INTERACTION BETWEEN SIGNAL COMPLEXITY AND PHYSICAL ACTIVITY IN VIBRO-TACTILE COMMUNICATION

QIN CHEN

NATIONAL UNIVERSITY OF SINGAPORE

2016

INTERACTION BETWEEN SIGNAL COMPLEXITY AND PHYSICAL ACTIVITY IN VIBRO-TACTILE COMMUNICATION

QIN CHEN

(BA. BNU)

A THESIS SUBMITTED

FOR THE DEGREE OF MASTERS OF ARTS
DEPARTMENT OF COMMUNICATIONS AND NEW MEDIA
NATIONAL UNIVERSITY OF SINGAPORE

2016

Supervisor:
Associated Professor Lonce Wyse

Examiners:
Assistant Professor Lu Weiquan
Assistant Professor Simon Perrault

DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis. This thesis has also not been submitted for any degree in any university previously

This thesis has also not been submitted for any degree in any university previously.

Chen Qin
2016

Acknowledgements

I would like to express my deepest thankfulness to my supervisor, Professor Lonce Wyse, for offering a continuous encouragement and support during my graduate studies at the National University of Singapore. His advice, guidance and knowledge throughout my journey from the process of finding an appropriate subject, conducting correct experiments, to the process of writing this thesis.

I must also express my appreciation to my examiners, Professor Simon Perrault and Professor Lu Weiquan, for reading my thesis and for their helpful feedback.

Thanks to my friends for their endless encouragement and technical supports Sincerely.

Finally, I must express my very profound gratitude to my parents and to my husband for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Table of Content

Summary

Haptic communication has been gaining attention in a variety of contexts such as hands and eyes busy applications, orienting awareness, private communication in public spaces, and in geographically distributed environments. Vibro-tactile signals are frequently used to create spatially distributed "displays" across body surface locations. Research has revealed how vibro-tactile stimuli detection and/or discrimination performances are affected by both the encoding process (the attributes of the vibro-tactile signal) and the decoding process at the bodily site of the display. However, the majority of studies have not considered real-world situations that reveal how physical activity and cognitive loads might interfere with performance. Therefore, my research intends to address the relationships between vibro-tactile signal complexity and physical activity conditions with regards to vibro-tactile identification performance. Based on the task complexity model (Wood, 1986), I classify patterns into three complexity levels depending on the accuracy of tactile identification performance and hypothesize that complexities of the physical activity conditions affect the identification performance efficacy, and furthermore that there is an interaction between the two factors with respect to performance. I report on three experiments. The first one evaluated the impact of physical activity and the tactile icon characteristics. The results were used to derive a measure of vibro-tactile pattern complexity used in the following experiments. Finally, in a series of trials across 8 participants engaged in various levels of physical activity, I explored how the level of physical activity interacts with the relationship between pattern complexity and performance. Both factors were shown to have main effects on identification performance. Moreover, physical activity conditionally interacts with vibro-tactile pattern identification depending on vibro-tactile signal complexity. A follow-up questionnaire with participants indicates that cognitive overload is the major factor interfering with identification performance. The main contributions of this thesis are first to link the vibro-tactile identification performance with practical physical activities such as walking and dancing. Furthermore, a guideline for vibro-tactile icon complexity classification and design was developed based on the finding that vibro-tactile icons should be considered as a whole rather than as a set of independent individual characteristics.

List of Tables

List of Figures

1. Chapter 1. INTRODUCTION

Recently, there has been growing interest in exploring the modalities used for computer-mediated communication. Human skin has long been recognized as a potential receptor for communicating information, and skin provides a sizeable and accessible input surface. Compared with graphics and sound, haptic and vibro-tactile displays have the advantages of being less intrusive, more private, and the information is delivered closely to users via physical contact. Specific "icons" can be created as symbols for haptic communication. People can learn and interpret haptic icons correctly and quickly in a variety of different situations, which motivates exploration of the effectiveness of tactile icon perception and identification. Numerous works have been conducted to investigate the efficiency of identification from both the encoding and the decoding perspectives. However, most previous research has examined the effectiveness of tactile identification only under the static physical activity condition. Few studies on vibro-tactile identification have explored basic physical dynamic activities such as walking and cycling, let alone more complex dynamic activities such as dancing and operating machinery, where both physical and cognitive factors play complicated roles. Furthermore, the interaction between encoding and decoding characteristics has not yet been investigated thoroughly.

Wood's Task Complexity Model (1986) provides a method of quantifying the complexity of a task. This theoretical framework provides motivation to examine the effectiveness of tactile identification when associated with different types of task complexity. Of further interest in tactile identification is the potential interaction between tactile icons and physical activity, which increases the dynamic complexity of tasks. Thus, we would benefit from a more comprehensive understanding of the interactions between tactile icons and physical activity in vibro-tactile identification.

Therefore, this thesis aims to address this gap by examining the efficacy of tactile identification from the two following aspects: 1) the complexity of physical activity, and 2) the interactions between the complexity of tactile icons and physical activity, based on a theory of task complexity. Three experiments were conducted, and subjective feedback was also collected. Preliminarily, a vibro-tactile belt with nine actuators (3 × 3 grid) was utilized in Experiment 1 to explore the associations between vibro-tactile characteristics and identification performances. An updated vibro-tactile device designed as a wristlet with five actuators (2 × 2 grid plus one at the point of intersection) and one physical button was utilized in Experiment 2 and Experiment 3.

This thesis consists of four chapters. It begins by introducing relevant concepts ranging from nonverbal communication, to computer-mediated communication, to the encoding-decoding model of communication, and to haptic and tactile communication (Chapter 1). As the display is a core material in computer-mediated haptic communication, there follows a further review related to the design of tactile displays and devices. Based on previous experimental research and guidelines regarding vibro-tactile devices and interfaces, a specific vibro-tactile wearable device was built for this thesis. Two versions were created to improve the experience of wearing and to minimize disruption to subjects in performance. Chapter 2 focuses on a range of reviews by specifying those studies featuring the theoretical framework applied in this thesis: namely, the task complexity model. Furthermore, hypotheses are proposed according to various dimensions of complexity. The three experiments are then described in Chapter 3; the results are interpreted, and further suggestions for haptic use in HCI are included. Lastly, Chapter 4 presents discussions related to both main effects of stimuli and physical activity, and how the interaction of those factors affects the effectiveness of identification. Also, factors that affect vibro-tactile identification performances are mentioned. A brief conclusion summarizes the limitations of this thesis, and finally, the potential applications of its findings are demonstrated.

1.1. Nonverbal Communication

This section reviews important notions regarding vibro-tactile identification, through a top-down process. It starts by introducing nonverbal communication, highlighting that touch is one of the most representative forms of nonverbal communication. Then, a general depiction of computer-mediated communication is presented. Furthermore, haptic communication is presented by combining the characteristics of nonverbal communication and computer-mediated communication. After introducing the classification of haptic communications, the focus of this thesis on vibro-tactile identification, a subcategory of vibro-tactile perception, is explained. There then follows a point-by-point review of the key attributes of both the encoding process and the decoding process in affecting vibro-tactile identifications, as identified from previous studies. After the review, the main research gap regarding the need for including realistic physical situations in the study of haptic communication is addressed. This chapter concludes with a review of wearable tactile devices/platforms from 2008 until recently.

It has been shown that almost 65% of all human interpersonal communication happens through nonverbal cues. People can understand each other even if they remain silent, as they can communicate through other mediums or channels, such as body movements and positions, facial expressions, eye behaviors, and postures, which are regarded as nonverbal communication. Research related to nonverbal communication has mainly focused on the following three units: the environmental structures, the physical characteristics of communicators per se, and the behaviors expressed by communicators (Knapp & Hall, 2006).

Touch is one of the most potent forms of nonverbal communication. Human skin has long been recognized as a potential receptor for communicating information (Geldard, 1957), and skin provides a sizeable and accessible input surface. It includes both self-touching and interpersonal touching. The act of touching crucially affects an individual's response, and the sense of touch is an effective communication channel, as it can strengthen any emotional experience (Knapp & Hall, 2006).

1.2. Computer-Mediated Communication

Although Communication is a well-established field, the term "Computer-Mediated Communication" (CMC) is relatively new. In general, it refers to both task-related and interpersonal communication conducted by computer (Pixy Ferris, 1997). In this thesis, I follow a more specific definition by John December (1997):

> Computer-Mediated Communication is a process of human communication via computers, involving people, situated in particular contexts, engaging in

processes to shape media for a variety of purposes.

In our daily lives, we use computers to mediate our communication or other performance tasks. For instance, we may use computers in a variety of work-related activities, to search for information, to send and receive emails, and so forth. In most cases, it seems that we rely on visual and auditory feedback. However, in applications where speed matters, a better understanding of touch could offer tremendous advantages, because the skin is considered to have a higher temporal acuity. Gescheider (1974) mentioned that humans can resolve a temporal gap of 5 milliseconds between successive signals on their skin, which is twenty times faster than vision (Heller & Schiff, 1991). As mediated by computers, the sensation of touch can be simulated through electric signals and then be delivered through computers. Another question, proposed by Abdulmotaleb et al. (2011), concerns the level of realism that can be achieved by simulating touch interactions in virtual environments. To answer this question, I additionally explore haptic modality.

1.3. Haptic Communication

Regarding haptic modality feedback, there are two main categories: direct person-to-person haptic communication, such as touch between people; and mediated person-to-person haptic communication that utilizes technological devices to provide vibration signals, which is described as "electrical stimulated signals." In this thesis, haptic communication is used in a narrow sense that refers to the second category: computer-mediated haptic communication.

1.3.1. Definition of "Haptic"

As mentioned earlier, the sensation of touch is described as "haptic." This term is derived from the Greek word "haptesthai," which refers to "the science of manual sensing (exploration for information extraction) and manipulation (for modifying the environment) through touch" (Saddik et al., 2011, p. 3). Importantly, the concept of "haptic" was expanded in the late 1980s to include all aspects of machine touch and human-machine touch interaction. The touching activity can be done by either humans, machines, or the combination of both, and the environment can be real, virtual, or a mix of both (Saddik et al., 2011).

In terms of computer-mediated haptic communication, a compulsory factor is the computer-controlled haptic system. Usually, such haptic systems include haptic devices (with sensors or actuators or both) and haptic interfaces that allow people not only to input the information to the computer, but also to receive signals or feedbacks from the computer in the form of a physical sensation in some part of the body. There is an interaction between people and haptic systems when people use such systems to receive information. The information conveyed during interactions is defined as a "stimulus." Specifically, it refers to an excitation or signal that is used when a (haptic) signal without further specification is presented to a user. Typical haptic stimuli are forces, vibrations, stiffnesses, or objects with specific properties (Hatzfeld & Kern, 2009, p. 9). The interactions can be divided into two main forms: motion control and perception (Kirkpatrick & Douglas, 2002). In each form of interaction, there are several operations. For example, haptic perception includes three main operations: detection, discrimination, and identification (Gall, Beins, & Feldman, 2001). Hatzfeld and Kern (2009) further explained and compared these three operations in detail. Firstly, detection is an operation that describes how a user detects the presence of a stimulus. The stimulus can only be "detected" or "non-detected," depending on the interaction conditions. Only if a stimulus is detected can the other perception (i.e., discrimination and identification) operations be applied. After the stimuli are presented and detected, discrimination describes the operation by which people discriminate the stimuli according to the attributes of the signals they receive. For example, two signals are discriminated by individuals because the amplitude of one stimulus is weaker than the other. In contrast, identification is an operation that associates the stimuli with particular meanings or knowledge. For instance, scholars have examined individuals' ability to identify the layouts (Chen, Santos, Graves, Kim, & Tan, 2008) or directions (Lam, 2006) of tactile stimuli.

From a physiological perspective, haptic perception can be classified into two subcategories based on the location of the sensory receptors: tactile perception and kinaesthetic perception. Hatzfeld and Kern (2009) defined kinaesthetic perception as "the perception of the operational state of the human locomotor system, particularly joint positions, limb alignment, body orientation, and muscle tension," whereas they defined tactile perception as "the perception based on sensory receptors located in the human skin." In terms of different forms of haptic interaction, kinaesthetic and tactile sensing predominantly include motion control interactions and perception operations, respectively. Hence, the perception of electrical stimulated signals should be categorized as a tactile perception.

1.3.2. Communicative Application

Touching is one of the most effective methods for communication, and it has a decisive impact on our responses to a situation. Touching was first proposed and systematically developed as a communicative medium by Geldard (1960). The sensation of touch is termed “haptic.” It can be electrically stimulated to facilitate touching-related nonverbal communications. In this case, computer-mediated haptic communication reflects how individuals communicate via electrically stimulated sense of touch, with the mediation of computers and haptic devices. Given that the sense of touch (haptic) is such an effective channel for communication in diverse situations, numerous studies have investigated the possibilities and the effectiveness of applying such electronic haptic information for communication. For instance, in terms of the modality comparison, numerous studies have shown that haptic communication is less distractive than other channels such as visual or auditory modalities. Another study implied that tactile cues are more effective than either visual or auditory cues as a navigation tool for elder people (Kim, Hong, Li, Forlizzi, & Dey, 2012). Even under multimodal conditions, ample research has also found that both visual distractions (Lee & Starner, 2010; Matscheko, Ferscha, Riener, & Lehner, 2010) and auditory distractions (Chan, MacLean, & McGrenere, 2005) can weaken the identification performance.

In other cases, haptic signals have also been utilized to guide people’s movements. One study investigated the possibility of teaching people simple dance steps via tactile icons (Rosenthal et al., 2011): the results showed satisfactory performance of computer-based tactile icons (95%–97% accuracy) as a nonverbal method to teach dance steps. Similarly, Anders et al. (2013;

2010) illustrated that their vibro-tactile system (haptic bracelet with tactile icons) was able to guide people in learning rhythm skills. The effectiveness of their system was evaluated through experiments as well as subjective feedbacks. Their results revealed that people are willing and able to be guided by haptic signals. Moreover, many researchers in this area have focused on optimizing haptic icons for information transfer. Wide ranges of characteristics, such as frequency, amplitude, time duration, spacing, and location, have been investigated. More details can be found in Section. 1.4.2.

Another application of haptic signals is a tactile interface for blind, visually impaired, or deaf subjects: the so-called "sensory substitution." Nanayakkara et al. (2009) found that the majority of deaf people desire to experience music, and that haptic signals significantly enhance their musical experiences. Another similar project explored how a blind audience could experience a dance performance via haptic signals (Wright, Lycouris, Timmons, & Ravenscroft, 2012). They linked the amplitude of the dancers' motions to the intensity of tactile vibration. Their results revealed the effectiveness of their haptic system, as highlighted by the positive feedbacks from most blind participants. Such devices provide interesting insights into how haptic signals can be used for sensory substitution in ways that are not currently possible.

1.3.3. Benefits of Haptic Communication

Compared with graphics and sounds, communication using haptic modality has appealing advantages. Firstly, communication via haptic modality is more intuitive than via auditory and visual modalities, because feedback comes simultaneously from whatever device the user is interacting with (Hatzfeld &

Kern, 2009, p. 21). Perhaps more importantly, haptic signals tend to be more personal, since the haptic information is directly delivered to users without intermediate media, unlike with visual and auditory information. For example, Diane et al. (2013) developed a wireless wrist-worn chair-speaker Haptic Notification System to help speakers better manage their presentation time through tactile cues. They concluded that haptic as a private communication channel successfully cued speakers to manage their presentation time without distracting audiences. In contrast, if the speaker was cued through a visual or auditory signal, the audience might be notified as well, and hence become distracted.

1.4. Encoding–Decoding Model

The above three sections have introduced the core conceptions of haptic communication and their properties, through a top-down approach. As a result, I summarize that from the haptic dimension, the particular focus of this thesis is on computer-mediated tactile identification. The following section describes detailed attributes of tactile stimuli that affect identification in an encoding-decoding process. Before utilizing this model to explain the characteristics of tactile stimuli, a general description of the encoding-decoding model is presented.

1.4.1. Definition

The encoding-decoding model of communication was first theorized by Stuart Hall, who proposed a theoretical approach to describe how media messages are produced, disseminated, and interpreted (1980). He emphasized that communication can be broken down into encoding and decoding stages: the encoding stage of a message is the invention of the message, and the decoding stage of a message involves translating the meaning and articulating it in practice (Hall, 1980, p. 129). In the process of encoding, the encoder uses either verbal or non-verbal signals that he or she assumes the decoders are able to understand. These signals can be spoken languages or rhythms (verbal); or gestures, facial expressions, body movements, or positions (nonverbal). How a signal is encoded is crucial to ensure an effective transformation of any communication process. The decoding process aims to transform the coded information and to interpret it in an understandable form. The outcome of the decoding process is highly individual-dependent, because the social contexts of different individuals play a variable but active role (Hall, 1980). The audience members reconstruct the ideas they receive by giving meanings to the signals, and by interpreting the signals as a whole in their own way. In other words, the encoding-decoding process is a process of information transformation, allowing information to be successfully communicated.

The original purpose of this model was to explain traditional mass communication, such as television programs, in depth. However, its applications have now been expanded to other media in the past few decades. For example, Raju (1998) investigated how tactile sensing shapes identification in both the encoding and decoding processes. Hertenstein et al. (2006) utilized the encoding-decoding model to probe the potentials of emotional communication by touching. Their results showed that people are able to effectively decode touch signals for emotions such as love, anger, or fear. Furthermore, they suggested that people could also accurately decode diverse emotions when combining touch and visual modalities together. A more recent study proved that haptic signals can even facilitate the online decoding of arm movement intentions, which may be further applied to physical therapies (Gomez-Rodriguez et al., 2011).

Importantly, Knapp and Hall (2006) proposed that when people generally refer to a nonverbal behavior, they mean only the encoding process (the properties of signals), whereas the process of decoding is ignored. However, the decoding process is equally critical, and should not be overlooked, especially in real-life situations. Therefore, specifically in this thesis, I am concerned with both the encoding process and the decoding process of tactile nonverbal communication. Particularly for computer-mediated haptic communication as discussed here, the encoding process involves decisive parameters of tactile stimuli, and the decoding process is referred to as the abilities of people to perceive and identify tactile signals.

1.4.2. Tactile Signal Identification

According to Gall et al. (2001, p. 9), there are in total three major operations (detection, discrimination, and identification of haptic information) involved in tactile perceptions. For a better understanding of tactile identification, it is important to distinguish the differences between these operations.

Detection

The detection operation refers to the presence of a stimulus detected by people.

There are only two results of a detection during tactile interactions between people and haptic devices: detected or not detected; and the result depends on both the sensory organs involved and the neural processing. Only if a stimulus is detected can other perception operations be applied. One simple example of the detection application is the vibration alert from our smartphones when we receive messages or emails.

Various studies have investigated the factors that might influence detection performances. An early study (Post, Zompa, & Chapman, 1994) investigated the relationships between people's detection abilities and 1) the location where people receive the tactile signals, 2) the motor activities of people, and 3) the vibration intensities. They found that the ability to detect vibro-tactile stimuli significantly decreased during the motor task, especially for the more closely spaced locations. These effects were more apparent if higher levels of vibration intensity were applied. Moreover, Karuei et al. (2011) expanded the factor areas to gender and multi-modality workloads. Their results corroborated that detection performance indeed depends on these factors. Recently, more studies have utilized tactile signals as notification cues, and explored the effectiveness of this application to facilitate daily life. For example, Diane et al. (2013) and Schumacher et al. (2013) succeeded in notifying people about time management during oral presentation performances and live music performances, using tactile signals. In addition, Roumen et al. (2015) compared the sensory sensitivities of different subjects using haptic channels, and concluded that vibration is the fastest channel for detecting signals, which suggests that haptic signals are suitable for urgent information notification.

Discrimination

As mentioned earlier, tactile signals can be easily detected and used as powerful cues to convey information. Because there will usually be more than one stimulus to ensure an optimal communication, different stimuli have to be discriminated promptly after they are detected. The discrimination (of vibration) describes how information is distinguished according to different properties of the signal, such as the frequency or the amplitude of a vibration.

Numerous studies have focused on the performance of tactile discrimination. An early study conducted by Geldard (1960) examined how people discriminate the duration, intensity, frequency, and location of tactile stimuli. More importantly, he found that those parameters interact with each other and thus affect the discrimination performance. For example, the difference threshold of intensity changed when frequencies of stimuli were different, and the difference threshold of frequency changed with differences in the locations or the duration of stimuli. Geldard's findings were supported by later studies: for instance, Lee and Starner (2010) found that people were able to accurately discriminate the differences of intensity, starting point, temporal differences, and the direction of tactile signals (up to 99% accuracy on average). Furthermore, Wang et al. (2016) found that people were able to discriminate approximately 4 to 5 vibration stimuli with different frequencies. Alvina et al. (2015) found that most directional linear signals could be successfully discriminated. Importantly, the effectiveness of tactile discrimination is significantly different in different body parts (the location to receive signals), and the palm seems to be the most sensitive part, rather than the arm, thigh, or waist. Furthermore, Vieira et al. (2016) focused on the hand region, and highlighted that increasing age correlated with the decline of tactile discrimination; however, no significant difference among gender was found. Furthermore, in terms of physical activity, when people were moving, their sensitivity in discriminating the tactile stimuli intensities decreased (Debats, Rohde, Glowania, Oppenborn, & Ernst, 2016). Consequently, this thesis considers the role of physical activity in tactile discrimination.

Identification

Similarly to discrimination, tactile identification occurs immediately after the stimuli are detected. However, all stimuli must be mapped to particular meanings, rather than being processed according to characteristics. Numerous studies have focused on the effectiveness of haptic communication by mapping haptic stimuli to human understandings of a certain domain. An early study (Enriquez, MacLean, & Chita, 2006) found that people were able to identify tactile stimuli with different frequencies (ranges from 7 Hz to 18 Hz) accurately (81% accuracy on average). Consistently, similar results were found by a later study (Wang et al., 2016), in which tactile signals were mapped to the priority level of mobile application notifications. Lower-frequency tactile signals were defined to represent a lower priority of application notification, and vice versa. As a result, relatively high identification accuracy (82.3% on average) was found, indicating the feasibility of this type of haptic communication.

The most commonly investigated application of tactile identification is guidance. For example, a recent research by Jeong an Yu (2016) developed a haptic device to guide visually impaired persons when walking. They mapped the tactile stimuli to the actual spatial locations ahead of the users when walking. In a real walking test, with obstacles on the pavement, subjects successfully avoided the obstacles with the aid of the tactile cues. Similarly, another study (Carcedo et al., 2016) mapped tactile signals to different colors on a color wheel, and evaluated how accurately colorblind people could identify those colors. They found significantly higher accuracy of identification (97.2% accuracy) in groups with tactile cues than in those without (76.9% accuracy). Other examples include research mentioned earlier (Sec. 1.3.2), showing that people are able to learn basic dance steps (Rosenthal et al., 2011) and drum techniques (Bouwer et al., 2013; Holland et al., 2010) with the aid of tactile signals.

One meta-analysis study by Wang et al. (2014) compared the efficiency of tactile signal perception in detection, discrimination, and identification operations. Vibration detection achieved the highest accuracy (90% accuracy on average). However, the accuracy diminished when the subjects were required to discriminate the locations or directions of the given tactile signals (78% accuracy on average), or to identify the meanings of the tactile signals (84.8% accuracy on average). According to the results from all studies examined in this meta-analysis, possible broad applications of haptic communication were highlighted. Although the confounding factors that affect tactile detection and discrimination have been intensively studied, far fewer studies have examined how the efficacy of identification is determined. Thus it is this question is the major focus of this thesis.

1.4.3. Encoding Process of Tactile Identification

In order to enhance the effectiveness of communication, researchers have been trying to address confounding factors in both the encoding process (the design of tactile icons) and the decoding process (the location for perceiving tactile icons, and the interactions with other modalities), because both processes are vital to tactile communication. Thus, it is important to design easily identifiable tactile icons (tactile patterns) and imbue them with a particular meaning (mapping). Importantly, no limitations of the mapping process have been reported, and several studies have investigated and proved the abundance of possibilities, as introduced in Section 1.4.2: Identification.

A tactile icon is an abstract signal that conveys information to people through touch, and it is commonly used as a fundamental element to support haptic communication. To provide insights into how we may design effective tactile icons, I review and divide previous studies into two groups. From the encoding perspective, the main factors affecting tactile icon identification are the basic parameters of tactile stimuli, including duration, intensity, frequency, form of signal, and the number of actuators. In the following section, I review in detail those crucial characteristics of tactile icons in the context of the encoding process.

Duration

Duration refers to the length in time of a vibration. The units of vibro-tactile duration can be seconds (s) or milliseconds (ms). When designing tactile icons, it is important to choose a suitable range of duration. It should be long enough to be detected, but if it is excessively long, the speed of information transformation could be reduced. Geldard (1960) suggested that the preferable duration of a stimulus ranges from 0.1 second to 2.0 seconds, because a duration of less than 0.1 second might feel like a nudge or a poke. However, any duration longer than 2 seconds may be less efficient. Furthermore, the duration of a stimulus should include the duration of intervals between vibrations if there are multiple vibrations within one icon/pattern. Several studies have sought to identify the optimal interval between vibrations (Kirman, 1974; Sherrick & Rogers, 1966), and they found that it varies amongst different durations of stimuli: 50 ms may be a minimum interval threshold.

Within the detectable range of duration, the longer the duration (from 80 ms to 320 ms) of a tactile stimulus, the better the performance of discrimination among tactile icons (Summers et al., 1997). McDaniel et al. (2008) compared the identification accuracies of tactile icons in blind people. Their results showed that identification accuracies of tactile icons with durations between 200 ms and 400 ms are higher than those with durations between 600 ms and 1000 ms. These results were consistent with earlier findings, showing that if tactile stimuli are used for a purpose as simple as notification, the subjectively preferable duration ranges from 50 ms to 200 ms, while a longer vibration is thought to be annoying (Kaaresoja & Linjama, 2005).

Intensity

Intensity refers to the strength or magnitude of a vibration: the unit of intensity is the decibel (dB). The decibel level is the minimum threshold for an optimal tactile detection. Usually, the terms “intensity” and “amplitude” are used interchangeably, because an increase in amplitude leads to an increase in the perceived intensity of tactile stimuli. A suitable intensity of a vibro-tactile signal should be sufficiently strong to allow an efficient detection, although it must not be strong enough to arouse discomfort. Verrillo and Gescheider (1992) suggested that an intensity up to approximately 55 dB is acceptable, and the minimum intensity should be greater than 2.3 dB (Brown, 2007, p. 10). One study found that below the detectable range of intensity, the stronger the intensity of tactile stimuli, the faster the vibration is detected (Lee & Starner, 2010), indicating that when designing tactile icons, a stronger intensity slightly below the maximum threshold is preferable.

Frequency

The term “frequency” refers to the rate of vibration. The unit of frequency is Hertz (Hz), 1 Hz meaning that an event occurs once every second. In human skin, there are four main different sensory receptors. Each has its specific characteristics, hence producing specific sensitivity during the detection of different haptic signals. Generally, people are capable of distinguishing haptic signals with frequencies between 0.3 and 1000 Hz (Zadeh, Wang, & Kubica, 2007), and the peak sensitivity appears at around 250 Hz. Table 1.1 summarizes their main characteristics, and Figure 1.1 presents a sectional view of the mechanoreceptors in our skin (Roberts, 2014).

Table 1.1 Main characteristics of mechanoreceptors in our skin.

Mechanoreceptor	Best at Sensing	Frequency Range
Merkel’s Cells	Pressure (slower movements)	0.4–100 Hz (5–15 Hz peak)
Ruffini Ending	Pressure (slower movements)	7Hz
Meissner’s Corpuscle	Touch, Vibration	10–200 Hz (10–50 Hz peak)
Pacinian Corpuscle	Vibration	40–800 Hz (200–300 Hz peak)

Resource from: Doug Roberts, 2014

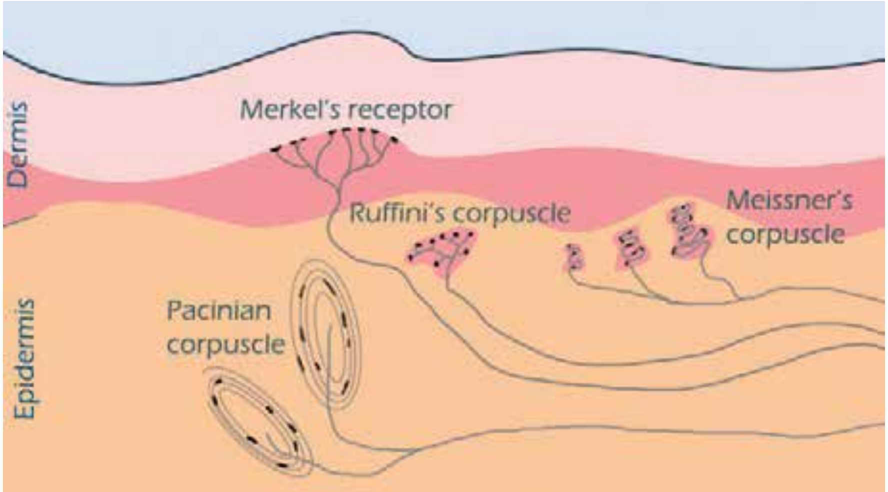


Figure 1.1 Cross-sectional view of mechanoreceptors under skin. Different mechanoreceptors have different frequency thresholds to detect haptic signals. *Resource from: Doug Roberts, 2014*

The suitable range of frequency sensitivity has been comprehensively examined since the 1960s. A recent study found that if multiple body parts are involved in receiving tactile signals, discrimination efficiency is better if the signals are delivered at different frequencies, rather than the same frequency (Tanaka et al., 2016).

Importantly, an interaction has been found between intensity and frequency when examining the difference threshold (Goff, 1967; Morioka, 2001; Von Békésy, 1959). Hence, Jones and Sarter (2008) suggested that when designing tactile icons for skin-based communication, it is more effective to use only one parameter (e.g., intensity or frequency) as the variable.

Signal Form

There are two main forms of tactile icons: single vibration and multiple vibrations. Tan et al. (2003) found that in directional tactile signal identification, simultaneous activation of multiple actuators did not significantly improve identification performance. Their results were supported by a more recent study (Paneels et al., 2013), which found that static patterns were less accurately identified, and that the vibration should be activated sequentially rather than concurrently, as it is difficult to discriminate different vibrating actuators from each other at the same time. However, these results were challenged by those of Mayuree and Eamonn (2011), which showed that if haptic information is presented by dual actuator, it is more effective than with a single actuator, especially for directional representation.

In terms of multiple vibration, there are also two main categories: actuators vibrating in sequence (only one actuator vibrating for a specific duration), and actuators vibrating concurrently (more than one actuator vibrating for a specific duration) (Rosenthal et al., 2011). The number of vibrating actuators might have an influence on tactile perception, even if they vibrate sequentially. Cholewiak (1979) conducted a study using increasing numbers of vibrating actuators from 1 to 64, and mounted the tactile device on the thigh. He found a positive linear relationship between the number of vibrating actuators and the intensity perceived by subjects. Geldard (1966) found that the number of simultaneous vibro-tactile stimuli that people can discriminate is between 6 and 14, whereas Bach-Y-Rita (2004) revealed that people perceive vibro-tactile patterns with excellent accuracy when wearing a matrix of 400 points on their back. A recent study by Carcedo et al. (2016) examined the relationship between the number of actuators and the effectiveness of tactile identification, and found that three actuators on the wrist is the optimum number for a tactile device. All these findings suggest that the sensitivity of tactile perception is not exclusively determined by any single characteristic.

Other factors

In addition to the factors discussed above, other factors, such as the waveform (Enriquez et al., 2006) and the rhythm (Paneels et al., 2013) of the stimulus have also been proved to affect tactile perception to a certain degree.

1.4.4. Decoding Process of Tactile Identification

The previous section reviewed relevant studies on the encoding process of tactile identification. In this section, tactile studies focusing on the decoding process are assembled and reviewed in detail. In terms of decoding, ample research has focused on the relationship between the bodily location for receiving tactile signals and the sensitivity of identification. Such locations can be divided into two subcategories: 1) the location where the tactile display is mounted, and 2) the inner spacing between actuators. In addition, people's cognitive workload, multitasking capability, and physical activity condition are all related to the effectiveness of tactile identification.

Location

The term "location," or "locus," refers to the bodily location of vibro-tactile stimulation. Tactile sensitivity varies among different locations on the body, particularly between glabrous and hairy skin. For decades, scholars have explored the sensitivity of tactile identification on almost every part of the whole body, including the fingertips, wrists, waist, torso, and lower limbs. A previous study compared the accuracy of tactile icon identification in different locations (forearm and waist), and revealed that the waist is superior to the forearm in producing effective identification of tactile icons (Piateski & Jones, 2005). Oakley et al. (2006) performed similar tests, and observed a consistent trend that people achieved only 53% accuracy of identification when the signals were delivered to the forearms. One reasonable explanation would be that the skin surface available is wider on the torso than on the forearm.

However, a recent study by Alvina et al. (2015) compared the accuracies of identification among different body parts, and found that the arm is the most sensitive part, whereas the waist is the least. In addition, Chen et al. (2016) found that subjects were able to correctly identify tactile icons mounted on lower limbs with at least 91% accuracy. In contrast, accuracy on the skin surface is relatively low. Indeed, increasing numbers of tactile devices have been designed as bracelets (Bouwer et al., 2013) or watches (Matscheko et al., 2010) to be worn on the wrist. Nevertheless, several studies have contradicted the above results, and found that the location for perceiving tactile stimuli does not affect perception performance. In particular, Chen et al. (2008) found no difference in tactile identification sensitivity between the dorsal and volar sides. Ng and Chan (2012) indicated that the detection time of tactile stimuli is not significantly different between the wrist and the leg.

Therefore, the above discrepancies must be considered carefully, from either a theoretical or a practical perspective, when deciding the most suitable locations to mount tactile icons. For example, although the fingertips are commonly utilized because of their high sensitivity to small amplitudes and their alert spatial acuity (Craig & Sherrick, 1982), these are an impractical body part for mobile and wearable devices, especially when additional tasks are demanded for hands. However, if we choose alternative body parts such as the forearms or wrists, the lower sensitivity of such body parts may be a potential issue that should be taken into careful consideration. Furthermore, as suggested by the results reviewed above, other factors, such as the array configuration or the inner spacing between actuators, can also significantly affect tactile identification.

Inner-spacing threshold

The inner-spacing threshold is also important when designing tactile icons, because it sets a baseline for our sensitivity in discriminating two signals. In terms of the spacing thresholds of tactile signals, the “two-point discrimination” describes how far apart two pressure points should be in order to allow an ideal discrimination between any two distinct points on the skin (Weinstein, 1968). This study also mentioned that for some complex tactile patterns, if the actuators are placed very close to each other and every actuator presents a unique signal, an observer may perceive the signals generated by different actuators as single ones, and thus miss the real underlying message. Therefore, this “two-point discrimination” measurement assists tactile device designers in choosing the spacing between two actuators. Moreover, Eskildsen et al. (1969) found that the two-point threshold is relatively stable, regardless of how tactile signals are received.

Cognitive workload, multitasking, and modality capability

Since the effectiveness of communication through haptic modality has been examined intensively, and thresholds of parameters such as duration, intensity, and frequency have been widely determined, increasing numbers of researchers are now focusing on how to determinate the thresholds of cognitive workload during the processes of decoding tactile information.

Hale and Stanney (2004) highlighted the advantages of adding haptic modality into visual cues. In a multi-model experience study, they proved that haptic interaction (specifically the interaction between all aspects of touch and computers) enhances the user’s experience, because haptic signals are cued by an independent sensory channel that can be easily processed by the brain. Also, they identified the most appropriate time to include haptic cues, specifically those that are effective as simple alerts. Furthermore, Kim et al. (2012) suggested that in tasks overloaded by visual and auditory modalities, such as driving, the most effective route of guidance for younger drivers is to add a haptic modality.

However, other scholars have been concerned with the negative effects of haptic modality. Andrew, Karon, and Joanna (2005) found no significant difference among icons (all at 95% accuracy) given the same level of workload. However, the time needed for both detection and identification increased when the workload was higher. Consistent conclusions can be found in a later study (Lee & Starner, 2010), which showed that the effectiveness of tactile identification will be impaired if there is extra visually distractive information. A recent study (Xu, Wang, Zhang, Song, & Wu, 2015) examined the effectiveness of learning with either single (auditory or vibro-tactile) or multi-modal cues (a combination of both modalities). It was found that for easy learning tasks, the multi-model cues were less effective than single-modal cues, because the presences of multiple modalities introduced undesired distractions.

Taken together, previous studies have suggested that the effectiveness of modality is enhanced when several modalities cooperate with each other, or when the purpose of utilizing multi-modals is consistent with the goals of the underlying task. Moreover, it is necessary to consider the cognitive workloads when intending to promote the effectiveness of haptic communication.

Physical activity conditions

The physical activity condition is an important factor that helps to determine the performance of tactile perception. One study has proved that even when the intensity of tactile stimuli is fixed, people who are moving perceive a lower intensity than do those in a static condition (Debats et al., 2016). Therefore, when trying to promote the effectiveness of tactile identification, the physical activity condition should be taken into consideration.

Though ample research has focused on the static situation, far fewer studies have investigated the impact of different physical activity conditions. Pakkanen et al. (2008) found that even for a performance as simple as the detection of tactile stimuli, accuracy decreases significantly when people are in dynamic situations such as cycling. Furthermore, this study highlighted that although that the accuracy of detection varies amongst different body parts, the physical activity condition is the main factor that influences detection results, regardless of the location. Edwards et al. (2009) designed a haptic belt with eight actuators, and evaluated the effectiveness of several performances under several physical activities, including standing and sitting (static), and walking and jogging (repetitive rhythmic dynamic movements). They observed that for easy discrimination performances such as the localization of tactile stimuli, although the accuracies were high for all activity conditions, accuracies during dynamic activities were lower than those in static activities (91% and 97% respectively). Similarly, Roumen et al. (2015) found that the haptic channel is effective for notification under both static conditions (lying, sitting, and standing) and repetitive rhythmic dynamic conditions (walking and running). However, the accuracies for static conditions (100%) were higher than those of dynamic activities (80% on average). For other complex activities such as dancing, researchers have found that people were able to perform easy dance steps such as forward/backward steps (Chen et al., 2015), or to synchronize with their partners, with the aid of haptic cues (Sofianidis & Hatzitaki, 2015).

1.4.5. The Learnability of Tactile Icon

According to the encoding-decoding model, signals remain meaningless unless they are translated or articulated in practice (Hall, 1980, p. 129). However, the mapping between the vibro-tactile stimuli and the specific information of a tactile icon is case-dependent. In other words, there is no intuitive connection between tactile icons and the information they convey. Therefore, people have to acquire the meanings before they can communicate using tactile icons, which highlight the importance of the learnability of tactile icons. Many studies have found that people are able to learn and interpret haptic icons correctly and quickly in a variety of situations. One study developed a haptic back-mounted display device to investigate whether and how haptic signals could be used as an effective intentional and directional cue (Tan, Gray, Young, & Traylor, 2003). The layout of the researchers' haptic actuators was a 3-by-3 array, mounted on a chair. They found that observers with some basic training were able to identify directional cues at an overall accuracy of 81%. Importantly, they mentioned that their main reason for choosing the back as the interface for their haptic device was because the area on the back is large enough for an interface. In a study by Allen et al. (2005), it was found that people were able to map the haptic icons to music parameters with an acceptable precision after a short 4-minute training session. Similar results were obtained by Chan et al. (2005): a 3-minute training is sufficient for subjects to learn how to map seven different haptic icons to seven different commands (with an average accuracy of 95%). These results provide motivation to further explore the effectiveness of tactile icon identification in a much more detailed setting.

1.5. Vibro-tactile Device Design

The previous sections have reviewed the basic communication-related concepts and various studies related to tactile identification in both the encoding and decoding processes. In particular, a device capable of delivering tactile information is found to be indispensable in computer-mediated haptic communication. Therefore, this section reviews and summarizes previous studies with reference to different devices that they created or applied, which helps to determine the parameters of the haptic device used in this thesis.

Typically, when designing tactile devices, factors such as the durability, cost, reliability, and wearability of the device should be considered. Furthermore, factors such as the weight, size, and power consumption may be equally important. Any attributes that may affect the sensitivity of a haptic device to tactile signals should never be ignored. Hence, a reliable tactile wearable device is designed here, after consideration of all the above factors.

A vibro-tactile device stimulates the skin using an actuator that translates an electrical signal into a mechanical displacement; this is typically used for presenting tactile cues to body parts. When introducing vibro-tactile signals using a specific device, the type of actuator and the method of mounting actuators are vital components because actuators need to function consistently and robustly under a variety of conditions. Numerous actuators have been used in different vibro-tactile devices. Choi and Kuchenbecker (2013) summarized and classified the main commercially available actuators into three categories: 1) linear electromagnetic actuators (an actuator made from an electrically conductive wire covered with an electrically insulating material and wrapped into a continuous coil), b) rotary electromagnetic actuators (an actuator designed to rotate continuously when a constant voltage or current is applied), and c) non-electromagnetic actuators (an actuator utilizing the piezoelectric effect and particular solid materials that can change their shapes when subjected to an electrical voltage) (Figure 1.2).

Figure 1.2 Examples of actuators for vibro-tactile devices. C2: A C2 tactor from EAI. Haptuator: A Haptuator from Tactile Labs, Inc. Tactaid: One complete Tactaid from AEC and one opened to show the suspension inside. E: Five shafted/cylindrical eccentric rotating mass motors. P: Three shaftless/pancake eccentric rotating mass motors. A U.S. quarter appears at bottom right for scale.

Resource from: (Choi & Kuchenbecker, 2013)

Moreover, actuators can only be activated when they are connected with a micro-controller that harbors the battery as well as the software components. Over the past decades, numerous devices have been designed that can be controlled wirelessly to enhance portability. Regarding approaches to mounting such tactile actuators, the most commonly used method involves Velcro strips, in order to mount the actuators on diverse body loci. Another commonly used method is to embed them into wearable items such as clothes (Cheok, 2010), gloves (Wang, Hoelldampf, & Buss, 2007), or shoes (Yao, Shi, Chi, Ji, & Ying, 2010). Jones and Sarter (2008) reviewed and summarized the main characteristics and applications of the major tactile devices commonly used before 2008 (Table 1.2).

Table 1.2 Tactile devices used in research projects prior to 2008.

Device	Function	Actuator	Location	Display Dimensions
Optacon (Bliss, Katcher, Rogers, & Shepard, 1970)	Reading device for those with visual impairments	Piezoelectric bimorphs	Fingertip	24 × 6 pin array, vibrating at 230 Hz
Videotact (VideoTact, n.d.)	Mobility aid for those with visual impairments	Titanium electrodes	Torso	768- and 32-electrode arrays
Balance prosthesis (Wall, Weinberg, Schmidt, & Krebs, 2001)	Provides feedback of body tilt	Tactaid tactors (Inertial actuators)	Torso	3 × 16 array of tactors around torso, vibrating at 250 Hz
Vibrating insoles (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003)	Balance control and postural stability	Linear actuators	Insoles of shoes	3 tactors in each sole, vibrating at 250 Hz
TSAS (Rupert, 2000)	Navigation aid for pilots	Pneumatic and electromechanical	Torso (vest)	22 pneumatic tactors, vibrating at 50 Hz; electromechanical tactors vibrating at 50 Hz
Personal tactile navigator (Van Erp, Van Veen, Jansen, & Dobbins, 2005)	Navigation aid in unfamiliar environments	DC pager motors	Waist belt	8 tactors vibrating at 160 Hz
CyberTouch (CyberTouch,	Interaction with virtual	Electromechanical actuators	Hand	6 tactors, one on each finger, one

n.d.)	environments			on the palm, vibrating at 0–125 Hz

Resource from: Jones & Sarter, 2008b, p. 100

With the rapid advancements of tactile technologies, many more tactile devices have been fabricated since 2008. Therefore, we must update our understanding to include the most recent devices. Table 1.3 presents a review of devices reported in studies from 2008 onwards.

Table 1.3 Tactile devices used in research projects between 2008 and 2016.

Device	Actuator	Location	Controller & Micro-controller	Connection	Mounting Approach
Haptic Knob (Enriquez, 2008)	DC coreless motor	Finger, Palm	Computer	Wired	Hold the knob
Tactile bracelet (Lee & Starner, 2010)	Button-shaped vibrating motors	Wrist	Wiring™ (http://www.wiring.org.co/)	Wired	Elastic strap
Tactor Placement (Matscheko et al., 2010)	C2 tactor	Wrist	CMOS single-chip micro controller	Wireless (Bluetooth)	Wristband
Tactile device (Karuei et al., 2011)	VPM2 eccentric-mass actors (coin)	Whole body, 12 parts	Duemilanove Arduino processor	Wired	Lightplast Pro sports tape; inserted in socks
Tactile belt (Srikulwong & O'Neill, 2011)	VPM2 vibrating motors	Waist	0/16/16 interface kit controller	Wired (USB)	Waist belt
Tactile belt (Rosenthal et al., 2011)	12 mm coin-type shaftless vibratio motor	Waist	Atmel ATtiny88 microcontroller	Wireless (ZigBee, Bluetooth)	Flat nylon webbing belt
Haptic chair (Kim, Lee, & Choi, 2012)	Coin-type eccentric-mass vibration motors	Back	Computer	Wired	Leaning against the chair cushion
Tactile	VPM2	Back	Arduino Nano	Wired	Velcro band

belt (Schumacher et al., 2013)	eccentric-mass actors (coin)		board	(USB) & Wireless (Xbee)	
TaSST (Huisman, Frederiks, Van Dijk, Hevlen, & Kröse, 2013)	Pancake-style eccentric mass vibration motors	Back of forearms	Arduino Mega micro-controller	Wired	Conductive wool, Velcro
HaNS (Tam et al., 2013)	Coin-type eccentric-mass tactors	Wrist	Arduino Fio micro-controller	Wireless (XBee)	Velcro band
Tactile belt (Cosgun, Sisbot, & Christensen, 2014)	Coin-type eccentric-mass tactors	Waist	Arduino Uno	Wired	Nylon belt
OmniVib (Alvina et al., 2015)	Coin-type eccentric-mass tactors	Palm, arm, thigh, waist	Arduino Pro Mini micro-controller	Wired (USB)	Velcro strap
Tactile watch (Lee, Han, & Lee, 2015)	Linear resonant actuators	Wrist	Arduino board	Wired	Silicon template, elastic band
NotiRing (Roumen et al., 2015)	Coin-type eccentric-mass tactor	Finger	Arduino Nano micro-controller	Wireless (Bluetooth)	3D printed ring using PLA
Mingle (Song & Kim, 2015)	Coin-type eccentric-mass tactor	Leg	Arduino Fio micro-controller	Wireless	3D printed module
Tactile watch (Wang et al., 2016)	Shafted eccentric rotating mass motor	Wrist	Computer	Wired	Watch
Hapticolor (Carcedo et al., 2016)	Coin-type shaftless vibration motor	Wrist	Arduino board	Wired (USB)	Velcro wrist band

It can be easily seen from Table 1.3 that the coin-type actuators, with Arduino board micro-controllers mounted by Velcro bands, are the most frequently used hardware sets for tactile device design. As for the location, the wrist has been the most popular body part for receiving tactile signals, possibly due to the wearability of tactile devices and the sensitivity of wrist skin to tactile stimuli. In terms of portability, a number of scholars have applied wireless technology to enhance their tactile devices, which appears to be a continuing trend for tactile device design.

2. Chapter 2 TASKS AND PERFORMANCE

In Chapter 1, the basic concepts related to haptic communications were introduced. Relevant studies have been reviewed in detail, with a particular focus on the encoding and decoding processes, and the design of tactile devices. In this chapter, I begin by describing the remaining gaps in the field of tactile identification, and further propose my motivations for bridging such gaps. Moreover, the theoretical framework of this thesis is based on the task complexity model (TCM), which is introduced here. According to different forms of task complexity, I sort the patterns into different levels and postulate several hypotheses, following which the main approaches utilized in this thesis are summarized.

2.1. Research Gap

From the perspective of haptic communication, as mentioned in Section 1.4, the specific focus of this thesis is on computer-mediated tactile identification, and its major concern is identifying how computer-mediated tactile identification can be performed as efficiently as possible. Previous studies have investigated the impact of various characteristics of haptic communication on the encoding process. However, although the "task" is one of the most common topics in the fields of human performance and behavior research, there is still a lack of studies that have considered the complexities of tactile stimuli when exploring tactile identification performance. Moreover, in terms of the decoding process, little research has investigated tactile identification in realistic and complicated physical activity conditions such as dancing, or the classifications of different complexities of physical activity conditions. Moreover, the existence of any interactions between different main effects in the identification performance has not received adequate attention in this field, which motivates me to closely examine any such interactions. Therefore, this thesis is conducted to bridge the research gaps regarding the effects of tactile pattern and physical activity on tactile identification, from the viewpoint of task complexity.

2.2. The Performance "Task"

For a better understanding of how the task complexity model is applied as a framework in this study, it is necessary to explain the meaning of a "task" in human performances, before introducing the task complexity model.

Identifying tactile stimuli is a specific performance of humans. During such a performance, subjects are requested to fulfill a series of tasks, such as wearing a tactile device, walking or dancing, receiving tactile signals, or identifying tactile patterns. In the research area of human performance and behavior, tasks are one of the most vital components being studied. In order to describe a task, Hackman (1969) summarized four approaches. The first approach is "*task qua task*," referring to "…the 'real world' dimensions such as the characteristics of stimulus, emphasizing the 'objective' properties of tasks, for example, those for which an experimenter can specify a single definite value by suitable measurement and control." The second approach is called "*task as behavior requirement*." It is defined in terms of the behavioral responses people should emit in order to achieve some criterion of success, which focuses on the behavioral function of a task. The third approach is "*task as behavior* *description*," which focuses on the actual responses from the performers. This approach is contrasted with the "*task as behavior requirement*." The last approach is named as "*task as ability requirement*." It "involves specification of the patterns of personal abilities or characteristics which are required for successful task completion" (Hackman, 1969, pp. 103–107). Later, Wood (1986) argued that the "*task as behavior description*" and "*task as ability requirements*" are unsuitable to define the complexity of tasks because they lack construct validity. Therefore, Wood (1986, p. 64) built a model by combining the descriptions of "*tasks as behavior requirement*" and "*task qua task*." His model examines the relationship between tasks and performances from a complexity perspective.

2.3. Task Complexity Model (TCM)

In this section, the task complexity model (TCM) is described in detail, from the components it contains to the forms of task complexity, and lastly, the key variables in this research are paired with the relevant terms used in the TCM.

Before building the model of task complexity, Wood (1986, p. 64) extracted three essential components based on the classification by Hackman that all tasks contain products, required acts, and information cues. Firstly, *products* are "entities created or produced by behaviors which can be observed and described independently of the behaviors or acts that produce them," which are associated with a set of attributes and are measurable results of acts. Secondly, *required acts* are activities within the tasks. They can be as easy as clasping fingers, or as complicated as activities with specific purposes such as lifting. It should be highlighted that the required act is the characteristic of the task, instead of the characteristic of the behavior of a subject. The last component is *information cues*, which refers to "the attributes of stimulus objects upon which an individual can base the judgments he or she is required to make during the performance of a task" (Wood, 1986, p. 65). It is noted that the required acts and the information cues are inputs of tasks. In other words, only when the products have first been specified can the required acts and information cues be defined. For example, a task performance may be "labeling the prices of stock." The staff should follow a printed list with prices of different brands of vegetable cans, to code each brand to its corresponding price. Then, the output or the results of this performance would be the products (labeled cans) of this task. The required act is the procedure of coding, and the information cue is the printed list. Therefore, linking these components to the argument of this thesis, I define that:

- The *product* refers to the reaction time and the accuracy of tactile identification.
- The *required acts* refer to the end-to-end process, including tactile icon identification, mapping tactile icons to poses, and performing specific poses, while walking or dancing.
- The *information cue* refers to the vibro-tactile stimuli, and more specifically, the distinct tactile patterns.

Based on the essential components of tasks, Wood (1986) built a model primarily focused on individual task performance, and provided a new definition of task complexity that is more complete and more general in terms of its application. Specifically, three types of task complexity are defined in his model: the following sections describe each of them thoroughly.

2.3.1. Component Complexity

The component complexity of a task refers to the number of required acts and the number of information cues in a specific task. Wood (1986, p. 66) explained that there is a positive relationship between the number of required acts and the knowledge and skill requirements necessary to complete a task, because more activities and events need more awareness and ability. He also mentioned that if multiple executions of the same act are required, there are moderations between the number of the (required) acts and the component complexity. Hence, when calculating the component complexity of a task, his term specifically refers to the number of distinct acts and information cues. With regard to the topic of this thesis, it is evident that identifying tactile patterns without alternative physical activities is easier than when physical activities are involved, according to the definition of the component complexity of a task. Furthermore, it is understandable that the component complexity of a task may vary among different activities. For instance, when individuals identify tactile patterns during repetitive activities such as walking or running, the component complexity should be lower than that in non-repetitive activities such as dancing or gymnastics. Hence, in this thesis, I define that:

> Component complexity refers to the complexity of physical activity conditions when identifying vibro-tactile patterns. It increases from non-active physical activity (low), to repetitive activity such as walking (medium), and to non-repetitive activity such as dancing (high).

All of the studies reviewed in previous chapters were conducted while the subjects were physically inactive, even though many of their applications involved physical activities (Antfolk et al., 2013; Chen et al., 2016; Lee et al., 2015; Matscheko et al., 2010). It is not clear whether the results from these studies would be supported in all other conditions.

However, although several studies have taken physical activity into account, their investigations were inadequate. Pakkanen et al. (2008) compared the effectiveness of tactile identification under either static conditions or dynamic rhythmic activities such as cycling. They found a significantly negative effect on perception accuracy and reaction time for tactile patterns identified during cycling. They also discovered that the optimal choice of location on the human body is dependent upon the type of physical activity, and that the wrist is the most sensitive area for identification during cycling. However, the degree of the dynamic activity was not taken into account in the Pakkanen study. Edwards et al. (2009) compared the accuracy of tactile identification during different levels of physical activity, such as walking and jogging. They found no significant difference between static and low-level activities, but their study did not consider the complexity of tactile patterns as a variable. Rosenthal et al. (2011) taught their participants basic dance steps through their responses to tactile icons. Although these tasks involved physical activity, the subjects were actually not moving at the time point when they were sensing tactile signals. A more recent research by Roumen et al. (2015) compared interactions between physical activity and modality (including haptic). They found a significant effect of physical activity on detection performance. However, this study considered only detection performance, which does not take account of discrimination and identification: for example, the cognitive workloads of these operations are different (Chan et al., 2005). Moreover, it has been proved that tactile perception performance varies amongst these three operations (Wang et al., 2014). Therefore, it is equally important to consider how identification may be affected by physical activities.

In summary, none of the above studies have examined all three factors, these being the complexities of physical activities, the complexities of tactile patterns, and the identification of tactile stimuli. Thus, there still remains a research gap regarding how different levels of physical activities affect identification performance.

2.3.2. Coordinative Complexity

Wood (1986, p. 88) defined coordinative complexity as “the nature of the relationship between task inputs and task products,” which includes the form, the strength, and the sequencing of the relationship. Specifically, the coordinative complexity of a task depends on all characteristics of required acts and information cues. In this thesis, all required acts have the same attributes under all conditions, and thus the main variance only results from the characteristics of information cues, i.e., the tactile stimuli (tactile patterns).

A variety of studies have examined the design of tactile icons in terms of their expressiveness and distinguishability. MacLean and Enriquez (2003) investigated the perception of tactile icons in terms of three dimensions: frequency, amplitude, and the wave shapes. They argued that the more variable factors of tactile icons there are, the more difficult the discrimination will be. Moreover, they highlighted that there is a nonlinear relationship between different parameters of tactile stimuli, which should be adjusted for particular purposes or environments when designing tactile icons. Chan et al. (2005) compared the reaction time used to identify seven different tactile icons whose frequency, duration, and amplitude were different. Moreover, they also compared the reaction time under different levels of workloads. Their results revealed that there is a significant main effect between workload and reaction time, and a significant interaction between tactile icon and workload that affects reaction time. These results suggest that generally there is a relationship between the complexity of the icons and the identification performance. More recent studies have tried to enhance the distinguishability of tactile icons delivered from different types of tactile devices, and have evaluated the effectiveness of those icons chosen in these studies (Bonanni, Vaucelle, Lieberman, & Zuckerman, 2006; Cosgun et al., 2014; Lam, 2006; Lee et al., 2015; Srikulwong & O'Neill, 2011; Ternes & MacLean, 2008). In most cases, they followed the widely accepted guidelines for tactile icon design (Hale & Stanney, 2004; Van Erp, 2002). However, such guidelines do not specify how we may define the complexity of tactile icons.

The TCM incorporates a relationship between task complexity and performance: higher levels of complexity lead to lower performance. Results in agreement with the model were reported by Chan et al. (2005), showing that there is a relationship between the complexity of the icons and the identification performance. As no previous study has discussed the complexity of tactile icons, I therefore categorize the distinct tactile icons into three complexity levels, depending on the efficacy of identification performance. Two measurements are chosen: accuracy and reaction time. According to the task complexity model, I define that:

The lower the accuracy, the higher the level of pattern complexity, *or*

The longer the reaction time, the higher the level of pattern complexity.

In order to evaluate this classification system, Experiment 2 was then designed.

2.3.3. Dynamic Complexity

Dynamic complexity is the last dimension of task complexity. In more realistic situations, people have to frequently adapt to changes during their performances of tasks. Therefore, dynamic complexity refers to that complexity which is "due to changes in the states of the world which have an effect on the relationships between task inputs and products" (Wood, 1986, p. 71). It is conceivable that more changes in either the number of required acts and information cues or in the relationships between such task inputs and products would enhance shifts in the knowledge and skills required for the task. While the existing studies provide valuable insights into tactile factors, most of them separated the encoding process from the decoding process. Thus the potential interactions between these two processes have not gained sufficient attention. A further study focusing on the effects of this interaction deepens our understanding of haptic communication within the context of physical activity. Specifically in this thesis, the issue of dynamic complexity motivates me to examine the efficacy of tactile icon identification when the complexities of both the tactile icons per se and the physical activity conditions are combined.

2.4. Hypotheses

In accordance with the task complexity model, the core research question of this thesis concerns the relationships between the effectiveness of tactile icon identification and the complexity of tasks, in both the encoding and decoding stages. Before testing these relationships, some preliminary questions shall first be investigated. For example, do the attributes of tactile icons affect their complexity? How can the selected tactile icons be classified into different levels of complexity”? In order to answer these preliminary questions, two pilot experiments are designed, while the main hypotheses are examined in Experiment 3.

2.4.1. Pre-Test Hypotheses for Experiment 1

As reviewed above, the performance of tactile icon identification depends on various factors, ranging from the encoding characteristics to the decoding attributes. Because most previous studies measured the performance of tactile icons in a static condition, I hereby examine the relationship between core factors of tactile icons and the identification performance under both static and dynamic conditions. However, it still remains obscure whether this relationship remains the same when individuals are in a relatively dynamic activity condition instead of in a static condition. In order to address this question under moderate dynamic activity conditions, three factors of the encoding process (duration, intensity, repetition) and two factors of the decoding process (location, and physical activity condition) are considered. From the encoding process, the duration, intensity and repetition of vibro-tactile patterns are all the attributes of tactile signals. From a macro perspective, I assembled those three factors as one variable – the “quality” of vibro-tactile pattern. Moreover, I defined that the longer, the intensive, and with more repetitions of one vibro-tactile pattern, the higher quality the pattern has. Therefore, several pre-test hypotheses are formulated for Experiment 1:

- H1-1: The location of the wearable device affects the accuracy of identification.

- H1-2: The physical activity condition affects the accuracy of identification.
- H1-3: The quality of tactile stimuli affects the accuracy of identification.

2.4.2. Pre-Test Hypotheses for Experiment 2

Results anticipated from Experiment 1 may reveal the differences in identification effectiveness between static and dynamic conditions, and their relationships with the location, duration, intensity, and repetition of tactile icons.

As few studies have focused on the complexity of tactile icons, it is necessary to classify the selected icons before exploring the relationship between task complexity and task performance. Given that the tactile icons used are spatial-temporal patterns that differ in duration and in the sequence of stimulation locations ("coordinative complexity" in TCM), two measurable factors were chosen: reaction time, and accuracy for specifically quantifying the effectiveness of tactile identification performance (Lee et al., 2015; Maculewicz, Erkut, & Serafin, 2016; Wozniak et al., 2016). According to the TCM, there is a relationship between the coordinative complexity and the performance, in that higher levels of complexity lead to lower performance. Hence, patterns are classified here into different levels of complexity based on the above measurable factors. Previous research focused only on the dynamic complexity of tactile stimuli detection and physical activity (Roumen et al., 2015), but how these differ from each other in terms of detection and identification remains unstudied. Therefore, some further pre-test hypotheses are postulated for Experiment 2:

- H2-1: There is no difference in different subjects' tactile stimuli detection times.
- H2-2a: Identification accuracy among tactile icons is significantly different, *and*
- H2-2b: Identification reaction times for tactile icons are significantly different.
- H2-3: There is a negative relationship between the accuracy of identification and the reaction time for identification.

2.4.3. Hypotheses for Experiment 3

According to Wood's Task Complexity Model (1986), there is a basic relationship between the different types of task complexity and performance. To test the applicability of the model, the tasks I conduct here involve subjects identifying various tactile icons and mapping them to specific physical poses in the context of three different physical activity conditions. In Wood's terms, the *information cues* refer to the vibro-tactile pattern; the *product* refers to the reaction time and the accuracy of tactile identification; and the *required acts* refer to the end-to-end process, including tactile icon identification, mapping tactile icons to poses, and performing specific poses while walking or dancing.

In this research, I include three different levels of physical activity: static, walking, and dancing, whose component complexities increase from static to walking, and from walking to dancing. Therefore, I hypothesize that:

- H1a: The level of physical activity is negatively associated with identification accuracy, *and*

- H1b: The level of physical activity is positively associated with reaction time.

More importantly, the third dimension of task complexity (i.e., "dynamic complexity" (Wood, 1986)) describes the potential interactions between the complexity of tactile icons and the complexity of physical activities, which prompts me to hypothesize that:

- H2a: There is an interaction between the level of physical activity and the complexity of the tactile signal, which impairs identification accuracy, *and*
- H2b: There is an interaction between the level of physical activity and the complexity of the tactile signal, which impairs reaction time.

2.5. Research Objectives and Approaches

In this section, having reviewed relevant research and described the specific research focus in terms of the objectives, approaches, and contributions of this thesis point-by-point, the core variables of this thesis are summarized.

As encoding-decoding processes take place during a communication, it is entirely possible for a recipient to misinterpret the information that the encoder tries to convey. Hence, a close investigation of the effectiveness of a specific communication process is of great significance. The particular objectives of this thesis are to investigate the relationships between vibro-tactile icons and physical activities in computer-mediated identification, using the task complexity model.

In order to understand the associations between factors and identification performances, I conducted Experiment 3 to examine my major hypotheses. Before testing these hypotheses, two pre-tests were carried out: a) to explore the relationship between characteristics of tactile icons (duration, intensity, location, physical activity condition) and the identification accuracy (Experiment 1); and b) to test human sensitivity to haptic modality, and furthermore to classify tactile icons into three levels (Experiment 2).

3. Chapter 3 EXPERIMENTS

The previous two chapters have introduced general concepts of haptic communication and more specific components of haptic identification by reviewing the factors influencing tactile identification from both encoding and decoding processes. Afterwards, in order to address the key motivations of this current work, the applicable theoretical frame – the task complexity model (TCM) from Wood (1986) was reviewed in depth and finally brought out the core hypotheses of this thesis according to the TCM. In this chapter, in order to objectively examine the relationship between task complexity and tactile identification performance, three experiments were conducted: two preliminary experiments (Experiment 1 & 2) and the key hypothesis test experiment (Experiment 3). In addition, subjective feedback from participants was also collected through a survey after Experiment 1 and Experiment 3 for a better understanding of how tactile icons and tactile identification performance were interpreted by participants. This research was conducted with the approval of the University Institutional Review Board (IRB).

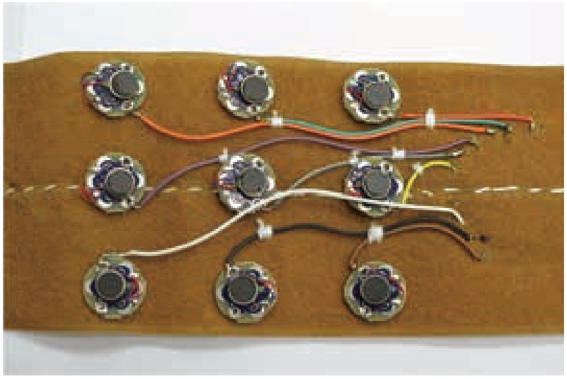
3.1. Experiment 1: Tactile identification with various parameters of tactile icons

The purpose of Experiment 1 is to validate the effects of characteristics of tactile icons on identification. Since the realistic physical situations are the focus of this thesis, it is important to investigate the relationship between the effectiveness of vibro-tactile patterns (icons) identification with their characteristics. Based on previous studies, three factors from both the encoding process (duration, intensity, repetition) and the decoding process (location, and physical activity condition) are considered. In this chapter, detailed individual components of Experiment 1 are explained comprehensively starting from the apparatus to the results of this experiment.

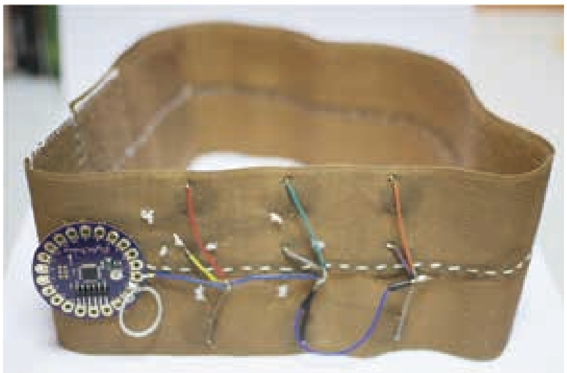
3.1.1. Apparatus

Based on the design of tactile devices from previous studies, the tactile device created for Experiment 1 is a wearable belt with 9 vibration actuators. Specifically, an Arduino Lilypad board is chosen as a micro-controller on the wearable belt. Nine 12-mm coin-type shaftless vibration motor wearable actuators are chosen to provide vibration, with a 3 × 3 array rectangle layout.

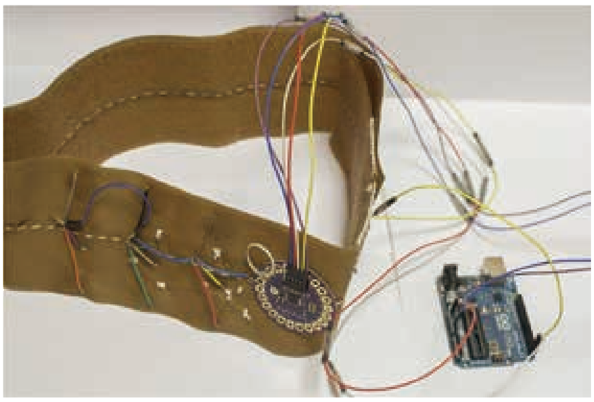
The belt is connected to an Arduino UNO board by five Dupond lines and then the Arduino UNO board is connected to a PC via a USB cable. This Arduino UNO board plays a role as a battery as well as a connector adapter between Arduino Lilypad board and the PC. It provides 5V to match the work voltage of actuators and to transport commands to Lilypad. The nine actuators are sewed on the belt made by Velcro strap, which is easy to stick and reusable. The length of the belt is 90cm. An external Velcro band is prepared to extend the length of the belt for irregular waist sizes of participants. The width is 9.8cm. In terms of actuators, it is designed as a 3 × 3 rectangle array, and the distance between rows is 1.5cm and 2.5cm between columns. The Arduino Lilypad board is at the reverse side of actuator array for the comfort of wearing (Figure 3.1).



(a) 3×3 grid actuator distribution sewed on Velcro.



(b) The wearable Velcro Belt with 9 vibrating actuators and a Lilypad micro-controller.



(c) The whole set consisting of of the belt (left) and the controller (right) connected by Dupont Line (center).

Figure 3.1 Configuration of the Apparatus used in Experiment 1.

3.1.2. Subjects

Twenty-four healthy participants (Male = 12, Female = 12) ranging from 22 to 31 years old (M = 24.75, SD = 2.59) who had no special experience with tactile communication devices volunteered in Experiment 1. The classification of subjects is in a 3 (location) × 2 (physical activity condition) × 2 (tactile signal parameter) dimensions and they are grouped randomly. Table 3.1 is a summary of the subject category.

Table 3.1 Subject categories in Experiment 1.

Location	Physical Activity Condition			
	Static		Dynamic	
Arm	Weak Signal (2)	Strong Signal (2)	Weak Signal (2)	Strong Signal (2)
Back	Weak Signal (2)	Strong Signal (2)	Weak Signal (2)	Strong Signal (2)
Leg	Weak Signal (2)	Strong Signal (2)	Weak Signal (2)	Strong Signal (2)

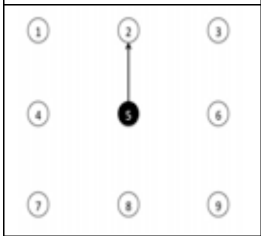
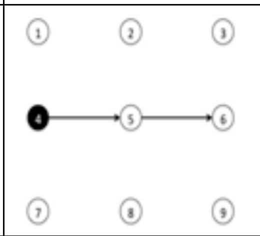
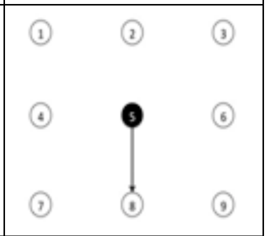
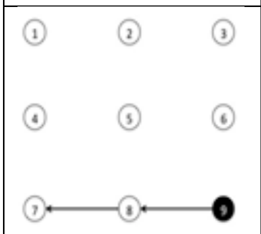
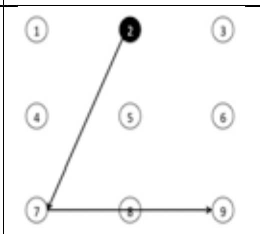
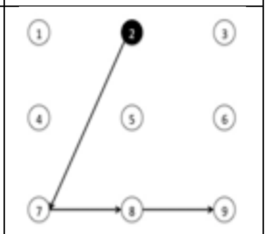
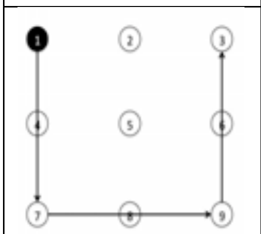
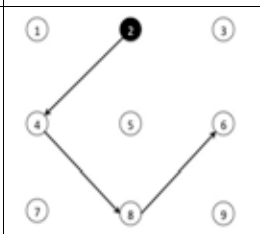
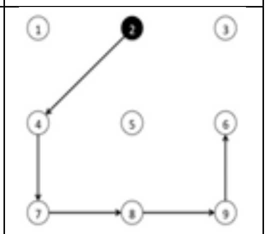
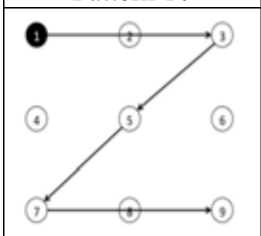
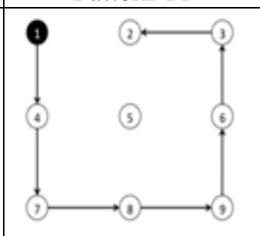
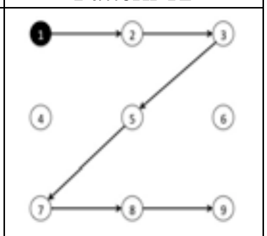
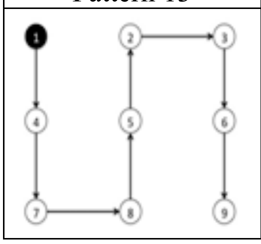
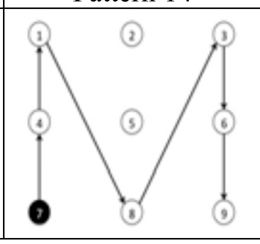
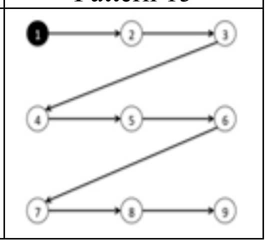
3.1.3. Stimuli

Vibro-tactile pattern selection is arbitrary and based only on a confusion matrix in order to test the efficacy of identification under different physical activity conditions independent from any application-specific mappings. There are 15 distinct patterns of vibro-tactile signals chosen for the testing. A blank 3×3 array layout is provided to participants showing the actuator array and the orientation of patterns on a paper is identical with the actual device worn by subjects (Figure 3.2), and Table 3.2 displays all 15 patterns. For each pattern picture in the table, the circled dot refers to the start point of each pattern that the first actuator vibrates, and the arrows refer to the order of the signals.

(a) 3×3 actuator grid distribution (b) Real actuator grid distribution

Figure 3.2 Distribution of nine ordered actuators.

Table 3.2 Layout of fifteen tactile patterns designed for Experiment 1.

Pattern 1	Pattern 2	Pattern 3
		
Pattern 4	Pattern 5	Pattern 6
		
Pattern 7	Pattern 8	Pattern 9
		
Pattern 10	Pattern 11	Pattern 12
		
Pattern 13	Pattern 14	Pattern 15
		

As discussed in section 3.1.2, three dimensions were considered during trials. The first one is the location to sense such stimuli. Three locations were selected to compare the ability of tactile identification: arm, waist, and thigh. As for the physical activity dimension, the static condition required participants be inactive when they are sensing the tactile stimuli. Participants assigned to static condition groups were required to keep still during the whole testing process. As for participants assigned to dynamic condition groups, they were requested to perform simple movements when receiving signals. Specifically, participants who were wearing the device on their arms kept swinging arms as naturally as possible; those who were wearing the belt on his/her back kept turning his/her waists; and those who were wearing the device on their leg repeated an up-and-down motion with their legs. All these movements were chosen arbitrarily, and it could be done without difficulty for most healthy people. For each pattern, there are 3 characters: intensity, duration and repetition. Specifically, intensity refers to the force of each actuator when vibrating. Duration refers to the time that each actuator vibrates. Repetition refers to the number of repeating the whole pattern. Based on these three parameters, two levels of quality of each pattern were designed. Every pattern was outputted in both levels. The specific parameters of two levels are shown in Table 3.3.

Table 3.3 Characteristics of the quality of pattern signals.

Quality	Intensity	Duration	Repetition
Weak	Half	500ms	Once
Strong	Full	1000ms	Twice

3.1.4. Procedure

The experiment began with participants wearing the haptic belt. After the hardware was set up, there was a training procedure during which the patterns and the experimental procedure were taught to participants. All 15 patterns were presented to participants in a randomized sequence. For each pattern presentation, participants were asked to draw the perceived pattern on a sheet of paper provided. After the sequence, any misidentified patterns were presented again. This process was repeated three times.

Experiment 1 was divided into two parts: the identification tests and the subjective feedback collections. During identification trials, the 15 patterns were delivered in a random order and with a random interval between signals. For each trial, participants were required to answer which patterns they identified by choosing the most similar pattern as they sensed on the multi-purpose choice answer sheet. Once participants confirmed their answers of each trial, the next signal was sent. There was no repetition of patterns during the trials. Thus there were 15 identification trials for each participant. For dynamic groups, the experiments were carried out in contexts of physical activities (swinging arms, turning waists, raising legs, respectively). After all trials were done, participants were requested to finish a questionnaire for the purpose of collecting their basic demographic information and their subjective attitudes towards the designs of hardware and tactile patterns. Every participant signed consent forms before experiments started. Experiment 1 took approximately 30 minutes for each participant.

3.1.5. Measurement

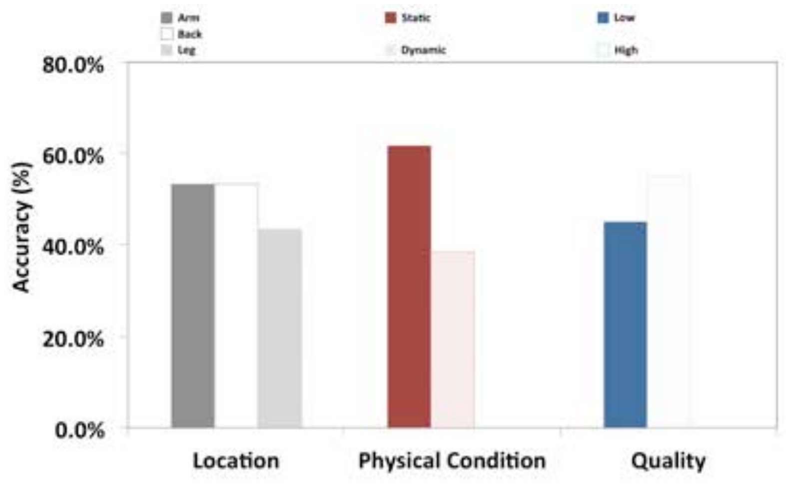
In order to test the effectiveness of the haptic communication, participants' results were marked. Each right answer gained 1 score, and the total score is 15. The score subjects got was seen as a reference of the effectiveness of tactile signal identification. Furthermore, the post subjective questionnaire (Attachment 1) was measured based on a 5-point Likert scale, with 1 referring to "strongly disagree " and 5 referring to "strongly agree".

3.1.6. Results

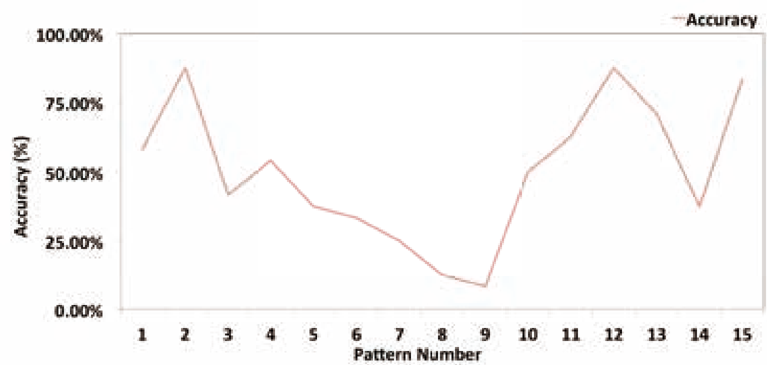
There were a total 360 trials of vibro-tactile pattern identification. Generally, the accuracy of tactile pattern identification is not as high as expected (Mean = 0.50, SD = 0.19). A mixed three-way 2 (quality of signals) × 2 (physical activity condition) × 3 (location) ANOVA was conducted to examine the impacts on pattern identification. Only a significant main effect between physical activity condition and pattern identification ($F(1,348) = 21.05$, $\rho < .001$) was observed (Figure 3.3(a)). Participants identifying tactile patterns when they are static (M = 0.62) are significantly more accurate than when they are moving (M = 0.38), inferring that the physical activity condition being a main factor to the effectiveness of tactile signal identification. Hence, all hypotheses except for H1-2 were rejected in Experiment 1. It worth noting that although H1-3 was rejected, there is a slight significance ($\rho = .050$) between the settings of tactile quality, inferring that the stronger (M = .55 for high group and M = .45 for low group) the characteristics of tactile icons are, the higher of accuracy to be identified.

Figure 3.3(b) showed the overview of the accuracy among those fifteen patterns. It was found that Pattern 9 is with the lowest accuracy, which is consistent with Figure 3.3(c) that Pattern 9 is the only pattern which has six actuators vibrated. This might because the layout of Pattern 9 is not a common formation such as triangle or rectangle, people are not familiar with it, and hence the identification performance was affected. This inferred that the design of vibro-tactile signal should avoid the uncommon or irregular shapes.

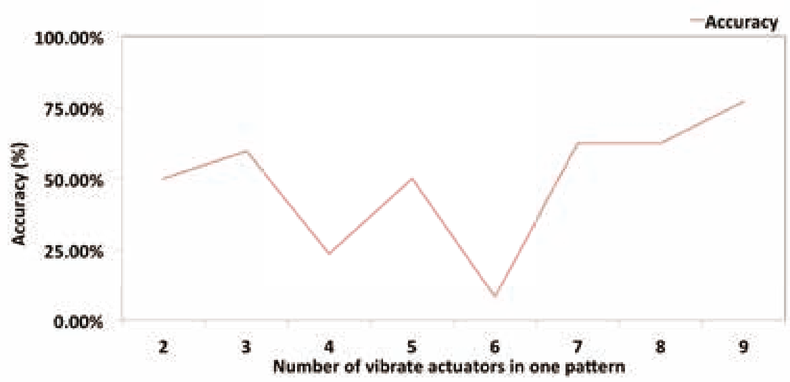
From Table 3.2, it is clear that there are several patterns with similar layouts but different vibrating numbers or the starting points (Pattern 5 & 6; Pattern 7 & 11; Pattern 10 & 12). I ran independent T-tests individually among those three pairs and unexpectedly found that for pairs of Pattern 7 & 11 ($t(46) = -2.77$, $\rho < .01$) and Pattern 10 & 12 ($t(40) = -3.00$, $\rho < .01$), patterns with more actuators vibrated are significantly more accurately identified. One possible reason might be the duration of the whole pattern was accordingly longer if more actuators vibrated in one pattern. This is consistent with the relationship between the total number of vibrated actuators in one pattern and the identification accuracy (Figure 3.3(c)) that when there are more than six actuators vibrated in one pattern, the accuracy is significantly higher ($t(250) = -5.17$, $\rho < .001$). Besides, there are several patterns similar to each other except for the orientation (Pattern 1 & 3; Pattern 2 & 4). The independent T-tests analysis results showed that for Pattern 1 & 3, there is no significant difference ($\rho > .05$) however a significant difference was observed between Pattern 2 & 4 ($t(40) = 2.67$, $\rho < .02$). This might because the right-left discrimination is a common difficulty among people, which in a way affected the identification (Ofte & Hugdahl, 2002; Wolf, 1973).



(a) The relationship between identification accuracy and (a) location, (b) physical activity condition and (c) vibro-tactile signal quality.



(b) Overview of the identification accuracy among individual patterns.



(c) Overview of the relationship between identification accuracy and the number of vibrated actuators in one pattern.

Figure 3.3 Overview results of Experiment 1. (a) The location to sense the pattern did not significantly affect the accuracy of identification, with slightly lower accuracy from the leg; similarly, the quality of tactile signal did not significantly associated with identification accuracy; the physical activity condition significantly affected identification accuracy. The accuracy from the static condition is dramatically higher than dynamic condition. (b) and (c) demonstrated that vibro-tactile patterns should not be uncommon shapes, and generally when there are more than six actuators vibrated in one pattern the accuracy is significantly higher.

According to the subjective feedback, I found that majority participants are satisfied with the comfort (M = 3.71, SD = 1.00) and convenience (M = 3.71, SD = .81) of the tactile device. What's more, it was found that participants subjectively agreed that they had higher ability of tactile stimuli detection (M = 3.13, SD = 1.22) than tactile icon identification (M = 2.67, SD = .96). Lastly, several relationships between the subjective attitudes and their identification accuracies were observed, for instance, the subjective feedback of both detection ($r = .43$, $\rho < .05$) and identification ($r = .50$, $\rho < .05$) are significantly positively associated with the accuracy. Interestingly, although there is a significantly positive association between participants' subjective experiences of vibro-tactile identification and their attitudes towards the communicative function through haptic modality ($\rho < .01$), the identification accuracy is not significantly related to their attitudes towards the communicative function ($\rho > .05$), which means that if the experiences of the vibro-tactile signals are not clear nor representative, even though people are able to identify vibro-tactile patterns, they might not be interested in the application. Table 3.4 complied all subjective results into a matrix showing the mean value, standard deviation and the Pearson correlation of each attitude.

Table 3.4 The descriptive results and correlations of subjective questionnaires

	Pearson Correlation									**Mean**	**SD**
	accuracy	Comfort	Convenience	Observation	Identification	Intensity	Frequency	Duration	Communication		
accuracy	1	0.187	0.065	**.433***	**.497***	0.326	0.267	0.391	**0.347**	50.00%	0.19362
Comfort		1	.591**	0.031	0.12	0.241	.406*	0.124	0.318	3.708	0.9991
Convenience			1	0.082	0.093	-0.149	0.212	0.209	0.042	3.708	0.8065
Observation				1	.478*	0.037	0.34	0.304	0.366	3.125	1.227
Identification					1	.406*	0.391	.524**	**.610****	2.667	0.9631
Intensity						1	0.391	.447*	.534**	3.333	0.9631
Frequency							1	.584**	.503*	3.375	0.9237
Duration								1	0.304	3.542	0.9771
Communication									1	2.583	1.3805

Note: significant at $\rho < .05$: *, significant at $\rho < .01$: **.

To sum up, Experiment 1 validated the impacts of vibro-tactile icon characteristics as well as the physical activity conditions on the identification performance. It was supported that people's sensitivity to tactile icons are significant lower when they are in dynamic physical activities. This result raised the subsequent experiments that to classify tactile patterns under dynamic situations instead of static (Experiment 2) and to investigate the relationship between pattern complexity and physical activity on tactile identification performances (Experiment 3).

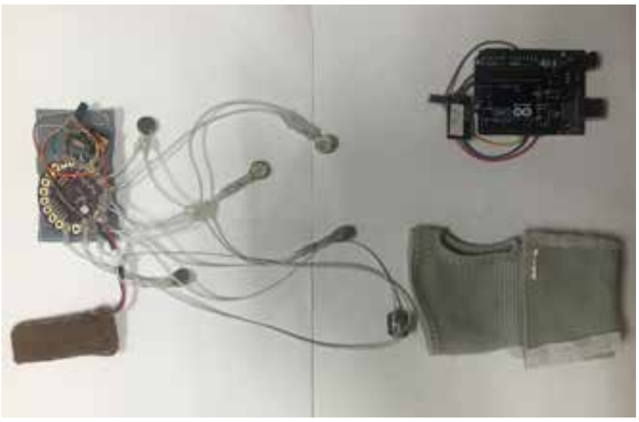
3.2. Experiment 2: Tactile pattern complexity classification

Experiment 1 showed that there is a significant difference between physical activity conditions on identification accuracy, which leads to the second experiment on categorizing patterns into different levels of complexity under dynamic physical activity condition. In this section, I introduce the whole process of Experiment 2 in detail. According to the "*coordinative complexity*" (Wood, 1986) which assumes that there is a positive association between performance and task complexity, I classify those vibro-tactile patterns depending on the identification performances. Before determining the classification, I also test the general reaction time of vibration as a baseline to show the ability of participant to sense vibration.

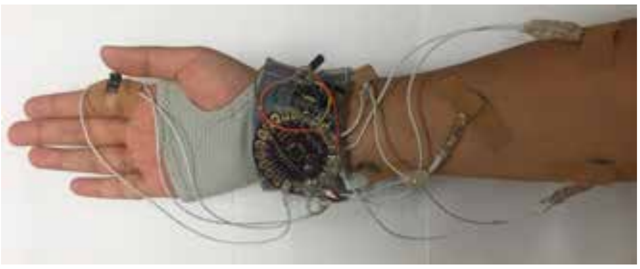
3.2.1. Apparatus

Based on the results from Experiment 1, there are several issues that need to be revised for the tactile device. The first part is about the characteristics of the tactile signals and the layout of those patterns. As mentioned in Experiment 1 that the inner spacing between two actuators are 15mm vertically and 25mm horizontally because of the limited width of the belt. However, it didn't match the minimum space of the "two-point discrimination threshold" requirement examined by Weinstein (1968) that the acuity is 40mm for upper arm, 32mm for back and 45mm for thigh, which makes subjects rarely distinguish the two stimuli from different actuators. Similar feedbacks of the subjects were received mentioning that it is easier to identify actuators vibrating latitudinally than longitudinally (because of boarder spaces). Secondly, the way to make the device wearable is also modified from a wired belt to a wireless device. In order to providing tactile stimuli cues under dynamic physical activity such as walking and dancing, it is necessary to receive haptic stimuli wirelessly. So, the device was advanced to a wireless version by adding a 2.4Ghz nRF24L01 wirelessly module on each Arduino board, as the wireless modules work in pairs, one playing as sender and the other as receiver. Hence, subjects would wear this tactile device to perform physical activities. Lastly, the location and the way to mount the device were revised, too. Considering the sensitivity to tactile stimuli and the convenience of wearing such device, I finally decided to select wrist to forearm area as the part to receive tactile signals. Because of the relative small skin surface of the forearm, I decreased the actuators from 9 to 5, and simplified the 3 × 3 grid distribution to a 2 × 2 grid plus 1 at the point of the intersection. Furthermore, in order to fix actuators as rigidly as possible especially under dynamic activities, I decide to tape actuators directly to the skin instead of mounting them through cloth.

Therefore, the new version hardware was constructed from two main parts: the controller connected to a PC, and the wearable device. The controller was built with an Arduino UNO board programmed to control the actuators which were connected to a Mac PC running OS X by a USB cable. For the wearable device, a wristlet was selected which is easy to wear and remove. A micro-controller running on an Arduino Lilypad board was sewn on to a small piece of cloth, which was mounted at the front side of the wristlet by Velcro. Five off-the-shelf vibration actuators (coin-type Precision Microdrives, model 312-101, dia=12mm, h=3mm) and a physical pressing button were connected to the Lilypad board. In order to fix the actuators tightly and directly to the skin without constraining the flexibility of movements, all actuators as well as the pressing button were securely attached with waterproof first aid tape. The wearable wristlet is powered by a slim 3.7V lithium-ion battery, mounted at the back side of the wristlet by Velcro. The communication between the controller and the micro-controller is done via a 2.4Ghz two-way wireless module (type - nrf24l01). Software written for the Arduino, was used to communicate vibration patterns to the wearable device and to collect data (Figure 3.4).



(a) The apparatus: one battery (lower left), one micro-controller with five actuators and a physical button, the wearable wristlet, and the controller (upper right) which sends and receives wireless signals from the wearable apparatus.



(b) Actuators are taped to the skin, and connected to the micro-controller. The button is visible between the thumb and index finger.

Figure 3.4 Outlook of the tactile device used in Experiment 2 and Experiment 3.

3.2.2. Subjects

Ten healthy participants (Female = 4, Male = 6) ranging from 24 to 30 years old (M = 27.0, SD = 2.58) who had no special experience with tactile communication devices and who did not participate in previous experiments were recruited from the university student population. No additional characteristics were required from participants.

3.2.3. Stimuli

I reduced the 15 tactile patterns from Experiment 1 to 12 and re-designed for Experiment 2 as I modified the number of actuators inserted in the devices and the distribution of the actuators. In order to make such tactile icons as distinguishable as possible, I first followed the two-point threshold (Weinstein, 1968) and other previous tactile-related results and guidelines to determine the characteristics of tactile icons. Since it has been shown that accuracy increases with greater spacing between actuators (Paneels et al., 2013). I maximized the space available on the forearm using spacing of 50mm from left to right, 100mm from top to bottom, and 60mm from the point of intersection to endpoints of the grid. The duration of vibration from each actuator was set to 500ms with a 50ms inter-onset interval following Matscheko et al. (2010) and Tan et al. (2003). The vibration frequency was 240Hz, and the rated normalized amplitude was 2.6g (PRECISION MICRODRIVES, n.d.), well within the range of tactile sensitivity (Matscheko et al., 2010).

In summary, the basic characteristics of tactile signals were as follows: 500ms duration of each vibration, followed with a 50ms inter-onset interval, under a frequency of 240Hz, amplitude of 2.6g. The number of actuators per pattern varied from 1 to 5. Thus the duration of one tactile icon ranged from 0.50s to 2.70s. Figure 3.5 shows the layout and sequence of the tactile patterns, and Table 3.5 summarizes the icon attributes for reference.

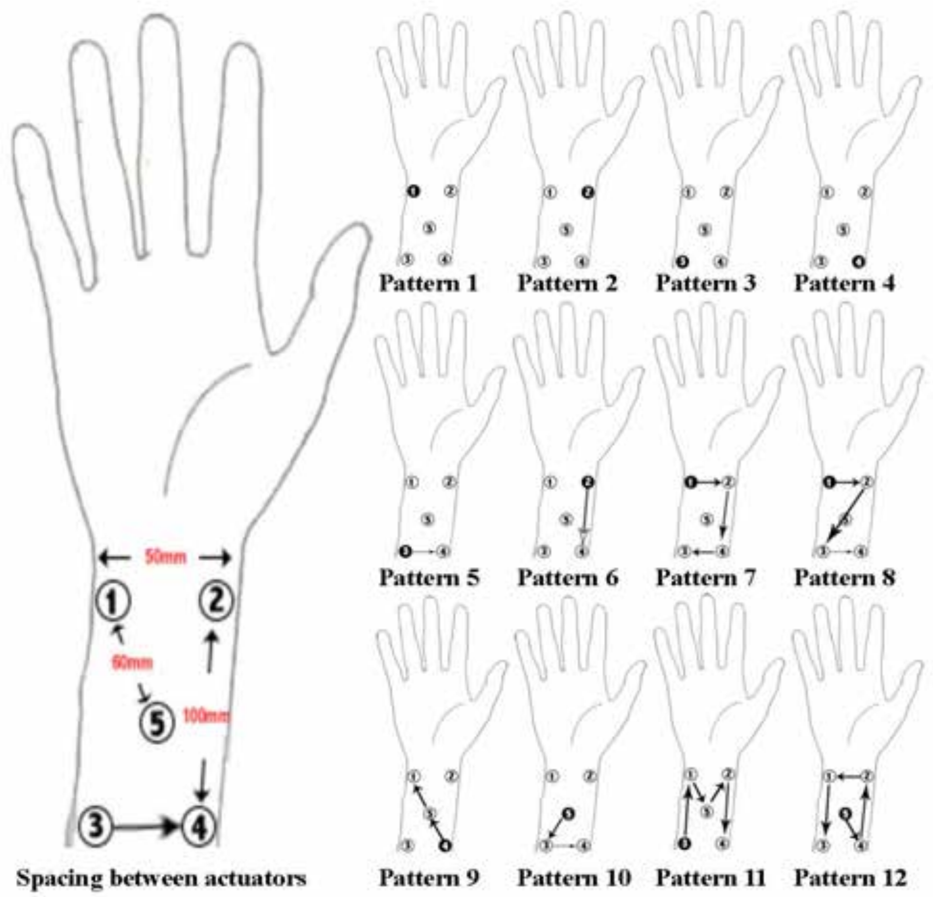


Figure 3.5 Twelve patterns used in Experiment 2 & 3. The five circles with numbers represent the five actuators. The black dot is the initial location for each pattern. The arrows indicate the sequence of vibrations.

Table 3.5 Attributes of tactile icons used in Experiment 2 & Experiment 3.

Pattern	Duration(s)	Spacing(mm)	How many actuators vibrated	Which actuators vibrated
1	0.50	N.A*	1	A1
2				A2
3				A3
4				A4
5	1.05	40	2	A3 & A4
6		100		A2 & A4
7	2.15	40 & 60	4	A1 & A2 & A3 & A4
8		40 & 120		
9	1.65	60 & 60	3	A1 & A4 & A5
10		40 & 60		A3 & A4 & A5
11	2.70	60 & 100	5	A1 & A2 & A3 & A4 & A5
12		40 & 60 & 100		

*N.A: Not applicable

3.2.4. Procedure

The experiment began with participants wearing the wristlet and taping actuators on their right forearms. The physical button was taped at the proximal phalanx of the right index finger where could be pressed by subjects with minimal efforts. After the hardware was set up, there was a training procedure during which the patterns and the experimental procedure were taught to participants. All twelve patterns were presented to participants in a randomized sequence. For each pattern presentation, participants were asked to press the button only once they had identified which pattern they perceived. Then, they drew the perceived pattern on a sheet of paper provided. After the sequence, any misidentified patterns were presented again. This process was repeated three times.

Experiment 2 was divided into two parts: the first (2a) measured reaction time to individual actuator vibration. The second (2b) measured identification. During (2a), fifteen signals were delivered to a randomly selected actuator and random intervals.

For the identification part (2b), participants were asked to draw the pattern they felt on the answer sheets after clicking the button. Then, the next stimulus would be sent. The twelve patterns were delivered in a random order and with a random interval between signals. Each pattern repeated three times during the trials. Thus there were thirty-six identification trials for each participant.

Both parts of the experiment (2a, 2b) were carried out in a context of my medium level physical activity – walking. Experiment 2 took approximately 30 minutes for each participant.

3.2.5. Measurement

Two factors were measured in Experiment 2: the reaction time (for detection (1a) and identification (1b)) and the accuracy (1b). The reaction time (Tn) of detection is the difference between the time that signal was sent (Sn) and the time the button was pushed (Rn):

$$\mathrm{T}n = \mathrm{R}n - \mathrm{S}n \quad (1)$$

For the reaction time (Tn) for identification, Sn refers to time the pattern begins, and the total reaction time is computed by subtracting the duration of the signal (Dn):

$$Tn = Rn - Sn - Dn \quad (2)$$

The accuracy score reported below are expressed as the proportion correct with the maximum of 1.

3.2.6. Results

There were a total 150 trials of detection and 360 trials of identification. Three cases due to misclicks under identification procedures were removed from the data analysis. I considered trials where reaction times were at least three standard deviations away from the mean to be outliers and removed them from the data analysis (Oakley, Sunwoo, & Cho, 2008; Trewin et al., 2012). A total of 3% of the reaction time trials and 2% of the identification trials were removed.

From Figure 3.6, it can be seen that people are physically sensitive to tactile signals (M = .60s, SD = .12). A one-way ANOVA with a Least Significant Difference (LSD) correction post hoc test was performed with the different actuators being the factor of interest. No statistical significant difference

(F(4,140) = .16, ρ > .05) between actuators was observed. Hence, **H2-1** was supported.

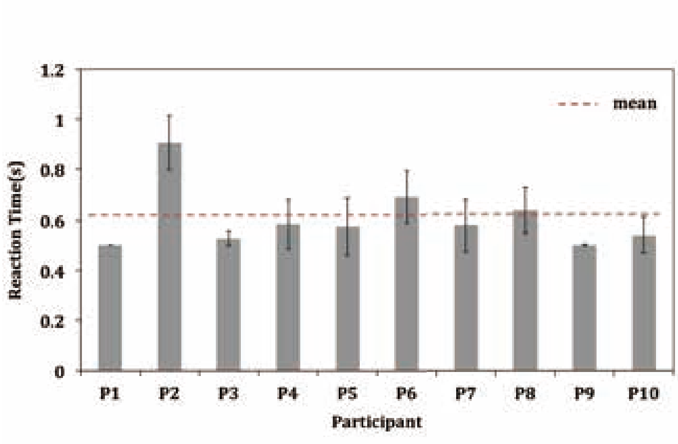


Figure 3.6 Reaction time of detection among participants. It is showing that people detect tactile information with quick response.

Overall, the identification performance (Figure 3.7(a)) has a relatively high accuracy (M = 77.99%, SD = .33) and short reaction time (M = 1.30s, SD=1.10). In detail, only the accuracy of the last 4 patterns (10,7,8,9) are lower than the mean. A one-way ANOVA with a LSD correction post hoc test was performed and found that for accuracy, it is significantly different generally (F(11,108) = 2.52, ρ < .01) whereas not for reaction time (ρ > .05). Hence, H2-2a was supported and H2-2b was rejected. From these results it was noticed that the accuracy is more sensitive than reaction time to reflect the performances of vibro-tactile patterns identification. Hence, the classification of pattern complexity was decided to on the basis of identification accuracy instead of identification reaction time. Specifically, from the results of the post hoc test, it was found that Pattern 9 with accuracy only half of the mean value, is significantly different from all other 11 patterns (Table 3.6). Except for the Pattern 9, no other significant differences in accuracy were observed among patterns (ρ > .05). Notably, considering previous research on accuracy based on individual characteristics such as the number, the spacing, or the location of actuators, I observed no connection between individual characteristics and accuracy.

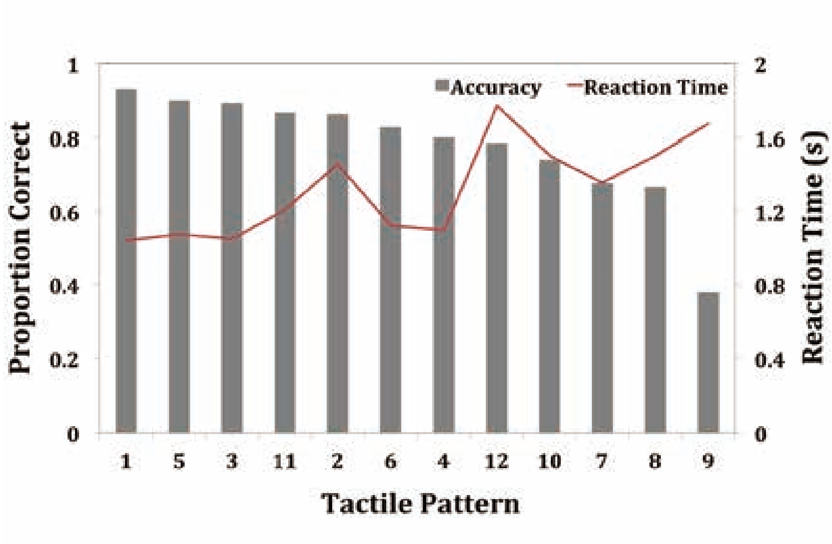
Table 3.6 The differences of accuracy between pattern 9 and other patterns.

Pattern		Mean Difference
9	1	-.57***
	2	-.50***
	3	-.53***
	4	-.43**
	5	-.53***
	6	-.47**
	7	-.31*
	8	-.30*
	10	-.38**
	11	-.50***
	12	-.43**

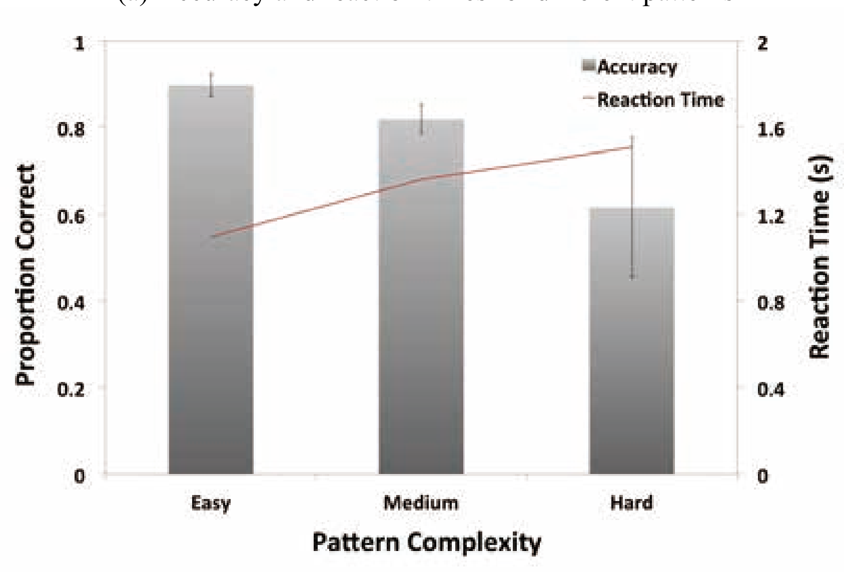
Note: significant at $\rho < .05$:* significant at $\rho < .01$:** significant at $\rho < .001$:***

A correlation analysis was performed between the accuracy and reaction time of tactile identification. Overall, the accuracy of tactile identification is significantly negatively correlated to reaction time ($r = -.65$, $\rho < .01$), and **H2-3** was supported.

Based on the accuracy of Experiment 2, I classified the 12 tactile patterns into 3 levels of complexity (easy – Pattern 1,5,3,11; medium – Pattern 2,6,4,12; difficult – Pattern 10,7,8,9, respectively; (Figure 3.7(b)). As there is a significant negative relationship between accuracy and reaction time, the reaction time is otherwise considered as an alternative factor to support the classification method in this thesis. A one-way ANOVA with a LSD correction post hoc test was performed and it was found that the accuracy of both easy and medium complexity levels are significantly different from that of difficult complexity level ($\rho < .001$, $\rho < .01$ respectively) whereas there is no significant difference between the accuracy of easy and medium levels ($\rho > .05$). For reaction time, no significant differences were observed among different complexity levels (F(2,117) = .95, ρ > .05), further in turn to support the validity of accuracy-based classification method.



(a) Accuracy and reaction times for different patterns



(b) Accuracy and reaction times among categories of pattern complexity.

Figure 3.7 Accuracy and reaction time of tactile patterns. It is showing with (a) individual patterns and (b) pattern complexity levels. It showed that increasing the complexity of pattern levels decreased the accuracy as well as increased reaction time.

As for the difference of the reaction time between detection and identification, it was found that the mean reaction time of detection of a tactile stimulus (0.61s) is dramatically shorter than the mean reaction time of identification (1.31s).

In summary, 12 tactile patterns were tested and classified into 3 levels of complexity associated with three distinct levels of identification accuracy.

3.3. Experiment 3: Tactile identification effectiveness examination

From the previous two sections demonstrating the preliminary experiments, I have firstly re-examined the validation of the characteristics of vibro-tactile patterns and further classified those revised patterns into three levels of complexity according to the task complexity model. In this section, I describe the central experiment of this thesis investigating the key hypotheses. Basically, there are three parts in Experiment 3. The first part was to validate the classification approach in Experiment 2 by examining the relationship between the complexity of patterns and the identification performances. Furthermore, according to the task complexity model, it is reasonable to assume the relationship between the physical activity conditions and the identification performance. More importantly, the novel interaction between pattern complexity and physical activity complexity was examined according to the "dynamic complexity" perspective. Therefore, the second part of Experiment 3 was to investigate how pattern complexity and physical activity affected the tactile identification performance. To do this, I defined three levels of pattern complexity and three levels of physical activity, and explored their combination in terms of pattern identification accuracy. In addition, pattern identification was indicated not by drawing on paper as in Experiment 2, but rather with physical movements, which are called poses. Participants received the vibro-tactile signals during one of the three physical activities and identified the patterns by moving their bodies into one of twelve specific poses. Lastly, the subjective feedback was collected to better understand their subjective impressions about what leads to tactile identification interpretation.

3.3.1. Apparatus

The device utilized in Experiment 3 is the second version – a wireless wristlet. It is identical with the apparatus in Experiment 2.

3.3.2. Subjects

Eight healthy participants (Female = 7, Male = 1; 19 to 23 years old) who did not attend previous two experiments were recruited for Experiment 3. They were selected from a non-professional, non-curricular university dance group. All were capable of learning and performing a one-minute dance routine, which I used for establishing a consistent complexity for the physical activity I termed dance.

3.3.3. Stimuli

The tactile stimuli are identical with those in Experiment 2 that I used twelve patterns categorized into three levels of pattern complexity. The pattern was delivered into three different physical activity conditions. The three levels of activity ranged from no activity ("static") to non-repetitive full-body activity ("dancing"), with a constant repetitive activity ("walking") as my intermediate level of my physical activity (See Figure 3.8).

(a) Participant receiving and identifying tactile patterns under Static activity.

(b) Participant receiving and identifying tactile patterns under Walk activity.

(c) Participant receiving and identifying tactile patterns under Dance activity.

Figure 3.8 Physical activities during tactile patterns delivery. Participants are in (a)static, (b)walking, and (c)dancing activity conditions when they are receiving and identifying vibro-tactile patterns.

3.3.4. Procedure

The set up and apparatus were the same as for Experiment 2. In addition, participants were told that all the trials would be video recorded for the purpose of accuracy measurement.

The training procedure for learning and identifying twelve patterns was the same as Experiment 2. Then, twelve specific dance poses were taught to participants, which mapped to the twelve patterns. This section was repeated until the participant could remember all mappings with 100% accuracy. Finally, participants were trained to identify tactile patterns under three activities (static, walking, and dancing respectively) one by one. For each activity, the pattern signals were sent randomly, and participants performed the mapped poses. Feedback was provided to participants in real time. If it was correct, the training would move on to the next signal, otherwise, this signal would repeat again. The walking activity was normalized to be as natural as possible. Participants were first shown a video and were encouraged to walk naturally with relaxed arm swing. After all patterns were correctly performed under three levels of activity, the training section ended.

The experiment was divided into two parts: the first part is tactile patterns identification under three activity conditions; the second part is a subjective feedback collection. Before trials started, it was highlighted that the quality of dance performance would not be evaluated. Participants had no idea about the classification of either activity levels or pattern complexity levels. A total of twenty-four identifications were set as one round, with each one of twelve patterns delivered twice in a random order and a random interval between two signals. Under each activity there were three rounds to complete and each participant was required to go through all three activities.

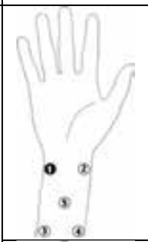
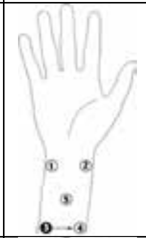
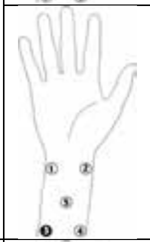
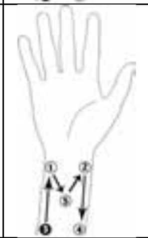
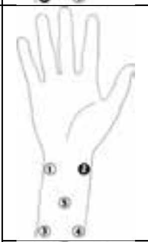
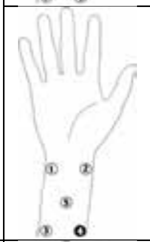
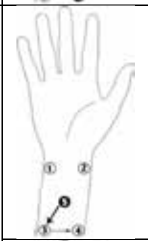
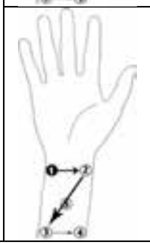
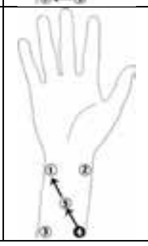
Following the activity sections, participants were required to complete a questionnaire (Attachment 2) about their subjective impressions of the tactile device as well as the identification process. It took ninety minutes to complete

Experiment 3 for each participant.

3.3.5. Measurement

The method to record the reaction time was identical with Experiment 2. Accuracy was measured by counting the number of correct poses struck following the delivery of the twelve tactile patterns and is expressed as proportion correct. As the focus of the experiment was on tactile pattern identification performance under dynamic physical activity conditions, physical poses rather than verbal responses to stimuli were used to examine the efficacy of haptic communication. To avoid distractions from other modalities, one pattern was mapped to one pose (in the same domain as the walking and dancing physical activity contexts) but not to a verbal response, which better suits the current nonverbal communication context. As for the selection of the particular twelve poses, I chose only basic and common positions which corresponding to patterns as intuitively as possible to minimize the cognitive workload at the same time. For example, Pattern 1 (vibrating left up actuator) refers to raising the left hand and Pattern 4 (vibrating right down actuator) corresponds to a right leg stride. Meanwhile, before each trial, subjects were trained to replicate each mapping correctly. This seems no more difficult than learning a verbal identification performance. Hence, to further examine the effects of physical activities, I tested whether the subjects replicate a simple movement correctly to reveal how they identify the patterns during the subjective feedback process. Table 3.7 illustrated the mappings between tactile patterns and physical icons in details.

Table 3.7 Mappings between each tactile pattern and the pose.

	Pattern	Mapped Pose	Pattern	Mapped Pose
Easy pattern				
				
Medium patterns				
				
Difficult patterns				
				

Furthermore, answers on the questionnaire used to understand participants' experiences of tasks and the subjective measurements of how intuitive the mappings between patterns and poses were given on a 7-point Likert scale.

3.3.6. Results

In total, there were 1728 trials. Three cases were not included because participants forgot to press button before they performed the pose. And 2% were outliers and were removed based on the same rule (three standard deviation away from the mean) in Experiment 2. Therefore, there are 1693 trials for data analysis.

I ran a mixed-effect model with two fixed factors (activity and pattern complexity) and one random factor (participant) on both reaction time and accuracy. Each fixed factor has three levels (Activity: static, walking, dancing; Pattern complexity: easy, medium, difficult). The random factor has 8 levels, participant 1 through participant 8. Pairwise comparisons were included with LSD correction.

Overall results of both accuracy and reaction time for each pattern were compiled from all participants into a matrix showing the mean value and standard deviation of each level of stimuli (Table 3.8).

Table 3.8 Identification performance of accuracy and reaction under 3×3 levels of task complexity.

Activity	Accuracy (%)							
	Easy		Medium		Difficult		Total	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Static	93.75	.10	88.84	.15	81.47	.21	88.02	.17
Walk	92.19	.12	85.42	.18	82.21	.15	86.60	.15
Dance	57.59	.23	62.35	.16	36.76	.22	52.23	.23
Total	81.18	.23	78.87	.20	66.81	.29	75.62	.25

(a) Overall results in terms of accuracy

Activity	Reaction time (s)							
	Easy		Medium		Difficult		Total	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Static	0.93	.33	0.91	.33	1.59	1.12	1.14	.76
Walk	1.00	.33	1.14	.46	1.50	.70	1.21	.55
Dance	1.66	.52	1.71	.37	2.19	.61	1.85	.56
Total	1.19	.52	1.25	.51	1.76	.88	1.40	.70

(b) Overall results in terms of reaction time

A significant main effect of pattern complexity on accuracy ($F(2,182) = 17.77$, $\rho < .001$) was observed. There is also a significant main effect of pattern complexity on reaction time ($F(2,182) = 27.59$, $\rho < .001$). More specifically, based on the results of pairwise comparisons (Table 3.9(a)), it was found that difficult patterns are significantly different from the other two levels on both the accuracy ($\rho < .001$) and the reaction time ($\rho < .001$) whereas no significant differences between easy level and medium level patterns on either accuracy or reaction time was observed ($\rho > .05$ both). These results supported the validity of my accuracy-based classification method derived in Experiment 2.

Similarly for physical activity, significant main effects on both accuracy ($F(2,182) = 122.69$, $\rho < .001$) and reaction time ($F(2,182) = 43.65$, $\rho < .001$) were observed. From the pairwise comparison results (Table 3.9(b)), the dance activity is significantly different from the other two activities on both the accuracy ($\rho < .001$) and the reaction time ($\rho < .001$) whereas no significant differences between static and walk activities on either accuracy or reaction time were observed ($\rho > .05$ both). Therefore, **H1a** and **H1b** are supported.

Table 3.9 Pairwise comparisons of mean differences on accuracy and reaction time.

	Accuracy			Reaction time		
	Easy	Medium	Difficult	Easy	Medium	Difficult
Easy	•	.02	.14***	•	-.06	-.57***
Medium		•	.12***		•	-.51***
Difficult			•			•

(a) Mean differences among pattern complexity levels on accuracy and reaction time.

	Accuracy			Reaction time		
	Static	Walk	Dance	Static	Walk	Dance
Static	•	.01	.36***	•	-.07	-.71***
Walk		•	.34***		•	-.64***
Dance			•			•

(b) Mean differences among physical activity levels on accuracy and reaction time.
Note: significant at $\rho < .001$: ***

Among (a) pattern complexity levels and (b) activity levels, it was showing that the difficult level of both types of complexity are significantly different from the other two levels in terms of accuracy and reaction time and there are no significant differences between easy/static and medium/walk levels on both accuracy and reaction time.

More specifically, Figure 3.9 showed individual results of both accuracy and reaction time. It was found that participants are able to identify different completed levels of patterns with acceptable accuracy when they are static or under regular repetitive dynamic activities, which strongly support that regardless of the complexity of vibro-tactile pattern, such spatiotemporal vibro-tactile patterns are more suitable for low level of activities.

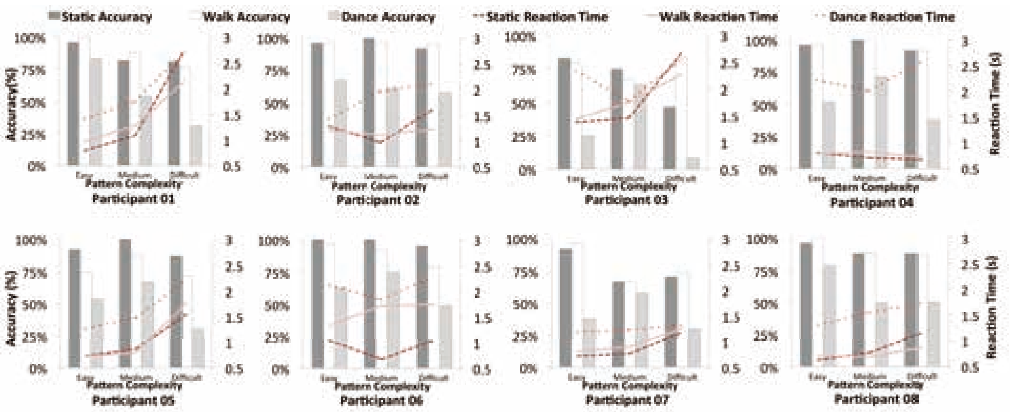


Figure 3.9 Individual results of eight participants in Experiment 3. It illustrated that people are able to identify vibro-tactile patterns when under either static or simple repetitive dynamic activity conditions. However, under dance activity, the accuracy decreased whilst the reaction time increased dramatically. It showed that the influence of physical activity is stronger than the pattern complexity on vibro-tactile signal identification performance.

In addition, a significant interaction between pattern complexity and activity on accuracy was observed (F(4,182) = 3.53, $\rho < .01$). Therefore, **H2a** is supported. However, there is no significant interaction between pattern complexity and activity on reaction time (F(4,182) = .61, $\rho > .05$). **H2b** is not supported. This can be seen in Figure 3.10 where the slopes of the lines connecting accuracy values for different activities differ for the different pattern complexity levels.

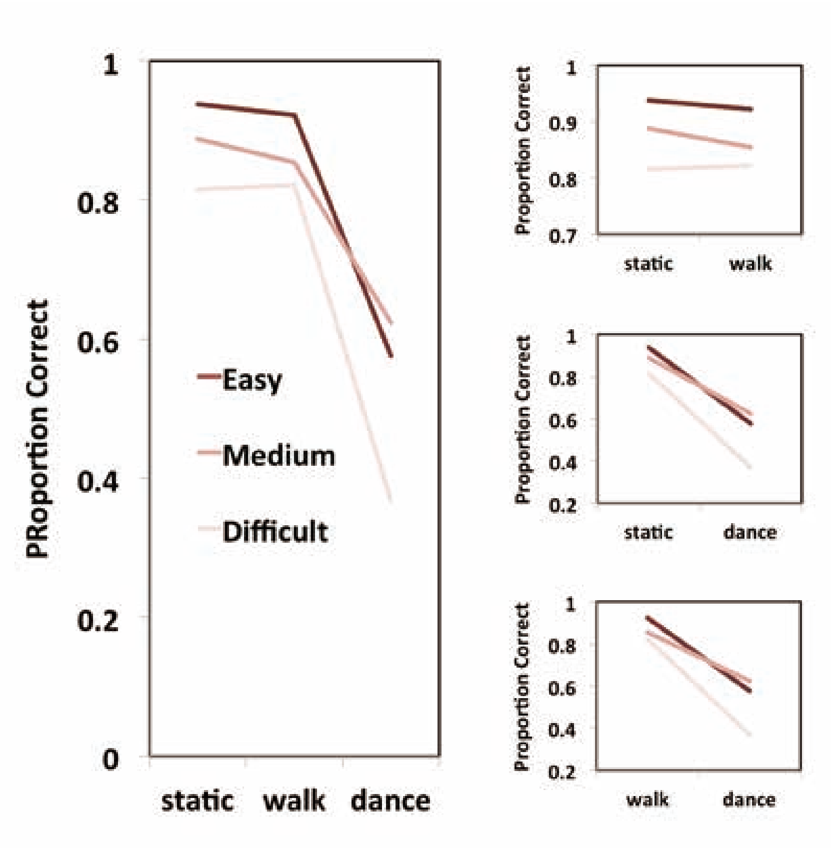


Figure 3.10 Interactions between physical activity complexity and pattern complexity on accuracy. The three lines (easy, medium, difficult) refer to the three levels of pattern complexity. Under static and walk condition, lines of the easy and medium patterns are in the same direction with a steeper slope for the medium patterns than the easy patterns whereas the line of difficult patterns is in the opposite direction. Under either static and dance or walk and dance activity conditions, those lines are in the same direction, but the slope for the difficult patterns is steeper than the other two. Furthermore, the steepness of the line for the medium patterns is smoother than that of the other two.

To summarize the results of the post experimental questionnaire, the questions about the subjective impressions of the comfort wearing the hardware were positively correlated with accuracy (r = .91, $\rho < .01$). I also found that all participants identified the number of tasks as being the main challenge for accurate identification (See Figure 3.11).

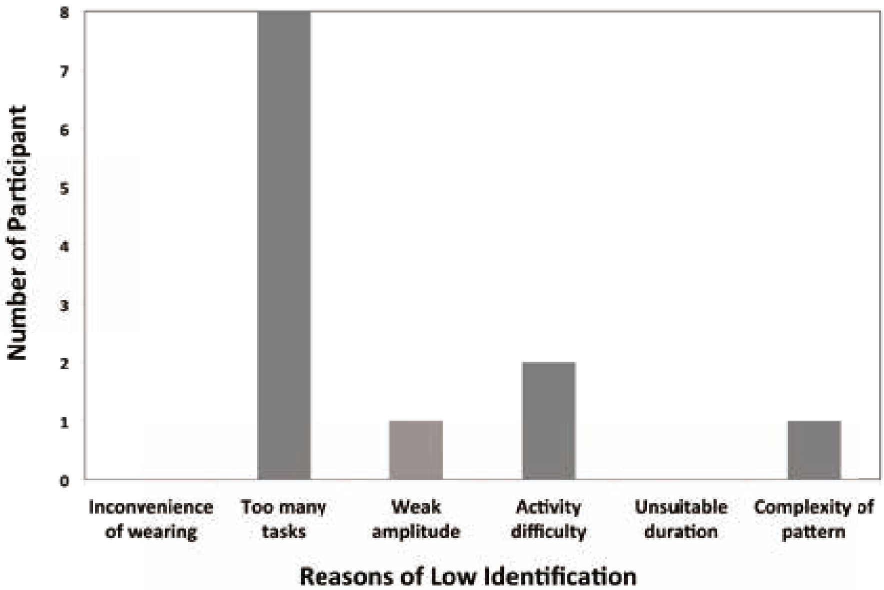
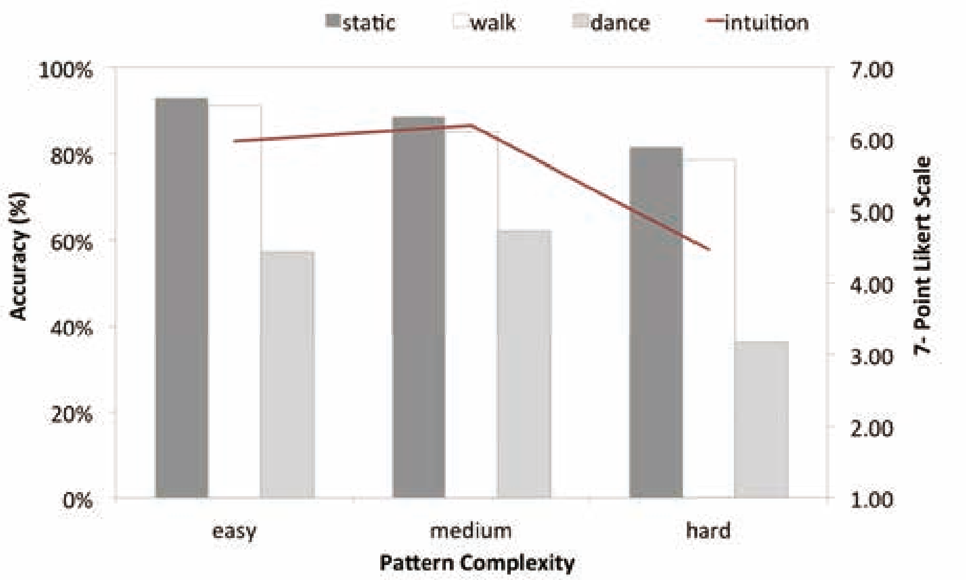
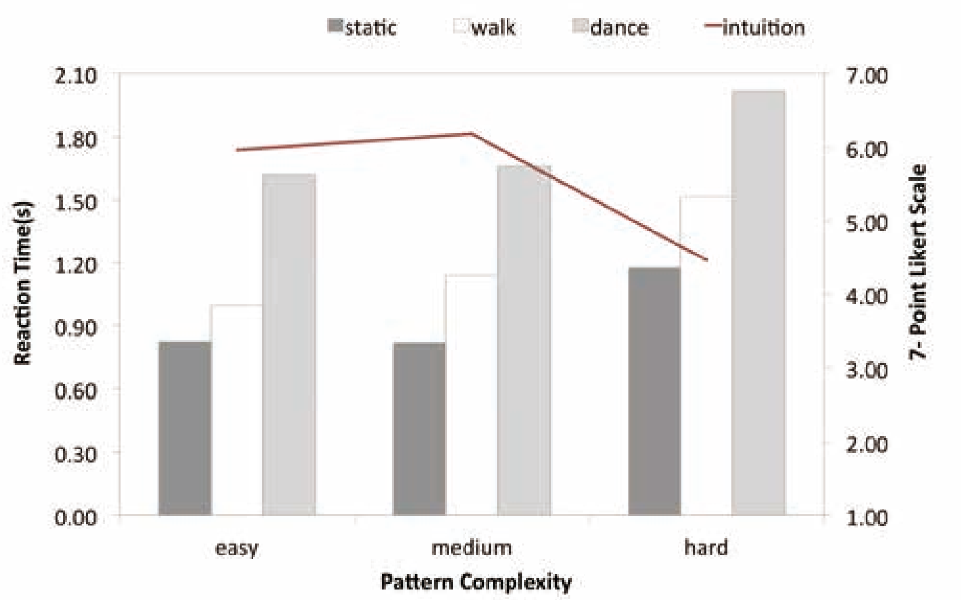


Figure 3.11 Subjective feedback of participants in Experiment 3. It is showing the options selected as reasons that the identification task was challenging. The fully filled bars are cognitive reasons and the light gray bars are physical reasons. The most frequently chosen reason concerns the cognitive load of multi-tasking.

In addition, I found that an intuitive relationship between tactile icons and the meanings they map to is also important to affect identification performance. From Figure 3.12 it can be observed that the more intuitive participants feel the mapping between tactile icons and poses is, the higher the accuracy they acquired and the shorter reaction times were that they achieved.



(a) Relationship between subjective intuition and experimental identification performance on accuracy.



(b) Relationship between subjective intuition and experimental identification performance on reaction time.

Figure 3.12 Relationships between subjective intuition and experimental identification performance on accuracy and reaction time. The intuition between tactile patterns and corresponding poses was accessed based on the subjective feedbacks. (a) The relationship between the perceived intuitions of mapping among tactile patterns (red line) and the complexity of tactile patterns on accuracy of identification (bars) is shown. Generally, it reveals that the perceived intuition is positively associated with the complexity of tactile patterns and the accuracy of identification (the more complicated the tactile patterns are, the lower the perceived intuition and accuracy are). (b) The relationship between the perceived intuition of mapping among tactile patterns (red line) and the complexity of tactile patterns on reaction time of identification (bars) is shown. Generally the perceived intuition is positively associated with tactile pattern complexity whereas it is negatively associated with the reaction time of identification.

In summary, there is a significant level if impact between pattern complexity and physical activity on tactile identification performance. Furthermore, I found a conditional interaction between physical activity and pattern complexity on tactile identification accuracy. Finally, subjective feedback revealed that the major interference of identification performance is the cognitive loads to multi-tasking. Alternatively, the comfort levels of the wearable device affects identification performance to a certain extend.

4. Chapter 4 GENERAL SUMMARY

Three experiments were conducted to investigate the associations between tactile identification performance and the complexities of tasks during both the encoding process (tactile pattern) and the decoding process (physical activity). This chapter consists of two main sections. The first deals with the results from Chapter 3 by discussing confirmation of the association between the effectiveness of tactile identification performance and factors (physical activity and pattern complexity), and how potential effects from variables such as the cognitive workload of tasks, the method for mapping tactile icons' meanings, and the suitable circumstances for tactile communications, affect tactile identification performance. The second section contains my final conclusions and states the major contributions of this thesis; finally, the study's limitations and suggestions for future work are discussed, for the benefit of follow-up studies.

4.1. Discussion

The overall impacts of physical activity conditions on tactile identification performance have been illustrated in Experiment 1. Identification was significantly less accurate when participants were moving than that when they remained static (**H1-2)**.

In Experiment 2, I first upgraded the hardware by confirming the location of the tactile device, by reverting back to a wireless version, and by decreasing the number of actuators. In particular, the number of tactile icons was reduced from 15 to 12 by consolidating similar pattern pairs. Moreover, it was confirmed that there are no significant differences among different participants with respect to their general sensitivity to tactile stimuli **(H2-1)**. Moreover, it was shown that different tactile icons produce significantly different results regarding how accurately they are identified **(H2-2a),** but not for how quickly they are identified **(H2-2b)**. On the basis of all these findings, the 12 specific tactile patterns were divided into three complexity levels with disparate accuracies of identification, whereas the reaction time was used as an auxiliary factor, given that accuracy of identification and reaction time are significantly negatively correlated **(H2-3)**.

Experiment 3 further confirmed the validity of such a classification approach. Overall, the main hypotheses for Experiment 3 were all supported: physical activity levels independently affected both identification accuracy **(H1a)** and reaction time **(H1b)**. Most importantly, physical activity was found to interact with pattern complexity during tactile identification performance **(H2a)**, whereas no significant interaction was found in reaction time measurements **(H2b)**. The relationship between pattern complexity and the identification performance (accuracy and reaction time) found in this thesis strengthens my proposal to use accuracy of identification as a classification tool.

Subjective feedback further indicated that participants did not attribute task difficulty to the physical activity per se, but to the act of having to identify the patterns while preparing to make their physical movements.

Based on the results reviewed above, I summarize the main points of these findings in the seven following conclusions:

Task complexity affects performance in tactile identification. The results from Experiment 3 confirmed that Wood's task complexity model (1986) can be applied to tactile identification performances. In particular, this work confirms the crucial influence of physical activities on tactile identification, which is consistent with the previous study by Pakkanen et al. (2008). Moreover, it highlights the necessity to shift our focus from how to separate encoding and decoding processes, to how they interact with each other and influence the effectiveness of tactile identification, especially for more complex physical activities such as dance.

Identification performance under diverse physical activity conditions varies significantly. My results (Table 3.9(b)) revealed that there is no significant difference between static and walking activities in terms of identification accuracy, which agrees with the results from Edwards et al. (2009). However, I did find a significant difference regarding reaction time. More importantly, both activities show significant differences from dancing activity in both accuracy and reaction time (all $\rho < .001$), which strongly supports the task complexity model (Wood, 1986). I postulate that this may be due to the far lower cognitive demands of rhythmic activities such as walking, jogging, or swimming. Such activities are repetitive activities, and do not require the participants to plan for them or to remember long sequences. My results (Figure 3.9) indicate that even when experienced dancers perform a familiar sequence of movements, the level of attention demanded is sufficient to reduce their performance in the identification of complex patterns: this finding has many implications for tactile display-based real-world applications.

Pattern is an irreducible unit per se. I classified the patterns empirically, based on identification accuracy as found in Experiment 2 (Figure 3.7), and found that no single characteristic (element spacing, number of elements in a pattern sequence) was solely responsible for pattern complexity. However, I did find that the diagonal pattern 9 produced significantly lower accuracy than all other patterns. This finding is consistent with Tan et al.'s conclusion (2003) that diagonal patterns are more difficult to identify than non-diagonal patterns. I conclude that complexity, at least as a determinant of identification accuracy, is a result of the combined influences from various characteristics, rather than arising from any single characteristic Results from Bach-Y-Rita (2004) also supported this conclusion. He compared his experimental results, which indicated that people perceive vibro-tactile patterns with a high degree of accuracy when wearing a matrix of 400 points on the back, with those of an earlier study by Geldard (1966), which showed that people are able to discriminate between 6 and 14 simultaneous vibro-tactile stimulus points. As a result, Bach-Y-Rita (2004) concluded that pattern perception capability is the primary factor, rather than any specific properties of tactile stimuli. Similarly, Paneel et al. (2013) suggested that to enable the correct perception of tactile patterns, the layout of haptic patterns should not be too similar, suggesting that a tactile pattern is a unique unit for perception, rather than a combination of the characteristics of stimuli.

Characteristics of tactile stimuli have a greater impact on detection than on identification. Numerous previous studies have revealed the relationships between the attributes of vibro-tactile icons and their detection performance, mostly known as "notification" (Alvina et al., 2015; Frid, 2014; Roumen et al., 2015; Tam et al., 2013; Wang et al., 2016). The results in Experiment 1 indicate a slightly significant (ρ = .050) difference between the tactile attributes and the accuracy of identification, which is only partially consistent with these previous findings. One possible reason may be that the detection of vibro-tactile stimuli is more physically driven, and is based on the sensitivity of human skin. However, the identification of vibro-tactile icons is more cognitively driven, because the mapping process requires more cognitive workload from people. Hence, considering this together with the previous point, I recommend that when considering the efficacy of vibro-tactile detection, it is necessary to combine all characteristics of tactile stimuli. However, for vibro-tactile identification, the effectiveness is determined by the tactile icon/patter as a unit *per se*.

Accuracy ranks as the primary indicator for the classification of complexity. From the results of Experiment 2 (Table 3.9(a)), it was found that accuracy is more sensitive than reaction time to pattern complexity. This may be due in part to the difficulty in defining reaction times for patterns of different duration, although reaction time is also less sensitive than accuracy to physical activity differences. The plausibility of this interpretation was also confirmed in Experiment 3. However, the results indicate that the complexity of patterns fluctuated slightly. This finding shows that the complexity of vibro-tactile icons is more subjective, which suggests that the definition of vibro-tactile icon complexity should be based on the circumstances in which they are used.

Cognitive workload influences tactile identification. The results of subjective feedback suggest that the decrease in tactile identification performance is due to the cognitive workload of multi-tasking, which is consistent with Wood's task complexity model (1986), and with Andrew et al.'s finding (2005) that distractors increase the workload in tactile identification tasks and decrease accuracy. Furthermore, Chen et al. (2016)

specifically explained that accuracy decreases dramatically under dancing activity, as it demands a higher cognitive load to translate the tactile information into appropriate movements: this finding agrees with my results from the subjective feedbacks. Another possible reason may be the specific technical skill levels required. Rosenthal et al. (2011) found that experienced dancers are more willing to accept this sensory augmentation than non-experienced participants, because experienced dancers only need to focus on haptic patterns and execute the corresponding movements. In contrast, non-experienced participants have to pay attention to both haptic patterns and dance movements, which increases their cognitive workload to a certain degree.

The mapping strategy of identification plays a vital role. As shown in Figure 3.12, it is of great interest that there is a positive association between perceived intuition of the mapping and the accuracy of identification, highlighting that the mapping strategy is relatively important, and that the intuitive links between tactile icons and the corresponding meanings should not be too low. Another previous study (Frid, 2014) also suggested that vibro-tactile cues should be intuitively mapped to information; however that study did not provide additional results to support this suggestion. Therefore, when including factors from both the encoding and decoding processes, the methods used to connect both stages also have a vital effect on the effectiveness of the performance, and thus their importance should not be underestimated in future studies.

4.2. Conclusion

The purpose of this thesis was to examine the association between the complexity of factors (tactile patterns and physical activities) and the identification performance for vibro-tactile information. I started by reviewing theoretical concepts of haptic communication with reference to the encoding-decoding communication model, from non-verbal communication to approaches to communication that are mediated by computer. Next, I presented a more specific review of the theoretical framework selected for this thesis, i.e., the task complexity model, and introduced the main terms in this model, which assisted the formulation of the main hypotheses of this thesis. Following these sections, the interactions between signal complexity and physical activity in vibro-tactile identification were examined in three experiments, using the task complexity model. Main effects from both variables (pattern complexity, physical activity) were observed in both accuracy and reaction time. The results showed the existence of a conditional interaction between pattern complexity and physical activity. Subjective feedbacks collected from Experiment 3 correlate well with the experimental results, further suggesting that the key reason for tactile identification interference is cognitive overload, especially in more demanding physical activities such as dancing. My findings shed light on how physical activity and cognitive load interact and may influence performance in real-world scenarios. The strategy of mapping vibro-tactile icons to a corresponding meaning for communication is also fundamental to the efficacy of identification, and thus should not be ignored.

4.2.1. Contribution

Although numerous studies have investigated haptic identification and communication from different perspectives and with different goals, little research attention has been directed to the question of how physical activity affects identification, and how it interacts with the effects of the tactile stimuli themselves. The main contributions of this thesis are the following three findings:

- Tactile patterns need to be considered as a whole, rather than as a set of independent individual characteristics, when designing them or classifying their complexity.
- In tactile identification, there exists a conditional interaction between the pattern complexity of tactile signals and physical activity.
- The cognitive workload of multi-tasking was reported by subjects to cause interference with tactile identification performance.

4.2.2. Limitations

Although this thesis provides important findings that bridge the remaining gaps in the tactile communication literature, having examined the potential associations between the complexity of factors and the identification performance for vibro-tactile information, nevertheless a few limitations must be considered.

The first main issue concerns the approach applied in this thesis to collect the reaction times in Experiment 2 and Experiment 3. It is important to note that recording the reaction time for identification without latency or variances is never easy, because our neural system has to process and decode what we detect in an identification task through several and highly variable sequential processes before we can perform any actions in response. Although I emphasized to all the subjects during the training sections that they should press the button as soon as they could confirm their identification of patterns with certainty, it is still inevitable that the reaction times for specific identification performances were confounded by other factors, such as the reaction interval involved in the pressing activity, the reaction interval in processing by the neural system, as well as the different durations of the signals themselves. The variance in the measurements of reaction time is also reflected in the results of both experiments, in that the reaction time fluctuated more than accuracy, even for the same participant. This highlights that reaction time is less sensitive or reliable as a benchmark for the classification of pattern complexity.

Another issue is the limited sample size of the experiments, due to constraints in both time and funding. The relatively small sample size may have resulted in unexpectedly high variances in the results, which are quite likely to contribute to masking the authentic relationships between the complexity of factors and the identification performance for vibro-tactile information in this thesis. However, statistically significant relationships and interactions are nevertheless observed, and these can form the basis of further work in identifying tactile display strategies in the context of physical activity.

4.2.3. Future Work

Given that the current classification of task complexity that was used in Experiment 2 and Experiment 3 is based on only three categorical levels, future studies should focus on the interactions between more continuous complexity levels and tactile identification performance. Secondly, my findings would be strengthened by a larger sample size, and by conducting experiments in a wider variety of realistic situations. A larger sample size will be utilized in future studies, to better control the learning effects and the random effects from participants. Thirdly, ongoing work is now exploring possible applications, such as interpersonal (multi-way) haptic communication to allow synchronization between individuals during physical activity.

BIBLIOGRAPHY

Allen, M., Gluck, J., MacLean, K., & Tang, E. (2005). An initial usability assessment for symbolic haptic rendering of music parameters. In *Proceedings of the 7th International Conference on Multimodal Interfaces* (pp. 244–251). ACM.

Alvina, J., Zhao, S., Perrault, S., Azh, M., Roumen, T., & Fjeld, M. (2015). OmniVib: Towards cross-body spatiotemporal vibrotactile notifications for mobile phones. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2487–2496). New York, NY, USA: ACM.

Antfolk, C., Cipriani, C., Carrozza, M. C., Balkenius, C., Björkman, A., Lundborg, G., … Sebelius, F. (2013). Transfer of tactile input from an artificial hand to the forearm: Experiments in amputees and able-bodied volunteers. *Disability and Rehabilitation: Assistive Technology*, *8*(3), 249–254.

Bach-Y-Rita, P. (2004). Tactile sensory substitution studies. *Annals of the New York Academy of Sciences*, *1013*(1), 83–91.

Bliss, J. C., Katcher, M. H., Rogers, C. H., & Shepard, R. P. (1970). Optical-to-tactile image conversion for the blind. *IEEE Transactions on Man-Machine Systems*, *11*(1), 58–65.

Bonanni, L., Vaucelle, C., Lieberman, J., & Zuckerman, O. (2006). TapTap: A haptic wearable for asynchronous distributed touch therapy. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems* (pp. 580–585). New York, NY, USA: ACM.

Bouwer, A., Holland, S., & Dalgleish, M. (2013). The Haptic Bracelets: Learning Multi-limb Rhythm Skills from Haptic Stimuli While Reading. In S. Holland, K. Wilkie, P. Mulholland, & A. Seago (Eds.), *Music and Human-computer*

Interaction (pp. 101–122). Springer London.

Brown, L. M. (2007). *Tactons: Structured vibrotactile messages for non-visual information display* (Doctoral dissertation). Retrieved from http://www.dcs.glasgow.ac.uk/~stephen/papers/theses/lorna_brown_thesis.pdf

Carcedo, M. G., Chua, S. H., Perrault, S., Wozniak, P., Joshi, R., Obaid, M., … Zhao, S. (2016). HaptiColor: Interpolating color information as haptic feedback to assist the colorblind. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 3572–3583). ACM.

Chan, A., MacLean, K., & McGrenere, J. (2005). *Learning and identifying haptic icons under workload* (No. 2004–15). IEEE. Retrieved from http://www.cs.ubc.ca/labs/lci/papers/docs2004/HapticIconWorkload-TR.pdf

Chen, C. Y., Chen, Y. Y., Chung, Y. J., & Yu, N. H. (2016). Motion guidance sleeve: Guiding the forearm rotation through external artificial muscles. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 3272–3276). New York, NY, USA: ACM.

Chen, D. K., Anderson, I. A., Walker, C. G., & Besier, T. F. (2016). Lower extremity lateral skin stretch perception for haptic feedback. *IEEE Transactions on Haptics*, *9*(1), 62–68.

Chen, H. Y., Santos, J., Graves, M., Kim, K., & Tan, H. Z. (2008). Tactor localization at the wrist. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 209–218). Springer.

Chen, T. L., Bhattacharjee, T., McKay, J. L., Borinski, J. E., Hackney, M. E., Ting, L. H., & Kemp, C. C. (2015). Evaluation by expert dancers of a robot that performs partnered stepping via haptic interaction. *PLoS ONE*, *10*(5), 1–24.

Cheok, A. D. (2010). Huggy pajama: A remote interactive touch and hugging system. In *Art and Technology of Entertainment Computing and Communication* (pp. 161–194). Springer London.

Choi, S., & Kuchenbecker, K. J. (2013). Vibrotactile display: Perception, technology, and applications. *Proceedings of the IEEE*, *101*(9), 2093–2104.

Cholewiak, R. W. (1979). Spatial factors in the perceived intensity of vibrotactile patterns. *Sensory Processes*.

Cosgun, A., Sisbot, E. A., & Christensen, H. I. (2014). Guidance for human navigation using a vibro-tactile belt interface and robot-like motion planning. In *2014 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 6350–6355). IEEE.

Craig, J. C., & Sherrick, C. E. (1982). Dynamic Tactile Displays. In *Tactual perception: A sourcebook* (p. 209).

CyberTouch. (n.d.). Retrieved from http://www.immersion.fr/en/cybertouch/

Debats, N. B., Rohde, M., Glowania, C., Oppenborn, A., & Ernst, M. O. (2016). The Influence of Motor Task on Tactile Suppression During Action. In F. Bello, H. Kajimoto, & Y. Visell (Eds.), *Haptics: Perception, Devices, Control, and Applications* (pp. 158–167). Springer International Publishing.

Doug Roberts. (2014, February 27). What vibration frequency is best for haptic feedback? [Blog]. Retrieved from http://www.precisionmicrodrives.com/tech-blog/2014/02/27/what-vibration-frequency-is-best-for-haptic-feedback-1

Edwards, N., Rosenthal, J., Moberly, D., Lindsay, J., Blair, K., Krishna, S., … Panchanathan, S. (2009). A pragmatic approach to the design and implementation of a vibrotactile belt and its applications. In *Haptic Audio Visual Environments and Games, 2009. HAVE 2009. IEEE International Workshop on* (pp. 13–18). IEEE.

Enriquez, M. J. (2008). *Design of haptic signals for information communication in everyday environments* (Doctoral dissertation). Retrieved from http://142.103.6.5/grads/resources/thesis/May09/Enriquez_Mario.pdf

Enriquez, M., MacLean, K., & Chita, C. (2006). Haptic phonemes: Basic building blocks of haptic communication. In *Proceedings of the 8th International Conference on Multimodal Interfaces* (pp. 302–309). New York, NY, USA: ACM.

Eskildsen, P., Morris, A., Collins, C. C., & Bach-y-Rita, P. (1969). Simultaneous and successive cutaneous two-point thresholds for vibration. *Psychonomic Science*, *14*(4), 146–147.

Frid, E. (2014). *Perceptual characterization of a tactile display for live electronic music performance: Designing a vibrotactile notification tool for the CIRMMT live electronics framework (CLEF)* (Master's Thesis). Retrieved from http://www.diva-portal.org/smash/get/diva2:783792/FULLTEXT01.pdf

Gall, S., Beins, B., & Feldman, J. (2001). Psychophysics. In *The Gale Encyclopedia of Psychology*. Gale.

Geldard, F. A. (1957). Adventures in tactile literacy. *American Psychologist*, *12*(3), 115.

Geldard, F. A. (1960). Some Neglected Possibilities of Communication. *Science*, *131*(3413), 1583–1588.

Geldard, F. A. (1966). Cutaneous coding of optical signals: the optohapt. *Perception & Psychophysics*, *1*(5), 377–381.

Gescheider, G. A. (1974). Effects of signal probability on vibrotactile signal recognition. *Perceptual and Motor Skills*, *38*(1), 15–23.

Goff, G. D. (1967). Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology*, *74*(2p1), 294.

Gomez-Rodriguez, M., Peters, J., Hill, J., Schölkopf, B., Gharabaghi, A., & Grosse-Wentrup, M. (2011). Closing the sensorimotor loop: Haptic feedback facilitates decoding of motor imagery. *Journal of Neural Engineering*, *8*(3), 36005.

Hackman, J. R. (1969). Toward understanding the role of tasks in behavioral research. *Acta Psychologica*, *31*, 97–128.

Hale, K. S., & Stanney, K. M. (2004). Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations. *IEEE Computer Graphics and Applications*, *24*(2), 33–39.

Hall, S. (1980). Encoding/decoding. In *Culture, Media, Language* (pp. 128–138). Retrieved from http://www.hu.mtu.edu/~jdslack/readings/CSReadings/Hall_Encoding-n-Decoding.pdf

Hatzfeld, C., & Kern, T. A. (Eds.). (2009). *Engineering haptic devices: A beginner's guide for engineers* (2nd ed.). Springer Science & Business Media.

Heller, M. A., & Schiff, W. (1991). *The psychology of touch*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Hertenstein, M. J., Keltner, D., App, B., Bulleit, B. A., & Jaskolka, A. R. (2006). Touch communicates distinct emotions. *Emotion*, *6*(3), 528–533.

Holland, S., Bouwer, A. J., Dalgelish, M., & Hurtig, T. M. (2010). Feeling the beat where it counts: Fostering multi-limb rhythm skills with the haptic drum kit. In *Proceedings of the 4th International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 21–28). ACM.

Huisman, G., Frederiks, A. D., Van Dijk, B., Hevlen, D., & Kröse, B. (2013). The TaSST: Tactile sleeve for social touch. In *World Haptics Conference (WHC), 2013* (pp. 211–216). IEEE.

Jeong, G. Y., & Yu, K. H. (2016). Multi-section sensing and vibrotactile perception for walking guide of visually impaired person. *Sensors*, *16*(7), 1070.

John December. (1997). Notes on defining of computer-mediated communication. Retrieved from http://www.december.com/cmc/mag/1997/jan/december.html

Jones, L. A., & Sarter, N. B. (2008). Tactile Displays: Guidance for Their Design and Application. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(1), 90–111.

Kaaresoja, T., & Linjama, J. (2005). Perception of short tactile pulses generated by a vibration motor in a mobile phone. In *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems World Haptics Conference* (pp. 471–472). IEEE.

Karuei, I., MacLean, K. E., Foley-Fisher, Z., MacKenzie, R., Koch, S., & El-Zohairy, M. (2011). Detecting vibrations across the body in mobile contexts. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 3267–3276). New York, NY, USA: ACM.

Kim, M., Lee, S., & Choi, S. (2012). Saliency-driven tactile effect authoring for real-time visuotactile feedback. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 258–269). Springer.

Kim, S., Hong, J., Li, K. A., Forlizzi, J., & Dey, A. K. (2012). Route Guidance Modality for Elder Driver Navigation. In J. Kay, P. Lukowicz, H. Tokuda, P. Olivier, & A. Krüger (Eds.), *Pervasive Computing* (pp. 179–196). Springer Berlin Heidelberg.

Kirkpatrick, A. E., & Douglas, S. A. (2002). Application-based evaluation of haptic interfaces. In *10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002. Proceedings* (pp. 32–39).

Kirman, J. H. (1974). Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration. *Perception & Psychophysics*, *15*(1), 1–6.

Knapp, M., & Hall, J. (2006). *Nonverbal communication in human interaction* (sixth). Thomson/Wadsworth.

Lam, A. R. (2006). *Vibrotactile pattern recognition on the torso with one and two dimensional displays* (Bachelor of science). Retrieved from http://dspace.mit.edu/bitstream/handle/1721.1/36738/77564719-MIT.pdf?sequen ce=2

Lee, J., Han, J., & Lee, G. (2015). Investigating the Information transfer efficiency of a 3x3 watch-back tactile display. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 1229–1232). New York, NY, USA: ACM.

Lee, S. C., & Starner, T. (2010). BuzzWear: Alert perception in wearable tactile displays on the wrist. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 433–442). ACM.

MacLean, K., & Enriquez, M. (2003). Perceptual design of haptic icons. In *Proc. of EuroHaptics* (pp. 351–363).

Maculewicz, J., Erkut, C., & Serafin, S. (2016). An investigation on the impact of auditory and haptic feedback on rhythmic walking interactions. *International Journal of Human-Computer Studies*, *85*, 40–46.

Matscheko, M., Ferscha, A., Riener, A., & Lehner, M. (2010). Tactor placement in wrist worn wearables. In *International Symposium on Wearable Computers (ISWC) 2010* (pp. 1–8). IEEE.

McDaniel, T., Krishna, S., Balasubramanian, V., Colbry, D., & Panchanathan, S. (2008). Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind. In *IEEE International Workshop on Haptic Audio visual Environments and Games, 2008. HAVE 2008* (pp. 13–18).

Morioka, M. (2001). *Psychophysical investigation of the perception of hand-transmitted vibration* (Doctoral dissertation). Retrieved from http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.484260

Nanayakkara, S., Taylor, E., Wyse, L., & Ong, S. H. (2009). An enhanced musical experience for the deaf: Design and evaluation of a music display and a haptic chair. In *Proceedings of the SIGCHI Conference on Human Factors in*

Computing Systems (pp. 337–346). ACM.

Ng, A. W., & Chan, A. H. (2012). Finger response times to visual, auditory and tactile modality stimuli. In *Proceedings of the International MultiConference of Engineers and Computer Scientists* (Vol. 2, pp. 1449–1454).

Oakley, I., Kim, Y., Lee, J., & Ryu, J. (2006). Determining the feasibility of forearm mounted vibrotactile displays. In *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 27–34). IEEE.

Oakley, I., Sunwoo, J., & Cho, I. Y. (2008). Pointing with fingers, hands and arms for wearable computing. In *CHI'08 Extended Abstracts on Human Factors in Computing Systems* (pp. 3255–3260). ACM.

Ofte, S. H., & Hugdahl, K. (2002). Rightleft Discrimination in Male and Female, Young and Old Subjects. *Journal of Clinical and Experimental Neuropsychology*, *24*(1), 82–92.

Pakkanen, T., Lylykangas, J., Raisamo, J., Raisamo, R., Salminen, K., Rantala, J., & Surakka, V. (2008). Perception of low-amplitude haptic stimuli when biking. In *Proceedings of the 10th International Conference on Multimodal Interfaces* (pp. 281–284). ACM.

Paneels, S., Anastassova, M., Strachan, S., Van, S. P., Sivacoumarane, S., & Bolzmacher, C. (2013). What's around me? Multi-actuator haptic feedback on the wrist. In *World Haptics Conference (WHC), 2013* (pp. 407–412).

Piateski, E., & Jones, L. (2005). Vibrotactile pattern recognition on the arm and torso. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint* (pp. 90–95). IEEE.

Pixy Ferris. (1997). What is CMC? An overview of scholarly definitions. Retrieved from http://www.december.com/cmc/mag/1997/jan/ferris.html

Post, L. J., Zompa, I. C., & Chapman, C. E. (1994). Perception of vibrotactile stimuli during motor activity in human subjects. *Experimental Brain Research*, *100*(1), 107–120.

PRECISION MICRODRIVES. (n.d.). Pico Vibe 12mm Vibration Motor - 3mm Type [Product Catalogue]. Retrieved from https://catalog.precisionmicrodrives.com/order-parts/product/312-101-12mm-vibration-motor-3mm-type

Priplata, A. A., Niemi, J. B., Harry, J. D., Lipsitz, L. A., & Collins, J. J. (2003). Vibrating insoles and balance control in elderly people. *The Lancet*, *362*(9390), 1123–1124.

Raju, B. I. (Balasundara I. (1998). Encoding and decoding of shape in tactile sensing.

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*(1), 114–125.

Roumen, T., Perrault, S. T., & Zhao, S. (2015). NotiRing: A Comparative Study of Notification Channels for Wearable Interactive Rings. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2497–2500). New York, NY, USA: ACM.

Rupert, A. H. (2000). An instrumentation solution for reducing spatial disorientation mishaps. *IEEE Engineering in Medicine and Biology Magazine*, *19*(2), 71–80.

Saddik, A. E., Orozco, M., Eid, M., & Cha, J. (2011). *Haptics technologies: bringing touch to multimedia*. Springer Science & Business Media.

Schumacher, M., Giordano, M., Wanderley, M. M., & Ferguson, S. (2013). Vibrotactile notification for live electronics performance: A prototype system. In *Proceedings of the International Symposium on Computer Music Multidisciplinary Research (CMMR)* (pp. 516–525). Retrieved from http://www.idmil.org/_media/projects/vibrofeed-livelectronics/computer_music _multidisciplinary_research_2013_schumacher.pdf

Sherrick, C. E., & Rogers, R. (1966). Apparent haptic movement. *Perception & Psychophysics*, *1*(3), 175–180.

Sofianidis, G., & Hatzitaki, V. (2015). Interpersonal Entrainment in Dancers: Contrasting Timing and Haptic Cues. *Posture, Balance, and the Brain. Sofia: Procon*, 36–44.

Song, Y., & Kim, J. (2015). Mingle: Wearable Devices for Enhancing Communications and Activities Between the Blind and Ordinary People Through a Waltz. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 367–370). New York, NY, USA: ACM.

Srikulwong, M., & O'Neill, E. (2011). A Comparative Study of Tactile Representation Techniques for Landmarks on a Wearable Device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2029–2038). New York, NY, USA: ACM.

Summers, I. R., Cooper, P. G., Wright, P., Gratton, D. A., Milnes, P., & Brown, B. H. (1997). Information from time-varying vibrotactile stimuli. *The Journal of the Acoustical Society of America*, *102*(6), 3686–3696.

Tam, D., MacLean, K. E., McGrenere, J., & Kuchenbecker, K. J. (2013). The design and field observation of a haptic notification system for timing awareness during oral presentations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1689–1698). ACM.

Tan, H. Z., Gray, R., Young, J. J., & Traylor, R. (2003). A haptic back display for attentional and directional cueing. *Haptics-E*, *3*(1), 1–20.

Tanaka, Y., Matsuoka, S., Tiest, W. M. B., Kappers, A. M. L., Minamizawa, K., & Sano, A. (2016). Frequency-Specific Masking Effect by Vibrotactile Stimulation to the Forearm. In F. Bello, H. Kajimoto, & Y. Visell (Eds.), *Haptics: Perception, Devices, Control, and Applications* (pp. 156–164). Springer International Publishing.

Ternes, D., & MacLean, K. E. (2008). Designing Large Sets of Haptic Icons with Rhythm. In M. Ferre (Ed.), *Haptics: Perception, Devices and Scenarios* (pp. 199–208). Springer Berlin Heidelberg.

Trewin, S., John, B., Richards, J., Sloan, D., Hanson, V., Bellamy, R., … Swart, C. (2012). Age-specific Predictive Models of Human Performance. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (pp. 2267–2272). New York, NY, USA: ACM.

Van Erp, J. B. (2002). Guidelines for the use of vibro-tactile displays in human computer interaction. In *Proceedings of eurohaptics* (Vol. 2002, pp. 18–22). Retrieved from http://www.eurohaptics.vision.ee.ethz.ch/2002/vanerp.pdf

Van Erp, J. B., Van Veen, H. A., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception (TAP)*, *2*(2), 106–117.

Verrillo, R. T., & Gescheider, G. A. (1992). Perception via the sense of touch. *Tactile Aids for the Hearing Impaired*, 1–36.

VideoTact. (n.d.). Retrieved from www.4thtdev.com/vidback.html

Vieira, A. I., Nogueira, D., Reis, E. de A., Rosado, M. da L., Nunes, M. V., & Castro-Caldas, A. (2016). Hand tactile discrimination, social touch and frailty criteria in elderly people: A cross sectional observational study. *Archives of Gerontology and Geriatrics*, *66*, 73–81.

Von Békésy, G. (1959). Synchronism of neural discharges and their demultiplication in pitch perception on the skin and in hearing. *The Journal of the Acoustical Society of America*, *31*(3), 338–349.

Wall, C., Weinberg, M. S., Schmidt, P. B., & Krebs, D. E. (2001). Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. *IEEE*

Transactions on Biomedical Engineering, *48*(10), 1153–1161.

Wang, Y., Millet, B., & Smith, J. L. (2014). Informing the Use of Vibrotactile Feedback for Information Communication An Analysis of User Performance across Different Vibrotactile Designs. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *58*(1), 1859–1863.

Wang, Y., Millet, B., & Smith, J. L. (2016). Designing wearable vibrotactile notifications for information communication. *International Journal of Human-Computer Studies*, *89*, 24–34.

Wang, Z., Hoelldampf, J., & Buss, M. (2007). Design and performance of a haptic data acquisition glove. In *Proceedings of the 10th Annual International Workshop on Presence* (pp. 349–357). Retrieved from https://www.researchgate.net/profile/Zheng_Wang9/publication/228452468_Design_and_performance_of_a_haptic_data_acquisition_glove/links/53f707140cf2fceacc74e8e0.pdf

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. R. Kenshalo, *The skin senses* (pp. 195–222). Springfield IL: Thomas.

Wolf, S. M. (1973). Difficulties in Right-Left Discrimination in a Normal Population. *Archives of Neurology*, *29*(2), 128–129.

Wood, R. E. (1986). Task complexity: Definition of the construct. *Organizational Behavior and Human Decision Processes*, *37*(1), 60–82.

Wozniak, P., Joshi, R., Obaid, M., Fjeld, M., & Zhao, S. (2016). HaptiColor: Interpolating Color Information As Haptic Feedback to Assist the Colorblind. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 3572–3583). New York, NY, USA: ACM.

Wright, M., Lycouris, S., Timmons, W., & Ravenscroft, J. (2012). *Choreohaptic experiments*. Retrieved from http://www.research.ed.ac.uk/portal/files/8127316/documentation_of_haptic_project.pdf

Xu, M., Wang, D., Zhang, Y., Song, J., & Wu, D. (2015). Performance of simultaneous motion and respiration control under guidance of audio-haptic cues. In *2015 IEEE World Haptics Conference (WHC)* (pp. 421–427).

Yao, L., Shi, Y., Chi, H., Ji, X., & Ying, F. (2010). Music-touch shoes: vibrotactile interface for hearing impaired dancers. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction* (pp. 275–276). ACM.

Zadeh, M. H., Wang, D., & Kubica, E. (2007). Human Factors for Designing a Haptic Interface for Interaction with a Virtual Environment. In *2007 IEEE International Workshop on Haptic, Audio and Visual Environments and Games* (pp. 21–26).

ATTACHMENT

Attachment 1. Questionnaire of Experiment 1

Questionnare of Haptic Communication Experiment

This questionnaire aims to investigate the criteria of effectiveness of nonverbal communication through haptic signals. In this questionnaire, some demographic and attitudinal information are required to be presented.

*Required

1. **Age** *

2. **Gender** *
   Mark only one oval.
   - ◯ Male
   - ◯ Female

3. **Location of wearable device** *
   Mark only one oval.
   - ◯ Back
   - ◯ Arm
   - ◯ Leg

4. **States when you are taking this experiment** *
   Mark only one oval.
   - ◯ Stable
   - ◯ Dynamic

5. **I think it's comfortable to wear this haptic device.** *
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

6. **I think it's convenient to wear this haptic device.** *
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

7. **I can observe these haptic signals easily.** *
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

8. **I can identify these haptic signals easily.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

9. **I think the intensity of haptic signals is suitable.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

10. **I think the frequency of haptic signals is suitable.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

11. **I think the duration of one signal pattern is suitable.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

12. **I think I can communicate with others nonverbally through these haptic signals easily.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Attachment 2. Questionnaire of Experiment 3

Feedback Questionnaire

This questionnaire is to get subjective feedback of both haptic device and haptic information identification from dancers who participated in this experiment. Please answer all questions below. Thanks for your cooperation.

*Required

Basic Information

1. **Participant No.** *

____

2. **Age** *

____

3. **Gender** *

Mark only one oval.

- ◯ Male
- ◯ Female

4. **Dance Experience** *

Mark only one oval.

- ◯ Less than 1 year
- ◯ 1-3 years
- ◯ More than 3 years

Device Feedback

5. **How easy was it to put on the wristlet and adjust the location of the vibration motors?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

6. **How easy was it to move while wearing the wristlet?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

7. **How comfortable was the wristlet?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely uncomfortable	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely comfortable

8. **How comfortable was the duration of vibration for each motor?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely uncomfortable	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely comfortable

9. **How lightweight was the wristlet?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely heavy	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely light

10. **How silent were the vibration motors?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Entirely noisy	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely silent

Specific Feedback

Please answer questions followed with this haptic pattern.

11. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

12. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

13. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

14. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.

19. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

20. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

21. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

22. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.

23. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

24. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

25. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

26. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely intuitive

Please answer questions followed with this haptic pattern.

27. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

28. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

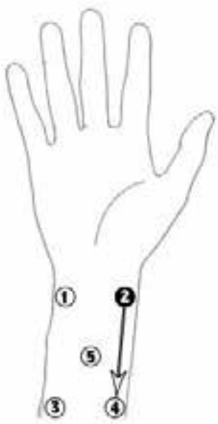
29. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

30. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.



31. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

32. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

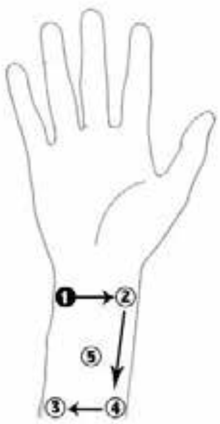
33. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

34. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely intuitive

Please answer questions followed with this haptic pattern.



35. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

36. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

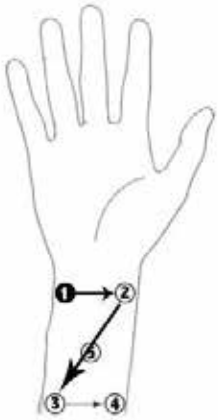
37. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

38. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely intuitive

Please answer questions followed with this haptic pattern.



39. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

40. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

41. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

42. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.

43. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

44. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

45. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

46. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.

47. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

48. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

49. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely easy

50. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Entirely intuitive

Please answer questions followed with this haptic pattern.

51. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

52. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

53. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

54. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

Please answer questions followed with this haptic pattern.

55. **How easy was it to recognize this haptic pattern corresponding to standing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

56. **How easy was it to recognize this haptic pattern corresponding to walking condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

57. **How easy was it to recognize this haptic pattern corresponding to dancing condition?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely difficult	◯	◯	◯	◯	◯	◯	◯	Entirely easy

58. **How intuitive was the mapping between the haptic pattern and the dance pose you had to perform?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely not intuitive	◯	◯	◯	◯	◯	◯	◯	Entirely intuitive

General Feedback

59. **Generally, I think haptic identification is the easiest under static condition.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely disagree	◯	◯	◯	◯	◯	◯	◯	Entirely agree

60. **Generally, I think haptic identification is the easiest under walking condition.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely disagree	◯	◯	◯	◯	◯	◯	◯	Entirely agree

61. **Generally, I think haptic identification is the easiest under dance condition.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely disagree	◯	◯	◯	◯	◯	◯	◯	Entirely agree

62. **Generally, what makes the identification hard?** *
Tick all that apply.

- [ ] The hardware is not convenient to be worn.
- [ ] There are too many tasks I should pay attention to simultaneously.
- [ ] The amplitude of vibration is weak.
- [ ] The condition is too hard to identify the haptic signal.
- [ ] The duration is un suitable.
- [ ] The haptic patterns are too hard to be identified.
- [ ] Other: ____________________

63. **If you wanted to dance in the future, how likely are you to use this system as a "cue provider"?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely unwilling	◯	◯	◯	◯	◯	◯	◯	Entirely willing

64. **Do you think others would like to use this system as a "cue provider" to perform dance?**
Mark only one oval.

	1	2	3	4	5	6	7	
Entirely disagree	◯	◯	◯	◯	◯	◯	◯	Entirely agree