would happen if he puts his phone in a different place.

"This one was like a pulsating feeling. I don't have something like a pulsation notification on my phone, so this pattern is a bit more unique."

He found the feature useful daily.

"Usually if I am going somewhere, I will look at my phone, and then I put it aside and trust my god and when I feel lost I again look at the phone, but if I get lost, and I have kinda a vibration that will help me to not go back would be perfect. because when I am crossing a street, I don't want to look at my phone."

He understood the strategy of the Symbolic effect, but he was not positive about that.

"Because they are both on your left hand, it might take a long time to figure out, okay; it's this pattern, and sometimes you might say was it fast or slow, so you don't want to go back and check."

Participant 11:

He was very confused about both the Implicit and Explicit effects. He was searching for feelings like sliding on his wrist or leg like participants 6,8,9.

When there was a specific pattern he could understand better.

Regarding the notification, if the vibration has a specific pattern, he could distinguish otherwise, it is hard.

He did not like the feature for himself to use.

"I am not sure. Because if I am using an online map, it means that I have a surface.Although I think it's very good for people who have disabilities. I prefer sound rather than vibration. I can't trust the vibrations because they were confusing."

He did not understand the Symbolic strategy and was searching to feel like sliding on his wrist.

Participant 12:

He changed his strategy over time. In the end, he could understand the Implicit effect; however, for the Explicit effect, he was relying on the vibration on his leg, and the strategy was a sliding feeling on his leg. If the vibration had the feeling of sliding to the right, he was choosing the right and reverse for the left like participants 6,8,9,11.

He could distinguish the most effects from a typical notification.

Regarding the feature, he found it useful in daily life.

"When you don't want to take it from your pocket, maybe while listening to music, and you don't want to take it off from your pocket."

She could understand the strategy of the Symbolic effect but did not like it to use.

"I need to focus on guessing. Maybe I am busy doing other things. Maybe I am running."

Participant 13:

He understood the Implicit effect very well, but he was not sure if he could distinguish that from a typical notification, and for him, the best was to receive Implicit effects but with different and specific patterns.

For the Explicit effect, he was relying on the side of the body that the effect ends. but he preferred the Implicit effect to the Explicit.

He found it useful for bad weather, especially in Canadian winters.

"I think about winter and winter coat, and with a lot of accessories, if you take it off, you need to take off your gloves. Your phone is dead already, so it's useful in winter.

He understood the Symbolic effect but did not find it very helpful.

"The thing is that if I need to think and analyze, I don't need a new challenge on my daily basis. Technology supposed to simplify my life."

2. Qualitative data of Experiment 2

Participant 1:

He preferred the Implicit effect and found it easier.

After talking about other notifications, he changed his mind and preferred the Explicit effect.

"Yes, that's the point in this case. The Implicit effect is not helpful, and I can make mistakes. At that point, starting on one side and going to the other side, but the ending is longer is better."

Participant 2:

He preferred the Implicit effect.

Regarding the notification, having a specific pattern that is different from a typical notification would be helpful.

Participant 3:

He preferred the Implicit effect because he did not need to concentrate.

"Implicit effect is easier because you don't need to focus, however for two other effects when you are walking, you need your concentration, so they are not useful."

Regarding the notification, he said if it is specific such as the effect that on the side is longer can be different from a typical notification.

Participant 4:

He preferred the Explicit effect.

"I have no logic; it just takes me to the left or right."

Regarding the notification, he believed if it is in the Explicit effect, he can distinguish that from notification.

Participant 5:

He preferred the Explicit effect. Because he could draw an arrow shape in his mind about the direction.

"It gives you an image in your mind; it's like an arrow goes to the left or right."

Regarding the notification, He believed different types of vibrations might help.

"I think if there is a difference between the characteristics of vibration, it might be better, but there is always a chance for confusion."

Participant 6:

He preferred the Implicit effect because he felt he needed to memorize other patterns.

"Because for the other patterns, you need to kinda memorize it, but as long as you get used to them, it would be more efficient. I just felt I had more control over this pattern."

Regarding the notification, he preferred the Symbolic effect that each directional effect and notification have different patterns.

"Once it has a pattern, it would be more efficient for making a difference with notification"

Participant 7:

He preferred the Implicit effect because he felt he needed to memorize the two other patterns.

Regarding the notification, it felt they were different.

Participant 8:

He preferred the Implicit effect, although it was not that much different from Explicit.

He found the Symbolic effect hard for older age patterns.

He did not have any idea about notification.

3. Qualitative data of Experiment 3

Participant 3:

He preferred the Implicit effect and Bilateral condition.

I could understand the notification. The bilateral condition works better.

I felt a jumping sensation.

Participant 4:

The Symbolic effect was more clear.

Bilateral is more natural, but I did better in the second one because I trained before.

My strategy was based on the last vibration and where it ends.

Participant 5:

Implicit effect was more clear.

He preferred the Bilateral is condition.

My strategy was based on the opposite side where the sequence starts.

Participant 6:

Explicit effect and Bilateral condition.

Unilateral condition is more difficult.

I did not have any strategy. I did not need to think.

Participant 7:

Explicit effect and Unilateral condition.

I preferred the Unilateral condition

My strategy was based on the opposite side where the sequence starts.

Participant 8:

Implicit effect and Bilateral condition.

Bilateral condition for Implicit and Unilateral for Explicit.

My strategy was like an arrow.

Participant 9:

Explicit effect and Unilateral condition.

I feel better for Unilateral.

It just showed me. I did not think.

Participant 10:

Explicit effect and Bilateral condition.

Bilateral makes more sense.

Once I learned, it started to be a natural reaction something like muscle memory.

BIBLIOGRAPHY

Amemiya, T. & Sugiyama, H. (2009). Haptic Handheld Wayfinder with Pseudo-Attraction Force for Pedestrians with Visual Impairments. *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility*, (Assets '09), 107–114. doi: 10.1145/1639642.1639662.

Bliss, J. C. (1974). *Summary of three Optacon-related cutaneous experiments*. Psychonomic Society.

Borhade, S. S. & Shelkar, A. (2019). A Survey of Computer Haptics.

Brewster, S. & Brown, L. (2004, 01). Tactons: Structured Tactile Messages for Non-Visual Information Display. pp. 15-23.

Bruce Goldstein, E. (2013). Sensation and Perception (ed. 9). Cengage Learning.

Choi, S. & Kuchenbecker, K. J. (2012). Vibrotactile display: Perception, technology, and applications. *Proceedings of the IEEE*, 101(9), 2093–2104.

Culbertson, H., Schorr, S. B. & Okamura, A. M. (2018). Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, 1, 385–409.

Darbar, R. & Samanta, D. (2015). SurfaceSense: Smartphone Can Recognize Where It Is Kept. *Proceedings of the 7th International Conference on HCI, IndiaHCI 2015*, (IndiaHCI'15), 39–46. doi: 10.1145/2835966.2835971.

Enriquez, M. & MacLean, K. (2003). The hapticon editor: a tool in support of haptic communication research. *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.*, pp. 356-362. doi: 10.1109/HAPTIC.2003.1191310.

Felten, D. L., O'Banion, M. K. & Maida, M. E. (2016). Peripheral Nervous System. In Felten, D. L., O'Banion, M. K. & Maida, M. E. (Eds.), *Netter's Atlas of Neuroscience* (ed. 3, vol. 2, pp. 153-231). Elsevier.

Floréen, P., Krüger, A. & Spasojevic, M. (2010). *Pervasive Computing: 8th International Conference, Pervasive 2010, Helsinki, Finland, May 17-20, 2010. Proceedings*. doi: 10.1007/978-3-642-12654-3.

Hannaford, B. & Okamura, A. (2008). Haptics (pp. 719-739). doi: 10.1007/978-3-540-30301-5_31.

Hayward, V. (2015). Tactile Illusions (pp. 327-342). doi: https://doi.org/10.2991/978-94-6239-133-8_27.

Hayward, V., Astley, O. R., Cruz-Hernandez, M., Grant, D. & Robles-De-La-Torre, G. (2004). Haptic interfaces and devices. *Sensor review*.

Hwang, S., Song, J. & Gim, J. (2015). Harmonious Haptics: Enhanced Tactile Feedback Using a Mobile and a Wearable Device. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (vol. 3205, pp. 295–298). Association for Computing Machinery.

Israr, A., Kim, S.-C., Stec, J. & Poupyrev, I. (2012). Surround Haptics: Tactile Feedback for Immersive Gaming Experiences. *CHI '12 Extended Abstracts on Human Factors in Computing Systems*, (CHI EA '12), 1087–1090. doi: 10.1145/2212776.2212392.

Karuei, I., MacLean, K. E., Foley-Fisher, Z., MacKenzie, R., Koch, S. & El-Zohairy, M. (2011). Detecting Vibrations Across the Body in Mobile Contexts. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 3267–3276. Retrieved from: https://doi.org/10.1145/1978942.1979426.

Kern, D., Marshall, P., Hornecker, E., Rogers, Y. & Schmidt, A. (2009). Enhancing Navigation Information with Tactile Output Embedded into the Steering Wheel. doi: 10.1007/978-3-642-01516-8_5.

Kim, E. & Schneider, O. (2020). Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). New York, NY, USA: Association for Computing Machinery. Retrieved from: https://doi.org/10.1145/3313831.3376280.

Lederman, S. & Klatzky, R. (2009). Haptic Perception: A Tutorial. *Attention, perception psychophysics*, 71, 1439-59. doi: 10.3758/APP.71.7.1439.

Norman, D. & Nielsen, J. (2016). The Definition of User Experience (UX). *Nielsen Norman Group*.

Pakkanen, T., Lylykangas, J., Raisamo, J., Raisamo, R., Salminen, K., Rantala, J. & Surakka, V. (2008). Perception of Low-Amplitude Haptic Stimuli When Biking. *Proceedings of the 10th International Conference on Multimodal Interfaces*, (ICMI '08), 281–284. doi: 10.1145/1452392.1452449.

Poole, A. & Booker, J. (2011). Design methodology and case studies in actuator selection. In *Mechanism and Machine Theory* (vol. 46, pp. 647-661). Elsevier.

Rosenthal, J., Edwards, N., Villanueva, D., Krishna, S., McDaniel, T. & Panchanathan, S. (2011). Design, Implementation, and Case Study of a Pragmatic Vibrotactile Belt. *Instrumentation and Measurement, IEEE Transactions on*, 60, 114 - 125. doi: 10.1109/TIM.2010.2065830.

Tsukada, K. & Yasumura, M. (2004). ActiveBelt: Belt-Type Wearable Tactile Display for Directional Navigation. *UbiComp 2004: Ubiquitous Computing: 6th International Conference, Nottingham, UK, September 7-10, 2004. Proceedings*, 3205(Lecture Notes in Computer Science), 384–399. doi: 10.1007/978-3-540-30119-6_23.

Zook, Z., Fleck, J. & O'Malley, M. K. (2021). Effect of Tactile Masking on Multi-Sensory Haptic Perception. *IEEE Transactions on Haptics*, 1-1. doi: 10.1109/TOH.2021.3112509.