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Spatial Touch in Presenting Information with Mobile Devices

ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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Abstract

Touch is essential in interaction with mobile devices such as smart phones. We access information in the devices by pressing buttons and tapping touchscreens. Yet, the devices provide little information in return via touch. Vibration alerts and feedback of touchscreen buttons are the most common uses today. From a physiological perspective, humans are capable of perceiving more complex tactile (skin) stimulation. Because we can accurately distinguish the spatial location of touch on our hand, it could also be possible to sense which part of the device is vibrating. This opens up new possibilities for human–computer interaction (HCI) research.

The aim was to study how spatial touch could be better supported in presenting information to mobile device users. In this thesis, spatial touch refers to both input and output. An example of spatial touch input is the use of a touchscreen that detects the user's point of contact. Spatial touch output can be enabled by adding multiple actuators to a device so that the actuators stimulate different areas of the user's hand.

We developed two types of applications to study the use of spatial touch. First, visually impaired users familiar with the Braille coding could read alphabetical information by sensing vibration. Second, two users could communicate emotional information by using vibration that mimicked interpersonal touch gestures. It has been envisioned that such mediated social touch could communicate emotions in a fashion similar to real touch.

We conducted user studies to empirically measure the usability of the developed applications. The results showed that alphabetical information in the form of single letters could be distinguished reliably by users familiar with Braille. Furthermore, we found evidence supporting the view that mediated touch could communicate emotional intention between people. Lastly, we learned that when stimulating the hand, linear tapping movement could be easier for users to localize as compared with the more commonly used vibration.

The findings of this thesis demonstrate that stimulating the sense of touch, and particularly different spatial locations of the user's hand, could be used more actively in presenting information with mobile devices. Touch is capable of compensating for audio and vision when they are not preferred or available for use. In addition, touch can support emotional communication between users who are physically apart.

Acknowledgements

Contents

List of publications

This thesis consists of a summary and the following original publications, reproduced here by permission.

I. Rantala, J., Raisamo, R., Lylykangas, J., Surakka, V., Raisamo, J., Salminen, K., Pakkanen, T., & Hippula, A. (2009). Methods for presenting Braille characters on a mobile device with a touchscreen and tactile feedback. *IEEE Transactions on Haptics*, 2(1), 28–39. doi:10.1109/TOH.2009.3   91

II. Rantala, J., Myllymaa, K., Raisamo, R., Lylykangas, J., Surakka, V., Shull, P., & Cutkosky, M. (2011). Presenting spatial tactile messages with a hand-held device. In *Proceedings of IEEE World Haptics Conference 2011 (WHC '11)*, 101–106. Washington, DC, USA: IEEE. doi:10.1109/WHC.2011.5945469   105

III. Rantala, J., Raisamo, R., Lylykangas, J., Ahmaniemi, T., Raisamo, J., Rantala, J., Mäkelä, K., Salminen, K., & Surakka, V. (2011). The role of gesture types and spatial feedback in haptic communication. *IEEE Transactions on Haptics*, 4(4), 295–306. doi:10.1109/TOH.2011.4   113

IV. Rantala, J., Salminen, K., Raisamo, R., & Surakka, V. (2013). Touch gestures in communicating emotional intention via vibrotactile stimulation. *International Journal of Human-Computer Studies*, 71(6), 679–690. doi:10.1016/j.ijhcs.2013.02.004   127

V. Rantala, J., & Raisamo, R. (2014). Preferences for touch gestures in audio-tactile communication. In *Proceedings of IEEE Haptics Symposium 2014 (HAPTICS '14)*, 247–250. Washington, DC, USA: IEEE. doi:10.1109/HAPTICS.2014.6775462   141

Author's Contribution to the Publications

Each publication in this thesis was co-authored, as the research was carried out in collaboration between several people. The collaboration took place in different stages of the research, but the present author was the main author in all publications and wrote the first draft of each publication. We used a donated hardware prototype for Study I, and the prototype of Study II was implemented by Kalle Myllymaa. The third prototype, used in Studies III–V, was implemented by Teemu Ahmaniemi, Jyri Rantala, and Kalle Mäkelä. The present author was responsible for designing the studies, implementing the software setups, and conducting the user experiments.
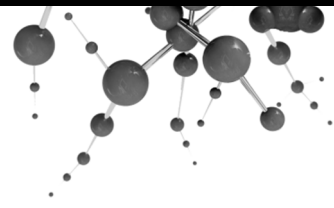
1 Introduction

Millions of people use touch-operated mobile devices such as smart phones every day. The devices sense button presses and touchscreen taps in order to provide us with the information we desire. Although touch is usually essential in providing input and controlling the devices, information content is presented mainly via visual and auditory modalities (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004). For example, we use our sight in reading text and our hearing in talking with each other during phone calls. There are, however, situations when the visual and auditory modalities are not preferred or ideal for presenting information to the user. Situationally induced impairments and disabilities (Sears, Lin, Jacko, & Xiao, 2003) can arise in everyday use, for example, when trying to look at the display of a mobile device when walking. In more severe cases, permanent visual impairments can result in complete loss of sight. Furthermore, the use of auditory information may not be socially acceptable in some situations, such as in a work meeting. In a noisy environment, it can be impossible to hear any type of auditory information.

Given that mobile devices are typically held in the hand, an alternative way to communicate information to the user would be to stimulate the user's sense of touch. Today, many mobile devices use vibration to inform users of incoming phone calls and messages. Another common use is to provide a short vibration when a user presses virtual buttons on a touchscreen device. This type of stimulation is usually created by using small vibration motors that vibrate the whole device. Because of the large vibrating area, the stimulation is generally easy for a user to perceive, and it is suitable especially for alerts that aim at grabbing the user's attention. Such stimulation can be felt even when the device is not in active use (e.g., in a pocket).

An alternative approach to vibrating the whole device would be to stimulate only certain areas of the user's hand. Hands are one of the most touch sensitive areas on the human body, and different locations of touch can be differentiated very accurately (Weinstein, 1968). For instance, the location of a fly walking on our hand can be detected due to the spatial sensitivity of human skin. A simple solution for mimicking this in mobile interaction would be to position several vibration motors to a device so that different areas of the user's hand could be stimulated selectively. Such stimulation could possibly allow for more freedom for interaction design and enable new ways to communicate information via touch.

1.1 OBJECTIVE

The research question of this thesis was to investigate **how spatial touch could be better supported in presenting information to mobile device users.** A central aspect in studying touch is to acknowledge its bi-directional nature in both manipulating and feeling things in our environment. In an attempt to take into account both uses, this thesis defines *spatial touch* as interaction that utilizes several spatially distributed locations of touch input and/or output. This is further illustrated in Figure 1, which presents an interaction space consisting of four different input and output combinations.
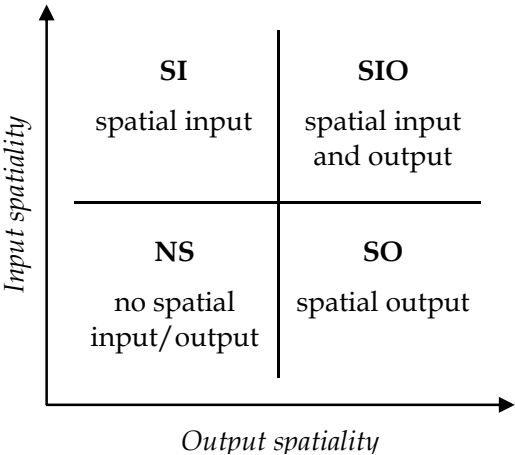
Figure 1. The interaction space of spatial touch consisting of possible input and output types.

The four different areas of the interaction space can be better understood by considering representative examples. An example use case with no spatial input or output (NS) is an alert that uses a single stimulation source, such as a vibration motor, and is triggered without explicit user input. This is the case with commonly used notifications of incoming calls or messages. Typing with a typical touchscreen keyboard falls under spatial input (SI), when the user gets vibration feedback of key presses. The input is dependent on the spatial location of touch, and the output is presented to the whole device using a single stimulation source. Despite

the single stimulation source, there can still be an illusion of spatial output, as users often perceive the feedback to be associated with the particular key they are touching.

The quadrants on the right side of the interaction space are less common in current interaction with mobile devices. Spatial output (SO) requires a device with several stimulation sources. This could be used, for example, for providing navigation cues that a user would sense through the sides of the device. In this case, the user would not need to provide any spatial input to feel the stimulation. Finally, spatial input and output (SIO) combines spatial touch input with several stimulation sources. An example of this could be a touchscreen device that senses the location of touch input and simultaneously presents tactile feedback to the user's hand on the very same location underneath the screen. This could essentially create an illusion that the user is touching his or her hand directly instead of touching the screen. In this thesis, the focus was on the last three interaction types that utilize either spatial input or spatial output or both (SI, SO, and SIO).

1.2 CONTEXT OF THE RESEARCH

This thesis builds upon knowledge of the human sense of touch and especially of the cutaneous or tactile sense. The tactile sense refers to sensory information derived from cutaneous input (Lederman, 1997). In practice, the input takes place via mechanoreceptors in the skin that are responsible, for example, for distinguishing between different textures when we explore surfaces or objects with our hands. By understanding the characteristics of human tactile sensing, it is possible to design ways to stimulate the skin receptors for communication purposes. Essentially, the characteristics of our tactile sense set the boundaries for communicating information; in an ideal case, the capabilities of technology would match those of our sensory system.

Researchers in the fields of human–computer interaction (HCI) and haptics have started to explore how the tactile sense could be utilized as an information transmission channel. Brewster and Brown (2004) defined tactons, or tactile icons, as "structured, abstract messages that can be used to communicate messages non-visually". They suggested that mechanical stimulation such as vibration could be varied by using parameters of frequency, amplitude, waveform, duration, rhythm, and spatial body location. Stimulation created with different parameters could then be assigned with specific information content. Using the definition of tactons, the current work explored ways to communicate information by using the spatial location of tactile stimulation as one parameter. Because the emphasis of this work was on interaction with handheld mobile devices, the spatial location of stimulation was varied only within the hand area.

To understand how spatial touch could be used in presenting information, it is convenient to start by considering the possible application types. MacLean (2009) divided haptic and tactile applications into three main categories according to their social aspects: *individual*, *shared*, and *public*. Applications designed for individual use present information to a single user. For instance, upon a forthcoming calendar event, a vibration pattern could grab the user's attention and inform of the type of meeting. Shared applications allow multiple users to interact with each other using touch. In the case of mobile devices, one intuitive example would be to use touch for interpersonal communication. Two users could feel the same touch stimulation via their devices. The last application type, public, is generally less suitable for mobile interaction because handheld devices are often perceived as private and rarely situated in public spaces. Thus, this work concentrated on studying the spatiality of touch in the contexts of individual and shared applications. Our motivation to incorporate the two contexts into the thesis was to get a more comprehensive understanding of the different uses of spatial touch.

The first part of this thesis focused mainly on studying spatial input in presenting information to an individual user. In this application field, it is typical that researchers have designed a set of touch stimuli and assigned specific information content to them. This was the case with many of the first touch communication systems that were designed primarily for sensory substitution (e.g., Gault, 1927; Geldard, 1957; Linvill & Bliss, 1966). The systems presented alphabetical and numerical information to users with visual and/or hearing impairments. More recently, the introduction of mobile technology and the possibility to incorporate tactile actuators to handheld devices has resulted in new uses. Tactons can be used to present information such as alerts (Brown, Brewster, & Purchase, 2006; Brown & Kaaresoja, 2006), key press confirmations (Hoggan, Brewster, & Johnston, 2008), and directions (Yatani & Truong, 2009). At the same time, rather less attention has been paid to presenting information to special user groups. The need for alternative ways to access alphabetical and numerical information still exists today with mobile devices. Therefore, the goal was to study how spatial touch could be used in presenting alphabetical information to visually impaired users.

The latter part of the thesis focused on spatial input and output in the context of shared applications. These applications typically give the users an active role in the interaction so that they can both initiate and sense touch. This is related to research on the use of touch in everyday interaction between people. We use touch, for example, for stroking, caressing, shaking hands, and patting on the shoulder. These are some examples of the vast number of gestures that people use in interpersonal touch communication (Hertenstein, Keltner, App, Bulleit, & Jaskolka, 2006; Hertenstein, Holmes, McCullough, & Keltner, 2009). In addition, it has

been shown that interpersonal touch is used most often by people who have emotional ties (e.g., McDaniel & Andersen, 1998). Touch can even communicate distinct emotions between people (Hertenstein, Keltner, et al., 2006; Hertenstein et al., 2009). Motivated by this, researchers in the fields of HCI and haptics have investigated whether touch mediated via technological means could be perceived similarly to a non-mediated touch (e.g., Haans, de Nood, & IJsselsteijn, 2007). With appropriate technology, some characteristics of human touch, such as intensity and duration, can be sensed and mediated to a remote device that replicates the touches using tactile technology (e.g., Chang, O'Modhrain, Jacob, Gunther, & Ishii, 2002). Our work continued this line of research. We focused on sensing and replicating the spatial aspects of touch gestures. In particular, we evaluated the use of gestures in mediating emotional intention between people.

1.3 METHODOLOGY

The research reported in this thesis was both constructive and empirical. In the beginning of each individual study, a prototype device was built or selected depending on the desired tactile stimulation and application type. This was followed by iterative hardware and software development where pilot tests were used to ensure the general feasibility of the interaction methods.

The next step was to evaluate whether a particular device and interaction method could successfully communicate the intended information content to potential users. For this purpose, experiments were carried out with volunteer participants. All the experiments reported in this thesis were conducted in a laboratory environment. This approach was chosen because we were primarily interested in how effectively information can be presented to the participants, and assessing this was easier in a controlled setting.

Both quantitative and qualitative research methods were applied. The main quantitative measure was the success rate of interpreting the intended information content. In general, the requirement for any meaningful communication is that the receiver understands the meaning of information. The success rate of communication is a key measure that has been used in a range of communication studies (e.g., Brown et al., 2005; Hoggan & Brewster, 2007; Levesque, Pasquero, & Hayward, 2007; Smith & MacLean, 2007). From the qualitative viewpoint, we were interested in how participants experienced the use of tactile stimulation. Subjective rating scales were applied to measure the subjective aspects of interaction. In addition, post-experimental interviews were carried out to gather further feedback.

1.4 STRUCTURE

This thesis consists of a summary and five individual research articles published in three peer-reviewed international journals and two conferences. Chapter 1 introduces the main objectives of the work, presents the contexts of the individual studies, and briefly introduces the used methods. Chapter 2 then provides information on the sense of touch, and this information is used as a basis for the work carried out in this thesis. Chapter 3 takes a look at early communication systems that have been influential in later development of mobile systems. These systems are discussed in Chapter 4, which introduces different parameters for coding information and also presents tactile actuator technologies suitable for mobile devices. It is good to note that the research discussed in Chapter 4 focuses primarily on presenting information to an individual. For example, textual information read via tactile stimulation is presented to a particular person. This differs from using shared interfaces for interpersonal communication, which is the focus of Chapter 5. In particular, Chapter 5 studies how touch mediated via technological means could be used in communicating emotional information. Chapter 6 provides a more detailed description of the used research methodologies. Chapter 7 introduces the five original research articles and their results. In Chapter 8, the main findings of the articles are evaluated from the perspective of previous HCI and haptics research. The thesis closes with Chapter 9, which briefly summarizes the contributions of the work.
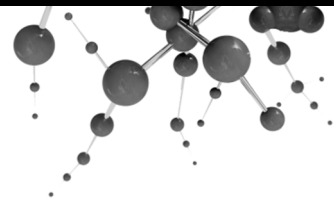
2   The Sense of Touch

The sense of touch provides us with a wealth of information on our surroundings. This information is mediated by the human somatosensory system. According to Goldstein (1999), the somatosensory system consists of the cutaneous senses (sensations based on the stimulation of receptors in the skin), proprioception (the sense of position of the limbs), and kinesthesis (the sense of movement of the limbs). The current work concentrates on stimulation of the cutaneous senses. This was chosen because proprioception and kinesthesis are related to felt forces, and providing force-based stimulation with a non-grounded device such as a mobile phone is challenging.

An important term when discussing the use of touch in interaction is *haptics*, which is defined as "sensory and/or motor activity based in the skin, muscles, joints and tendons" (ISO, 2009). This definition can be seen to encompass the whole somatosensory system. The part of haptics that focuses only on the stimulation of skin is generally referred to as *tactile*. Lederman (1997) defined tactile as pertaining to sensory information that is derived from cutaneous inputs.

As we can note, the terms *tactile* and *cutaneous* both refer to stimulation of the skin. However, it is still useful to separate the two. According to a classification by Goldstein (1999), tactile is one of the three submodalities of the cutaneous senses. The other two submodalities are temperature and pain. All three are mediated by the skin, but the neural structures and the resulting subjective perceptions are very different. The limitations of temperature and pain were noted already by Geldard (1960), who wrote that the communicative value of temperature variations is rather low, and creating discomfort or painful sensations is not realistic in practical use. This leaves us with tactile stimulation, which is the focus of this thesis.

2.1 TACTILE PERCEPTION AND MECHANORECEPTORS

Perception of tactile stimulation is mediated by mechanoreceptors in the human skin. On the basis of physiological studies, researchers have identified different mechanoreceptors in hairy and glabrous (or non-hairy) parts of the skin. The four main types of mechanoreceptors in the glabrous skin are Merkel receptors, Meissner corpuscles, Pacinian corpuscles, and Ruffini endings (Gardner, Martin, & Jessell, 2000; Goldstein, 1999). Figure 2 illustrates the locations of these receptors in the human skin. It can be seen that the Merkel receptors and Meissner corpuscles are found in the superficial layers of the skin, whereas the Pacinian corpuscles and Ruffini endings lie deeper in the subcutaneous tissue.

In addition to the depth of the receptors, the size of individual receptors partly defines how they sense stimulation. Because the Merkel receptors and Meissner corpuscles are small and located in the superficial skin layers (Johansson, 1976), they generally sense information from a small skin area. These two receptor types convey mainly fine spatial differences of touched objects and surfaces (Gardner et al., 2000). On the contrary, the Ruffini endings and Pacinian corpuscles with bigger receptive fields lie in the deeper skin layers, and their innervation density is lower than that of the superficial receptors (Goodwin & Wheat, 2008). Thus, the Ruffini endings and Pacinian corpuscles are not well suited to spatial localization of stimulation (Loomis, 1981). The Pacinian corpuscles sense vibration occurring several centimeters away from the end organ.
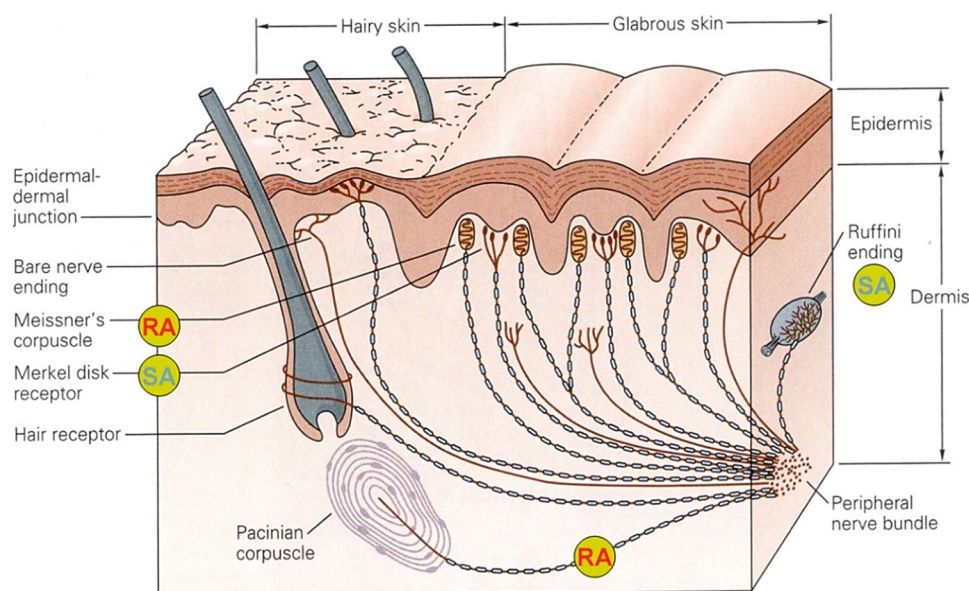
Figure 2. Mechanoreceptors in hairy and glabrous parts of the skin (Gardner et al., 2000). Reproduced from E. Kandel, J. Schwartz, & T. Jessell (Eds.), *Principles of Neural Science*, 4th edition, © 2000 McGraw-Hill, with permission from McGraw-Hill Education.

The receptors also differ in their fiber types, as indicated in Table 1. Slowly adapting fibers (SA I and SA II) fire when touch stimulation is applied and continue responding as long as the stimulation lasts. In everyday touch interaction, the SA fibers transmit information such as pressure of touch and shapes of objects. Conversely, rapidly adapting fibers (RA I and RA II) are activated when the stimulation is applied. After this, the response drops to zero, even though the stimulation would continue. The RA fibers sense, for example, pressure waves when the hand contacts an object and vibration when the object oscillates against the skin.

The four main receptor types are specialized in sensing stimulation with different frequencies. The Pacinian corpuscles respond to high frequencies with an optimal sensitivity at approximately 250 Hz. The Pacinian corpuscles are responsible for sensing a range of different stimulation types such as tickling (Kaczmarek, Webster, Bach-y-Rita, & Tompkins 1991), the hum of an electric motor, and frictional displacement of skin when moving one's hand across an object (Gardner et al., 2000). The Meissner corpuscles are the most sensitive to stimulation, with frequencies ranging from 3 to 40 Hz. This corresponds to detecting taps on one's skin (Goldstein, 1999) or small bumps and ridges in surfaces that are otherwise flat (Gardner et al., 2000).

The Merkel receptors respond to stimulation with frequencies as low as 0.3 Hz. This would correspond to someone pushing and releasing the skin with his or her finger (Goldstein, 1999). The Merkel receptors fire continuously at low rates if the touched surface is flat, whereas sharp edges such as a pencil point result in stronger responses (Gardner et al., 2000). Finally, the Ruffini endings sense stimulation such as stretching of skin and movement of joints.

Receptor structure	Receptive field size	Fiber type	Best frequencies	Perception	Best stimulus
Merkel receptor	Small	SA I	0.3–3 Hz	Pressure	Pressure
Meissner corpuscle	Small	RA I	3–40 Hz	Flutter	Taps on skin
Ruffini ending	Large	SA II	15–400 Hz	Buzzing	Stretching of skin or movements of joints
Pacinian corpuscle	Large	RA II (PC)	10 > 500 Hz	Vibration	Rapid vibration

Table 1. The properties of the main mechanoreceptor types found in the human glabrous skin (adapted from Goldstein, 1999).

2.2 SPATIAL SENSITIVITY

The sensitivity to touch varies in different body parts. A classic way to study this is to use the two-point threshold test, which measures the smallest separation between two points on the skin that is perceived as two points rather than only one (Goldstein, 1999). In the test, a participant is always presented with two points with varying distances, and the task is to indicate whether one or two points were perceived. Weinstein (1968) reported that the human spatial acuity is the highest in the distal parts of the body and decreases when moving to more proximal parts. That is, fingers are more sensitive than the palm, which in turn is more sensitive than the forearm. Figure 3 shows the two-point discrimination thresholds for different body parts. The thresholds are the lowest in fingers (2–3 mm), facial area excluding forehead (5–7 mm), palm, and hallux (10 mm). The least sensitive parts are the calf, thigh, and upper arm (45–50 mm).

Although the two-point discrimination threshold is still the most commonly used measure of tactile spatial resolution, there are also alternative measures. One of these is point localization, where two adjacent points on the skin are touched, and the participant's task is to answer whether the two points were the same or different. Weinstein (1968) showed that people can distinguish smaller spatial differences with point localization as compared with the two-point discrimination threshold. The discrepancy between the results has gained some interest (e.g., Craig & Johnson, 2000), as it suggests that the two-point discrimination threshold may not provide the most precise estimation of the spatial resolution.
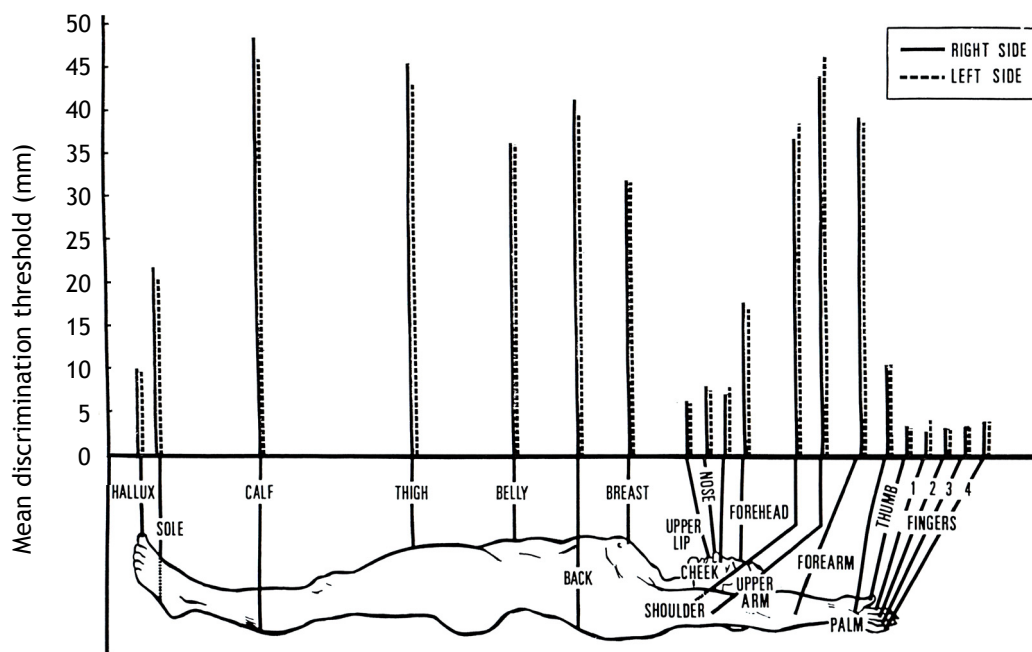
Figure 3. Means of two-point discrimination thresholds for different body parts (adapted from Weinstein, 1968). Used with permission from Charles C. Thomas.

Johnson and Phillips (1981) evaluated two alternative measures: gap detection and grating orientation. In gap detection, an edge with or without a gap is pressed against the skin, and the participant's task is to tell whether there was a gap. In grating orientation, a grating with alternating grooves and ridges is used. The orientation of the grooves and ridges can be varied by rotating the grating, and the task is to indicate the current orientation. Johnson and Phillips used the two measures to investigate the spatial sensitivity of the finger pad. The results showed that with gap detection a threshold level of 75% correct responses was reached with a gap size of 0.87 mm. For grating orientation, the gap size was 0.84 mm. Thus, it is possible to detect spatial differences less than 1 mm on the finger pad.

According to Goldstein (1999), the variations in spatial sensitivity between different body parts are partly explained by the innervation densities of mechanoreceptors. Vallbo and Johansson (1978) found that the densities of SA I and RA I fibers with small receptive fields were higher on the fingertips than elsewhere on the hand. When Vallbo and Johansson compared the innervation densities and reported two-point discrimination thresholds, they observed a direct relationship between the two. This indicates that the closer the two receptive fields are, the more probable it is that two adjacent touches stimulate different fields and the touch locations are perceived separate. A second factor explaining the differences in spatial sensitivity is the physiology of the somatosensory cortex in the human brain (Goldstein, 1999). Receptor signals from different parts of the body are processed in separate areas of the somatosensory cortex. The sizes of these cortical areas are related to the spatial sensitivity of the corresponding body part. For instance, the area processing receptor signals from the index finger is roughly the same size as the area for the whole trunk.

2.3 TACTILE ILLUSIONS

Illusion has been defined as "the marked and often surprising discrepancy between a physical stimulus and its corresponding percept" (Lederman & Jones, 2011). In daily life, we experience mainly auditory and visual illusions. One example of a visual illusion is the moon illusion, which is based on the notion that the moon appears much larger close to the horizon than when it is higher in the sky (Kant, 1900). Tactile illusions are experienced less often, even though some of them share similarities with visual illusions (Goldstein, 1999). By understanding how tactile illusions take place, it is possible to utilize them in designing interfaces that stimulate the sense of touch. Of particular interest throughout this thesis is the tactile apparent motion (also known as phi or beta movement). An example of tactile apparent motion is shown in Figure 4.
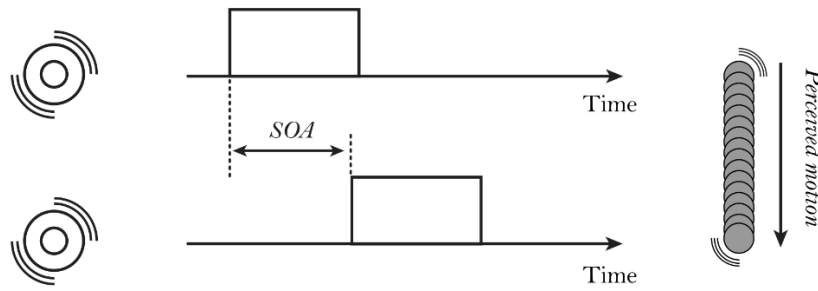
Figure 4. Tactile apparent motion created using two stimulation points (Israr & Poupyrev, 2011, Figure 1b, © IEEE 2011).

Tactile apparent motion is an illusory perception of motion created by the discrete stimulation of points approximately separated in space and time (Harrar, Winter, & Harris, 2008). This can be created in practice, for example, by sequentially vibrating several spatially distributed actuators against the user's skin. The illusion was first observed with visual stimuli by Korte (1915). Later research showed that the findings of Korte apply also to tactile stimuli (Sherrick & Rogers, 1966). In Figure 4, the two points are stimulated in a sequence so that the resulting sensation feels like a single continuous stimulus moving across the skin.

Stimulus onset asynchrony (SOA) defines the timing of two subsequent stimuli. Sherrick and Rogers (1966) used mechanical vibration to study the effect of SOA and stimulus duration on the subjective sensation of apparent motion. The best movement (i.e., longest uninterrupted feeling of movement between the first and second stimulus sites) was achieved by increasing the SOA linearly based on the stimulus duration. That is, for the illusory perception to take place with longer stimuli, more time was required between the onsets. Kirman (1974) found that the impressiveness of the illusion increases when longer stimulus durations are used.

Provided that the stimulation parameters are suitable, the illusion of tactile apparent motion is quite robust. Sherrick (1968) demonstrated that the illusion was preserved when stimuli were given to different sides of the body (i.e., both forearms). The subjective perception, however, was weaker as compared with a case where the stimuli were given to a single body site. Also, Sherrick and Rogers (1966) showed that the illusion is not limited only to vibrotactile stimulation. They demonstrated that the illusion could also be replicated with electrocutaneous stimulation.

A related tactile illusion is cutaneous saltation, where several pulses are presented to each stimulus site on the body. The cutaneous saltation was first discovered by Geldard (1975), who placed three actuators linearly on the forearm and stimulated them successively with a series of short taps. Instead of feeling separate pulses from each actuator, users perceived a stimulus moving in a smooth progression from the first actuator to the last. The sensation has been described as if a tiny rabbit were hopping on the

skin, and therefore the cutaneous saltation is also widely referred to as the cutaneous rabbit (Tan, Gray, Young, & Traylor, 2003).

From the viewpoint of communication applications, the benefit of tactile apparent motion and cutaneous saltation is that they allow for the perception of a single moving stimulus instead of separate successive stimuli. This can be used, for example, for mimicking a human touch moving on one's skin (e.g., Haans & IJsselsteijn, 2009; Park, Lim, & Nam, 2010). Another advantage of utilizing tactile illusions is that the design of communication devices can be simplified because the perceptual resolution is higher than what the number of individual actuators would indicate (Tan et al., 2003). This enables the presentation of more complex information with fewer actuators.

2.4 SUMMARY

In this chapter, we have introduced some of the main concepts related to human tactile perception. The human skin senses a variety of tactile stimulation types thanks to its different mechanoreceptors. In everyday life, touch perception is attributed to the interplay of the receptors. However, in this thesis work, knowledge of the receptor properties was used as a basis for designing interfaces that deliberately stimulate certain receptors. When designing such interfaces, it is also important to consider the tactile spatial sensitivity of the human body, which varies between different areas. The research reported later in this thesis concentrated on the hand area. The human hand is one of the most promising stimulation sites because its spatial sensitivity is high and adjacent stimulation points can be distinguished accurately. In addition, tactile apparent motion was used to increase the number of perceived stimulation points without adding to the mechanical complexity of tactile displays.
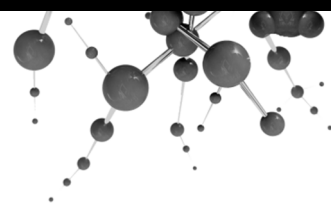
3 Early Tactile Communication Research

This chapter presents an overview of early research carried out on presenting information using tactile stimulation. The majority of the communication systems were developed for sensory substitution for individuals with visual and/or hearing impairments. With these systems, information that is typically received via the visual and auditory modalities (e.g., alphabets and numbers) is coded using tactile stimulation. The very first systems were developed in the 19th century. Since then, different technological solutions have been introduced, and the research in this field has been progressing steadily. Despite being designed primarily for non-mobile use, the early systems are relevant also to the development of mobile touch communication devices.

3.1 Sensory Substitution Systems

Tactile stimulation used in sensory substitution systems can be either mechanical or non-mechanical. The first two systems introduced in this section can be classified as non-mechanical because they do not rely on technical aids. People typically read Braille by moving their fingers on an embossed paper, whereas in Tadoma the whole hand senses information related to speech production. Even though technical aids are not required, they can be helpful. For example, material written in Braille is typically prepared using mechanical embossers. From the 1920s onwards, the sensory substitution systems increasingly started to utilize mechanical devices for stimulation. The latter part of this section presents five mechanical systems that have advanced the research on tactile sensory substitution systems.

Braille (1829)

Braille is a reading and writing system for the blind that was published in 1829 by Louis Braille (Warren, 1978). Overall, there are 39 million blind people worldwide (WHO, 2013), and 6.6 million reside in the United States (NFB, 2011). Of these 6.6 million, approximately 10% are frequent users of Braille. Braille transliterates written text such as letters into tactile characters. The characters are typically presented by using embossed paper with raised and absent dots. In standard six-dot Braille, each character or cell consists of a rectangular array of two columns and three rows (see Figure 5). Thus, the dots can be positioned in 64 different configurations. People read Braille by gliding their fingers over the characters. It is often more efficient to use one hand for reading single characters and two hands for reading longer lines of text (Millar, 1997). In two-handed reading, the left hand can locate the start of the next text line, while the right hand finishes reading the current line. Comprehension of text is not based on individual dots but rather on shapes outlined by the dots. It has been argued that the shapes are used for constructing a geometric model of the character's layout (Roberts, Slattery, & Kardos, 2000). An alternative theory suggests that the perception is based on dot density disparities that are learned over time (Millar, 1994, 1997).
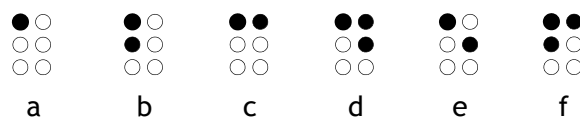
Figure 5. Examples of six-dot Braille characters. Black dots represent raised dots, and white dots represent lowered (absent) dots.

The reported reading speeds of printed Braille vary between different studies. Measured in words per minute (wpm), average reading speeds have been reported to be 100 wpm (Warren, 1978), 124 wpm (Legge, Madison, & Mansfield, 1999), and 136 wpm (Knowlton & Wetzel, 1996). Some sources suggest that speeds as high as 200–400 wpm are possible (Ford & Walhof, 1999). One natural factor affecting the achieved reading speed is the reader's prior experience of Braille. It has also been shown that the reading speeds depend on the reading task (Knowlton & Wetzel, 1996). When the task was simply to read aloud without having to recall the read text, an average speed of 136 wpm was measured. However, when the participants were told that they later had to give a narrative of the read text, the average speed decreased to 105 wpm. Regardless of the high variation, it is generally accepted that the average reading speeds in Braille are lower than those in visual print reading. The reading rates of sighted individuals are typically between 250 and 300 wpm (Millar, 1997). It has been argued that the limitation of Braille reading speed is caused by the linear (Warren, 1978) or serial (Foulke, 1991) nature of the input process. People read Braille one cell at a time, whereas in visual reading they perceive text at the word level.

Nowadays, embossed Braille is used together with refreshable Braille displays that are connected to desktop computers or mobile devices. The displays usually have either 40 or 80 cells positioned in front of a regular keyboard (Figure 6). Each cell is controlled mechanically so that the dots can be raised or lowered depending on the information to be presented. Refreshable Braille displays generally use eight-dot Braille that adds a fourth row for two additional dots. The additional dots are used, for example, to indicate the letter case. Some displays also have input buttons for typing information with the Braille notation. Although Braille displays are a significant step forward in providing non-visual access to digital information, one limiting factor for potential users is the price of the displays (Levesque, Pasquero, Hayward, & Legault, 2005; Ramstein, 1996; Roberts et al., 2000). A typical Braille display for a desktop computer costs between U.S. $3,500 and $15,000. Mobile Braille readers for devices such as smart phones cost upwards of U.S. $1,000. The high price is mainly due to the number of required mechanical parts (Levesque, 2005).

Because of the high price of Braille displays, a range of research has been carried out to develop cheaper alternatives. One way is to try to cut down on the number of individual Braille cells in a display. Roberts et al. (2000) proposed a design with a rotating wheel that had moving pins attached to it. The pin positions were refreshed continuously as the wheel rotated. Users could sense Braille cells by holding one or more fingers stationary on top of the wheel. This resulted in a sensation of a continuous line of Braille cells. An alternative prototype was developed by Levesque et al. (2005), who utilized lateral skin deformation of the fingertip for creating a sensation of Braille dots. The first prototype could present two dots simultaneously. Later, Levesque, Pasquero, and Hayward (2007) introduced an extended version that used two-dimensional skin deformation for presenting all six dots simultaneously. In a user study, participants could read five-letter words with an average success rate of 69%.

Figure 6. Example of a 40-cell refreshable Braille display placed in front of a regular laptop (Brailliant 40 from Blinksoft, http://http://www.blinksoftinc.com/).

Tadoma (1920s)

Tadoma is a method of receiving speech information via the tactile sense, and it has evolved within the deaf-blind community (Reed et al., 1985). People receive speech by placing a hand on the face of a person who is talking. Typically, the thumb rests lightly on the talker's lips while the other fingers are touching the cheek and jawline. This hand position allows monitoring of several facial actions related to speech production such as jaw movement, airflow, and vibration of vocal cords. Experts in Tadoma can receive information with a performance close to normal listening.

Tadoma is less widespread than Braille (Pasquero, 2006). The use of Tadoma was most common between 1930 and 1960 in North America, where it was taught in schools for deaf and deaf-blind children (Reed, 1996). Some efforts were made to develop a synthetic Tadoma system for presenting signals recorded from a talker's face. Reed et al. (1985) introduced an artificial face that mimicked the facial actions of vibration, oral airflow, jaw movement, and lip movement. A study on presenting single letters indicated that the synthetic Tadoma could provide a rough simulation of natural Tadoma (Leotta, Rabinowitz, Reed, & Durlach, 1988).

Teletactor (1927)

Teletactor was a sensory substitution system that used vibration to present speech for the deaf (Gault, 1927). The system was based on an idea of directly converting different frequencies of human speech to vibration so that the skin could "hear." For this purpose, the system had five vibrators attached to the user's fingers. Each vibrator presented a different frequency band of speech. For instance, the letter "a" with an ascending frequency was first felt on the thumb and then on the ring finger.

Studies reported by Goodfellow (1934) indicated that the Teletactor was successful in improving the lip reading ability of deaf children who used the system alongside traditional lip reading. On the other hand, further studies showed that only a few people could interpret speech by using the vibration alone. As Geldard (1957, 1960) later noted, the main limitation of the system was caused by the fact that it did not take into account the properties of the human skin. Linguistically important information in human speech typically falls between 200 and 3500 Hz (Kirman, 1973), whereas the frequency range of the cutaneous sense varies between 0.3 and 500 Hz (Goldstein, 1999). Thus, there was a mismatch between the presented stimulation and the capabilities of people to perceive it.

Vibratese (1957)

Vibratese was a tactile communication method that was based on systematic design and results of psychophysical experiments on tactile perception (Geldard, 1957). Instead of using vibration frequency as a parameter, Geldard chose to vary the amplitude, duration, and body

location of stimulation. Three different amplitude levels and three durations could be recognized robustly by users. In addition, the spatial location was varied by attaching five actuators to the user's chest. With these three parameters, it was possible to present 45 different stimuli, which was enough for all letters, numerals, and some frequently used short words. To optimize the presentation speed and avoid confusion, the most frequently occurring letters were assigned to the shortest durations and different spatial locations.

Experiments with the Vibratese method showed that hours of training were needed to achieve satisfactory reading levels. According to Geldard, users required approximately 12 hours to learn the symbol–signal connections so that the users could move on to reading English words. In a later study, Geldard (1960) reported that users required 65 hours of learning to understand sentences consisting of five-letter words with 90% accuracy when presented at a rate of 38 wpm. A theoretical rate of 67 wpm could be reached by decreasing the time required to present letters. However, this could not be tested in practice because the increased rate would have required an automatic coder instead of a manually operated typewriter. Even though Vibratese was one of the most successful early touch communication systems, it never gained wider popularity.

Optacon (1966)

Optacon was a direct translation reading aid that made printed material readable for the blind (Linvill & Bliss, 1966). This was achieved by using an array of photocells to sense printed characters on paper or in a book. Information from the photocells was converted into a tactile image presented to the user's finger through an array of 96 vibrating pins. A more refined version of Optacon had an array of 144 pins and a mouse-like optical probe to scan printed information (Bliss, Katcher, Rogers, & Shepard, 1970). People used one hand for sensing the tactile stimulation and the other for moving the probe.

Experiments reported by Bliss et al. (1970) indicated that random strings could be read successfully with an average rate of 92–98%. A longitudinal experiment with one user indicated that an initial reading rate of 20 wpm increased to approximately 51 wpm after 128 hours of practice. Optacon was later used in a range of other studies related to reading and tactile pattern recognition (e.g., Cholewiak & Craig, 1984; Heller, Rogers, & Perry, 1990; Hislop, Zuber, & Trimble, 1985). Optacon also achieved moderate commercial success within the blind community in the United States, where over 15,000 devices were sold (Jones & Sarter, 2008) before manufacturing of the device was stopped in 1996. This left devoted Optacon users disappointed because the device had helped them significantly in independently carrying out daily tasks such as browsing gift catalogues and sorting print mail.

TVSS (1969)

The tactile vision substitution system (TVSS) was developed to convert an optical image into a tactile one (White, 1970). Compared with the Optacon, the TVSS was less portable. A television camera captured a video image that was presented to the back of a user who was sitting in a chair. The chair had an array of 400 vibrating actuators that could be controlled individually. White, Saunders, Scadden, Bach-y-Rita, and Collins (1970) reported results of studies that were conducted to evaluate the potential of the system. Discrimination of objects placed in front of the camera was facilitated when the user was allowed to move the camera and, thus, actively scan the objects. In another study, blind users who had to judge the orientation of black and white lines performed similarly to sighted users who saw the same lines visually from a display. Further observations with blind users who had over 40 hours of experience with the TVSS showed that they could discriminate between 25 things such as a coffee cup and a telephone. According to Bach-y-Rita (1970), the findings showed that the cutaneous receptors and pathways were capable of carrying pictorial information to the brain.

Tactuator (1996)
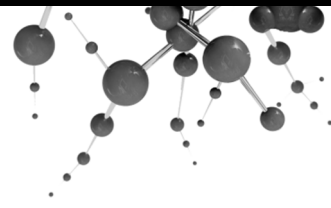
Tan and Rabinowitz (1996) presented the Tactuator, which was a sensory substitution system for people with hearing and/or visual impairments. The design was motivated by the abilities of experienced Tadoma users who could perceive speech at very high rates. Tan and Rabinowitz observed that Tadoma users sensed a range of perceptually rich stimulation types such as jaw movement and vibration, whereas previous tactile communication systems had utilized mainly vibration.

To make the stimulation of the Tactuator versatile, Tan and Rabinowitz (1996) provided both low-frequency motions and high-frequency vibrations to the user's hand. This was achieved by using three rods that stimulated the finger pads of the user's thumb, index finger, and middle finger. Tan, Durlach, Reed, and Rabinowitz (1999) developed a set of stimuli by varying the duration, spatial location, frequency, amplitude, and direction of the motion. The information transmission capabilities of the Tactuator were assessed in a study where three participants who were familiar with the device had to recognize randomly presented stimuli. The results were promising and showed that a theoretical transmission rate similar to that obtained by experienced Tadoma users was achievable.

3.2 SUMMARY

Early research on tactile communication systems showed that information can be presented successfully via touch. Braille is one of the most widely used tactile communication methods today. This is partly due to its long history and versatility. Braille can be read with either embossed paper or

mechanical displays. However, the high price of Braille displays is still an issue, for the displays cost thousands of dollars. This was one of the motivating factors behind Study I, which explored the use of vibrotactile stimulation for presenting letters. Vibrotactile stimulation could offer an alternative to traditional Braille displays if the capabilities and limitations of the human skin are taken into account. For example, studies with the Teletactor indicated that directly transferring speech to vibrotactile stimulation is not feasible due to the different sensing frequencies of hearing and touch. Also, achieving moderate to high reading rates with sensory substitution systems often requires hours of practice. A benefit of studying Braille was that, because of its existing user base, we could find people capable of evaluating new presentation methods without extensive practice.

4 Tactile Stimulation with Mobile Devices

Whereas the early communication studies were motivated mainly by the need for sensory substitution systems, the recent trend toward mobile computing has brought out new challenges that could in part be alleviated by tactile technology. The use of devices such as mobile phones often results in a situation where our senses and cognitive resources are overburdened. According to Oulasvirta, Tamminen, Roto, and Kuorelahti (2005), this can lead to slowing down, postponing, or stopping the interaction altogether. They observed that when users carry out tasks with a mobile phone while walking, their attention was fragmented into bursts of 4 to 8 seconds. One way to cope with cognitively demanding scenarios is to utilize several senses simultaneously. Oviatt, Coulston, and Lunsford (2004) found that users spontaneously responded to cognitive load by shifting from unimodal to multimodal interaction. Interestingly, Geldard (1957) discussed the oversaturation of visual and auditory channels nearly 60 years ago. He suggested that the tactile channel could be useful, for example, in presenting alerts and directional information.

4.1 TACTONS AND STIMULATION PARAMETERS

The number of studies on using tactile stimulation with mobile devices grew significantly in the early 2000s. This could be due to the introduction of mobile phones that had user-controllable tactile actuators. The first explorations in this field led to definitions of central concepts that have been used as a basis in further research. Brewster and Brown (2004) introduced tactons for conveying complex interface concepts, objects, and actions non-visually. The visual and auditory counterparts to tactons are

graphical icons and earcons, respectively. A related concept was introduced by MacLean and Enriquez (2003), who defined haptic icons as "brief computer-generated signals, displayed to a user through force or tactile feedback to convey information such as event notification, identity, content or state." The main difference between the two definitions is that the latter also includes icons created by force-feedback devices.

The construction of tactons requires at least one controllable parameter so that different stimuli can be assigned with specific information content. This is essentially the same process as the one used with the sensory substitution systems. Intuitively, it would seem that varying as many parameters as possible enables more complex tactons and, thus, extends the information space that can be communicated. However, the situation is not this simple in practice. At least three restricting factors must be considered when designing tactons. First, the number of available parameters and, consequently, stimulus dimensions depends on the used tactile technology. For instance, not all actuator types provide separate control of both stimulus frequency and amplitude. Second, there are limits as to how many separate levels humans can distinguish within one stimulus dimension. For example, using more amplitude levels than what can be separated by the user is not meaningful. Third, the total number of different tactons should be chosen so that users can learn their meanings in a reasonable time and recall them later.

The following subsections introduce the most typically used parameters for coding information with tactile stimulation: frequency, amplitude, waveform, spatial location, duration, and rhythm. Although the relevant psychophysical, perceptual, and design-related findings of each of these parameters are presented, additional emphasis is put on the use of spatial location because of the topic of this thesis. For further information on the different parameters, the reader is kindly referred to prior reviews (Brown, 2007; Cheung, van Erp, & Cholewiak, 2008; Hoggan, 2010; Jones & Sarter, 2008).

Frequency

As discussed earlier in Chapter 2, the mechanoreceptors in human skin respond to stimulation frequencies ranging from 0.3 Hz to over 500 Hz (Goldstein, 1999). However, not all values within this range are equally suitable for use from the viewpoint of practical applications. Studies have been conducted to find optimal frequency levels that would require the lowest threshold amplitudes for the stimulation to be perceivable (e.g., Gescheider, Bolanowski, Pope, & Verrillo, 2002; Sherrick, 1953). The results showed that the optimal frequency range for sensing vibration is approximately 150–300 Hz. Frequencies outside this range can also be felt, but higher amplitudes are required for the stimulation to be perceivable.

Consequently, frequencies between 150 and 300 Hz are often used with vibrotactile actuators.

One challenge in coding information with frequency is that changing the frequency also tends to change the perceived intensity of stimulation. This was observed by Geldard (1957), who wrote that "frequency and intensity, the two basic stimulus dimensions for all hearing, typically get thoroughly confounded in the cutaneous mediation of them." Thus, the possible effect of frequency change on perceived intensity should be considered before coding information with frequency. Even though providing guidelines for the number of usable frequency levels is far from straightforward, some general suggestions exist. Rothenberg, Verrillo, Zahorian, Brachman, and Bolanowski (1977) estimated that there could be up to seven differentiable frequency levels on the forearm and 10 on the finger. The findings of Sherrick (1985) indicated that participants could differentiate between three and five frequency levels. The estimation of Sherrick is likely more realistic in practical-use scenarios. Also, Choi and Kuchenbecker (2013) stated that a frequency chance of at least 20–30% is needed for two levels to be distinguishable in practical applications.

Amplitude

In short, the amplitude or intensity of tactile stimulation should be such that it can be detected by the user while still being low enough not to cause pain (Craig & Sherrick, 1982). The detectable threshold is often specified with a reference to sensation level (dB SL). According to Geldard (1957), there are about 15 detectable amplitude levels above the sensation level. Another important measure is the relative difference threshold that is used to study the smallest detectable difference between two amplitude levels. Craig (1972) studied the relative difference threshold of stimulation applied to the fingertip. His results showed that, on average, a 16% (1.5 dB) change to a base amplitude (14, 21, 28, or 35 dB SL) was needed for the difference to be perceivable.

Several factors affect the perception of amplitude. A study by Verrillo, Fraioli, and Smith (1969) indicated that the objective and subjective intensity levels of vibration could differ. This means that doubling the objective intensity does not necessarily double the subjective perception (Cheung, van Erp, & Cholewiak, 2008). Other factors affecting amplitude perception include the size of the tactile contactor area (Verrillo, 1963), the intensity and frequency of preceding stimuli (Verrillo & Gescheider, 1975), and the spatial body location of stimulation (Jones & Sarter, 2008). Because of the interaction between amplitude and frequency, it has been suggested that in tactile stimulus design only one of these parameters should be used (Jones & Sarter, 2008) or they should be combined into one (Brewster & Brown, 2004). Geldard (1957) concluded that even though humans can detect over 10 amplitude levels in a laboratory setting, in practice no more

than three should be used to ensure robust identification. The results of Brown and Kaaresoja (2006) showed that three is a good estimate for practical use, for in their study participants could recognize three levels with a mean success rate of 75%.

Waveform

Waveform refers to the shape of the signal that is fed to a tactile actuator. The recommended waveform for many actuators is a sine wave. Other possibilities include, for example, square and sawtooth waves. Brewster and Brown (2004) pointed out that the usefulness of wave shape in tactile stimulation design is limited compared with sound design, where its counterpart (i.e., timbre) is one of the central parameters. Furthermore, Brown (2007) observed that some commercially available tactile actuators are not capable of accurately reproducing waveforms other than sine waves. Therefore, the physical movement of an actuator does not necessarily follow the exact shape of the driving signal. An alternative to varying the waveform (e.g., sine and square) is to use a modulated sine wave. Modulated sine waves can be created by multiplying two sine waves that have different frequencies (see Figure 7).
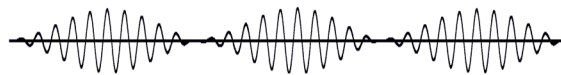
Figure 7. A modulated sine wave with a base frequency of 160 Hz.

Weisenberger (1986) showed that participants perceived a modulated sine wave as "rougher" as compared with an unmodulated sine wave. In a later study, Brown, Brewster, and Purchase (2005) evaluated the use of roughness as a design parameter and showed that participants could recognize three roughness levels (i.e., smooth, rough, and very rough) with a mean success rate of 80%. On the other hand, there is also evidence suggesting that changes in waveform could be easier to distinguish than amplitude modulation. This was the case in a study by Hoggan and Brewster (2007), who found that three waveforms (i.e., sine, square, and sawtooth) were recognized correctly with a mean success rate of 94%, whereas three modulated sine waves were recognized correctly with a mean success rate of 61%. In summary, waveform has shown promise as a design parameter, but information on its use is still somewhat limited.

Spatial Location

The spatial sensitivity of the human body was discussed in Chapter 2, where it was shown that especially the fingers, palm, and facial area are sensitive to touch stimulation (Weinstein, 1968). Although the two-point discrimination threshold used by Weinstein provides a good general estimation of the human touch sensitivity, it should be noted that the classic measurements were made using pressure stimulation. For example, Weinstein used specific probes that touched the skin briefly. This is different from vibrotactile stimulation that is often used with wearable

and mobile devices. When the skin is vibrated, the vibration is not localized only to the point where the actuator touches the skin. Instead, the stimulus can travel for many centimeters as a wave that is similar to the circular waves resulting from dropping a stone in water (Cholewiak & Collins, 2003).

To study how accurately people can localize vibrotactile stimulation, Cholewiak and Collins (2003) conducted measurements on the volar (under) side of the forearm. An array of seven actuators was distributed evenly from the elbow to the wrist so that the distance between two adjacent actuators was approximately 25 mm. The results showed that the localization accuracy of stimulation increased at the two ends of the array (over 65%) as compared with the middle of the array (30–40%). This indicated that the localization performance will increase if the stimulation is close to anatomical reference points such as the elbow or wrist. The results also demonstrated that an actuator separation of 25 mm was insufficient for very accurate localization on the forearm. When the separation of the seven actuators was stretched from 25 to 50 mm by extending the array from the shoulder to the wrist, the average localization accuracy increased from 46 to 66%.

In a following study, Cholewiak, Brill, and Schwab (2004) investigated the localization accuracy of vibrotactile stimulation on the abdomen. A total of 12 actuators were placed evenly around the user's abdomen so that the locations corresponded to the 12 hours of the clock. The results showed that the localization accuracy depended on the actuator's proximity to the spine and navel, where the accuracies were 98% and 96%, respectively. The accuracies for the rest of the actuators were 62–74%. Therefore, when stimulating the abdomen, the natural reference points or anchor points (van Erp, 2005a) were the spine and navel. Further experiments by Cholewiak et al. (2004) indicated that the average localization accuracy on the abdomen can be improved by reducing the number of actuators. This was demonstrated by measuring average localization accuracies for 12, 8, and 6 actuators that were 74%, 92%, and 97%, respectively.

Taken together, the main factors affecting the localization of vibrotactile stimulation on the body include the actuator's proximity to anatomical reference points, the number of actuators, and separation between actuators (Cholewiak et al., 2004; Cholewiak & Collins, 2003; van Erp, 2005a). For example, frequency of stimulation has little effect on localization (Jones, Held, & Hunter, 2010). One factor that warrants further discussion is the separation between the actuators (i.e., intertactor spacing). This is especially important with two-dimensional arrays because the available skin surface is limited (Jones & Sarter, 2008).

To evaluate the feasibility of two-dimensional vibrotactile displays, Oakley, Kim, Lee, and Ryu (2006) attached a 3 × 3 array of actuators on the

dorsal (upper) side of the forearm with an intertactor spacing of 25 mm. They found that the localization accuracy of an individual actuator varied between 23 and 77%, and localizing was easier across the back of the forearm (i.e., between left and right sides of the hand) as compared with along the back of the forearm (i.e., from the wrist toward the elbow). The enhanced localization accuracy across the back of the forearm was also observed by Piateski and Jones (2005), confirming the importance of natural reference points. Furthermore, Chen, Santos, Graves, Kim, and Tan (2008) investigated localization accuracies between the dorsal and volar sides of the forearm by using a 3 × 3 actuator array. Their results for the dorsal (25–72%) and volar (34–70%) sides showed little differences, and the accuracies were in general similar to those reported by Oakley et al. (2006). Chen et al. (2008) suggested that error-free localization could perhaps be achieved by placing three actuators on both sides of the forearm.

As indicated by the aforementioned studies, the location of vibrotactile stimulation has often been varied on the torso (Geldard 1957; White, 1970), abdomen (Cholewiak et al., 2004; van Erp, 2005a), or forearm (Chen et al., 2008; Cholewiak & Collins, 2003; Oakley et al., 2006; Piateski & Jones, 2005). In general, these locations are practical in applications where the fingers and hands are needed for other activities (e.g., orientation systems for visually impaired people or aircraft pilots). In the case of mobile devices, however, the natural site for varying the spatial location of stimulation would be the palm and fingers. Hoggan, Anwar, and Brewster (2007) placed three vibrotactile actuators on the sides of a PDA and one on its back. In practice, the actuators stimulated the index finger, the ring finger, and the upper and lower parts of the thumb. The results of a user study indicated that participants could distinguish the vibrating locations without errors (i.e., 100% accuracy).

Furthermore, Yatani and Truong (2009) placed five vibrotactile actuators to the back of a mobile device so that stimulation could be presented to the base of the fingers and to the palm. The results showed that participants could distinguish vibration from a single actuator with an average accuracy of 90%. Sofia and Jones (2013) studied the localization of vibrotactile stimulation on the palm of the hand, the forearm, and the thigh by using an array of 3 × 3 actuators with an intertactor spacing of 22 mm. The results indicated that localizing an individual stimulation point was easier on the palm (81% mean accuracy) as compared with the forearm (49%) and thigh (46%). A likely explanation for the differences is the higher mechanoreceptor density of the palm. Thus, it seems that the palm and fingers are promising sites for sensing spatial stimulation.

In summary, the spatial location is an effective parameter for varying vibrotactile stimulation. The number of actuators and spacing between

them are important factors to consider. The reviewed studies indicate that when placing more than five or six actuators close to each other on the skin, the localization accuracy generally decreases. Thus, it might be more effective to use fewer actuators to guarantee adequate intertactor spacing and accurate localization. The body site also affects the use of stimulation. For example, the low spatial sensitivity of the back can be compensated for by increasing the spacing between actuators.

Duration

The duration of actuation defines how long the skin is stimulated. The skin is very sensitive to even the briefest stimuli; depending on the used actuator technology, very short stimulus durations can be perceivable. Geldard (1957) suggested a minimum duration of 0.1 second because stimulation shorter than this could be mistaken for a "poke" or "nudge." Naturally, this depends on the application field, for in some cases such a perception can even be desired (e.g., alerts). Also, too short durations may pose difficulties for perceiving and recognizing the details of stimulation. A study by Summers, Cooper, Wright, Gratton, and Milnes (1997) demonstrated that increasing the duration of stimulation from 80 to 320 milliseconds made it easier to recognize whether the frequency of the stimulation was ascending, constant, or descending.

On the other hand, too long stimulus durations may result in certain disadvantages. First, Geldard (1957) stated that stimuli longer than 2 seconds would be too time consuming for practical communication purposes. Second, Kaaresoja and Linjama (2005) reported that vibration from a mobile phone can become irritating if the stimulation continues for longer than 200 milliseconds. Even though this is likely dependent on the particular actuator type and the amplitude of stimulation, prolonged vibration can become annoying. Third, adaptation can take place if a particular body site is exposed to sustained stimulation. Hahn (1966) showed that after several minutes of vibration, the detection threshold to subsequent stimulation was increased. That is, higher amplitudes were required to reach the sensation level. Interestingly, adaptation to a particular stimulus has an opposite effect on amplitude and frequency discrimination. It can be easier to discriminate the particular stimulus from others based on its frequency and amplitude (Goble & Hollins, 1993, 1994). This could indicate that adaptation in fact helps in adjusting the somatosensory system to the present stimulation conditions.

Finally, it is important to consider the number of different duration levels that are meaningful to utilize in practical applications. The experiments of Geldard (1957) suggested that participants in a laboratory setting could differentiate as many as 25 distinct duration levels within the range of 0.1–2 seconds. However, in real use cases, differentiating durations becomes more difficult. If there is no prior training of users, Geldard (1957, 1960)

advised to use only three different levels of duration to code information. This recommendation is still reasonable today.

Rhythm

Rhythmic stimuli can be created by presenting several temporally separated pulses. This requires adequate delays between the pulses so that the user can perceive them as separate. Gescheider (1974) studied the minimum delay between tactile stimuli by presenting two successive stimuli to the fingertip of a participant. His results showed that a delay of at least 5.5 milliseconds was necessary for the stimuli to be perceived as separate instead of a single fused sensation. In a study by Hirsh and Sherrick (1961), the task was to judge the temporal order of two stimuli presented to the index fingers of the left and right hands. They found that a delay of 20 milliseconds was required between the onsets of two stimuli to report their order correctly on 75% of trials. Craig and Baihua (1990) observed that judging the temporal order of two stimuli with different patterns was easiest when the stimuli were presented to the same fingertip (12-millisecond delay between onsets of stimuli). The task became more difficult when using two fingertips of the same hand (69 milliseconds) and two fingertips of opposite hands (125 milliseconds).

Provided that the delays between individual pulses are sufficient, the design space of different rhythm-based stimuli is vast. Brown et al. (2005) used prior knowledge from the use of earcons as a basis for designing three different rhythms for tactons. They used a number of different notes (i.e., stimulation pulses with different durations) to compose distinct stimuli. The results of a series of experiments proved rhythm to be an effective parameter, for the three different rhythms were recognized with a mean success rate of over 90% (Brown et al., 2005, 2006).

In an alternative approach, Ternes and MacLean (2008) used perceptual principles rather than prior auditory experience in designing tactile icons with rhythm. To create a set of perceptually distinguishable icons, Ternes and MacLean chose 21 different rhythms that were varied by two levels of frequency and amplitude. Thus, the size of the stimulus set was 84. The results of multidimensional scaling suggested that amplitude was the most important parameter when users attempted to distinguish the stimuli from each other. In terms of rhythm, the most useful perceptual subdimensions in distinguishing the stimuli were note length (i.e., duration of stimulation burst) and evenness (i.e., repeating or irregular nature).

Learning of rhythmic icons was studied by Enriquez and MacLean (2008), who used the set of 84 rhythm-based stimuli as a starting point. They selected two sets of 10 stimuli for studying whether users learn and recall the meanings of stimuli better if they can assign meanings to the individual stimuli themselves. The results indicated that a training period

of 10–15 minutes was needed to correctly identify 80% of the stimuli. After 2 weeks, the users correctly recalled 70% of the original stimuli. The learning method did not affect the recall of the stimulus meanings. These findings indicate that rhythm is an efficient parameter for coding information, and that the majority of the learned meanings coded using rhythm can be remembered after several weeks.

Summary of Parameters

According to prior studies, spatial location, duration, and rhythm can be identified as the most promising parameters for presenting information via the tactile sense. Recognizing the spatial location of touch stimulation is an immediate and precise process that can be exploited in tactile interface design. At the same time, it is important to consider the number of actuators and their intertactor spacing in order not to exceed the spatial resolution of the skin. Duration and its derivative rhythm offer a second dimension that can be used efficiently for coding information with tactile stimulation. In addition, amplitude or frequency can be used as a supporting dimension. Varying both at the same time is not advisable because of their interaction. The main findings of each parameter are summarized in Table 2.

Parameter	Advantages	Disadvantages	# of levels
Frequency	Easy to control with most actuators	Can interact with amplitude; optimal frequencies vary between actuators	3–5
Amplitude	Proportional to the intensity of stimulation	Subjective sensitivity of users varies; too high amplitudes can be unpleasant	3
Waveform	Affects the felt roughness of stimulation	Requires actuators capable of reproducing different waveforms	N/A
Spatial location	Easy for users to distinguish	Usefulness depends on body site, the number of actuators, and their intertactor spacing	>1
Duration	Easy to control; users sensitive to temporal changes	Can become irritating if stimulation is prolonged	3
Rhythm	Vast design space; enables large stimulus sets	Requires knowledge of rhythmic design	N/A

Table 2. Summary of the advantages and disadvantages of the stimulation parameters, along with the recommended number of different levels.

4.2 ACTUATOR TECHNOLOGIES

Tactile stimulation can be created using different technological solutions. In this section, we introduce some of the most commonly used tactile actuator technologies in everyday products and research prototypes: vibration motors with an eccentric rotating mass (ERM), linear voice coils, and piezoelectric actuators. It should be emphasized that this list is by no means comprehensive. Other possible technologies include, for example, electrovibration (Bau, Poupyrev, Israr, & Harrison, 2010; Wijekoon, Cecchinato, Hoggan, & Linjama, 2012), ultrasonic vibration (Marchuk, Colgate, & Peshkin, 2010; Winfield, Glassmire, Colgate, & Peshkin, 2007), and pneumatic systems (Sodhi, Poupyrev, Glisson, & Israr, 2013). In this thesis, special emphasis was put on actuators that were available in the beginning of the research and could stimulate different spatial locations of the user's hand. This sets limitations on the actuators' size and operating principle. For instance, the actuators should be small and lightweight so that they can be attached to mobile devices.

Vibration Motors with an Eccentric Rotating Mass

The most common actuator type in current commercial products such as mobile phones and game controllers is a small DC motor with an ERM. The stimulation of ERM motors is based on an off-axis weight attached to a shaft that creates vibration when current is on (Figure 8). These actuators have been used in a range of studies to provide stimulation with mobile phones (e.g., Brown & Kaaresoja, 2006; Hall, Hoggan, & Brewster, 2008; Hoggan, Stewart, Haverinen, Jacucci, & Lantz, 2012; Kaaresoja & Linjama, 2005).

The advantages of ERM motors include simple, existing, and inexpensive technology as well as easy control. At the same time, they have a number of limitations. Starting and stopping the vibrating mass take some time, which results in a limited temporal resolution. Furthermore, the intensity and frequency of stimulation are often coupled, preventing independent control of the two parameters (Jones & Sarter, 2008). The actuators are also designed to vibrate the entire mass to which they are attached (e.g., a mobile phone). This results in vibration that is easy to perceive in all areas of the device but conversely makes it difficult to localize the vibration to only a specific area. Thus, ERM motors are not particularly suitable for providing spatial stimulation.
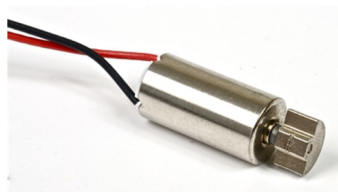
Figure 8. Example of a vibration motor based on an eccentric rotating mass (JPR Electronics Ltd., http://www.jprelec.co.uk).

Linear Voice Coils

Linear voice coil actuators are based on a magnet and movable coil (i.e., contactor) that interact when current is turned on. The operating principle resembles an audio speaker with the exception that the contactor moves perpendicularly to the skin. Voice coil actuators can be controlled easily by using any audio signal as long as the driving frequency is suitable for the particular model. Many voice coil actuators are optimized for frequencies of 200–300 Hz. This is because the peak sensitivity of the Pacinian corpuscles is approximately 250 Hz.

Voice coil actuators such as the C2 (see Figure 9, Engineering Acoustics, Inc.) can be attached either to a device (Hoggan et al., 2007) or directly to the skin (Cholewiak et al., 2004; Lylykangas, Surakka, Rantala, & Raisamo, 2013; Raisamo, Raisamo, & Surakka, 2013; Wheeler, Shull, & Besier, 2011). Compared with ERM motors, voice coil actuators provide better control over stimulation parameters because it is possible to vary both amplitude and frequency independently (Jones & Sarter, 2008). Also, the response time of the actuator tends to be lower compared with ERM motors, which take time to ramp up.

Figure 9. The C2 tactor with a moving contactor visible in the middle (Engineering Acoustics, Inc., http://www.atactech.com).

Piezoelectric Actuators

Piezoelectric actuators utilize thin layers that either shrink or expand depending on the polarity of the driving signal (Poupyrev & Maruyama, 2003). When these layers are attached to other material, the whole structure bends. The layers can be manufactured in various shapes and sizes, making piezoelectric actuators suitable for many devices. Tikka and Laitinen (2006) placed an actuator under the touchscreen of a mobile device (see Figure 10) to create stimulation with different amplitudes and waveforms. The amplitudes could be varied from a few micrometers to a few hundred micrometers.

Figure 10. A piezoelectric actuator placed under the touchscreen of a mobile device. The actuator is shown in its bent stage (Laitinen & Mäenpää, 2006, Figure 2, © IEEE 2006).

Poupyrev, Maruyama, and Rekimoto (2002) placed a smaller piezoelectric actuator inside a PDA device to enable stimulation with low latencies and multiple waveforms. It is also possible to use multiple piezoelectric actuators in an array to provide stimulation varying in its spatial location. Linvill and Bliss (1966) used piezoelectric elements in the Optac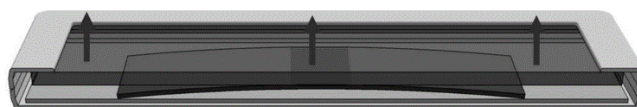on to vibrate a two-dimensional array of 96 pins placed against the user's finger. Piezoelectric actuators are used in many commercial Braille displays where individual pins are positioned linearly in two static modes so that they are either raised or lowered. In addition to using linear skin indentation, piezoelectric elements can be actuated laterally, which results in skin deformation or stretch. This principle was used in the Tactile Handheld Miniature Bimodal, a PDA-like device that provided lateral stimulation to the user's thumb (Luk et al., 2006; Pasquero et al., 2007). The created stimulation resembled a small object sliding under the thumb.

The advantages of piezoelectric actuators include accurate control of pulse dynamics (Tikka & Laitinen, 2006) as well as small size and power efficiency (Pasquero et al., 2007). In addition, they enable both high-frequency vibration and static modes, thereby making the actuators versatile. On the downside, piezoelectric elements need high activation voltages (Pasquero et al., 2007), and the overall cost of a tactile display with associated electronics can be relatively high if dozens of elements are required.

4.3 NUMBER OF ACTUATORS

The number of individual actuators and their arrangement in a mobile device partly defines how and what type of information can be presented. According to Choi and Kuchenbecker (2013), there are two main approaches for arranging the actuators. One can either vibrate an entire rigid object to deliver a widespread vibrotactile cue or embed several actuators in an object or a garment to deliver localized cues. The latter approach seems to be suitable for presenting spatially coded information; by pulsating a specific, spatially localized actuator, it is possible to vary the meaning of vibration. On the other hand, an illusion of spatially localized stimulation can be achieved with a single actuator if it is coupled with a touchscreen device. Poupyrev and Maruyama (2003) observed that if vibration was given when a user interacted with a touchscreen, he or she felt as if the vibration were localized to the point of contact, even though the entire screen moved. In the following review, prior research on presenting information with mobile devices is divided into two parts based on the number of used actuators.

Single Actuator

Presenting alerts via vibrotactile stimulation has been explored in several studies. Stimulation of the sense of touch tends to grab the user's attention,

and the use of a single actuator is sufficient to achieve this. Brown et al. (2005) varied the rhythm and roughness (waveform) of tactons that were presented by a C2 tactor to a user's finger. With these parameters, they encoded the type of information (i.e., voice call, text message, or multimedia message) and its priority (i.e., low, medium, or high). The results of a user study indicated that participants could recognize the information successfully with a mean rate of 71%. In a later study, Brown et al. (2006) presented the same information with a standard ERM motor of a mobile phone. The type of alert was again encoded with rhythm, and the priority of alert was encoded using the intensity of stimulation. Participants recognized the alerts successfully with a mean rate of 72%, which was comparable with the rate achieved with the C2 tactor.

Another application field is to present tactile feedback of interaction with graphical user interface (GUI) elements. One of the first researchers to explore this were Fukumoto and Sugimura (2001), who mounted a voice coil actuator to the back of a touchscreen PDA so that vibration was given to the hand holding the device. They presented vibration when a user clicked on a touchscreen button, and they compared this with the use of an audio beep. The results indicated that the tactile feedback made the use 5–15% faster as compared with the audio feedback. Furthermore, Hoggan et al. (2008) added vibration to virtual buttons with a device that had a linear resonant actuator (LRA) inside. LRA actuators are similar to voice coil actuators but are typically enclosed in a casing that carries the vibration to the surrounding object. In a user study, participants typed in phrases using a virtual QWERTY keyboard that either did or did not provide tactile feedback. A third condition was to use a mobile device that had a physical keyboard. The results showed that participants were more accurate and spent less time typing with the virtual keyboard that provided tactile feedback. However, the physical keyboard was still slightly superior to the virtual keyboard with tactile feedback.

In addition, Kaaresoja, Brown, and Linjama (2006) proposed that tactile feedback could be given of text selection, scrolling, and drag-and-drop interaction. They utilized a prototype device based on a touchscreen and piezoelectric actuators to implement demonstrations of the three interaction types. Leung, MacLean, Bertelsen, and Saubhasik (2007) used a more refined version of similar technology in studying augmentation of GUI elements with tactile feedback. They added vibrotactile feedback to buttons, progress bars, and scroll bars. In a user study, participants were instructed to complete interaction tasks either with or without tactile feedback. The results showed that the participants completed the tasks faster with progress bars and scroll bars that provided tactile feedback.

Multiple Actuators

As discussed earlier, humans can accurately localize the spatial site of a tactile stimulus on the body. This provides a natural cue for egocentric orientation; a single tap on the right shoulder usually makes a person turn to the right (Choi & Kuchenbecker, 2013). Although in most prior studies multiple actuators have been used to stimulate the abdomen (e.g., Cholewiak et al., 2004; van Erp, 2005a) or forearm (e.g., Chen et al., 2008; Cholewiak & Collins, 2003), it is also possible to mount them in a handheld mobile device to stimulate the fingers and the palm. An important factor in the design phase is to ensure that the vibration is truly localized and does not travel through the body of the device.

The importance of the way of attaching actuators to a mobile device was demonstrated in a study by Sahami, Holleis, Schmidt, and Häkkilä (2008). They placed six ERM motors inside a rigid mobile phone mock-up so that three actuators were located along both sides of the phone, close to the back cover. In a user study, the participant's task was to hold the device and try to distinguish which of the actuators was vibrating. The results showed that the average localization accuracy was 36%, suggesting that distinguishing the location of stimulation was difficult for users. It is likely that the vibration dispersed and was carried throughout the body of the phone mock-up due to its rigid material.

Hoggan et al. (2007) attached four C2 tactors to the outside casing of a handheld PDA so that the actuators stimulated the index finger, the ring finger, and the upper and lower parts of the thumb. The actuators were used in creating a tactile progress bar that utilized the illusion of cutaneous saltation. The speed of the illusory motion across the actuators represented the progress speed of a file download. The actuator arrangement was successful, for participants could distinguish the stimulation from different actuators with perfect accuracy. This could be because the C2 tactors are based on a moving contactor that is in direct contact with the user's hand. However, the C2's rather large diameter of 3 cm makes it difficult to place several actuators inside a mobile device.

Yatani and Truong (2009) used five smaller vibration motors in their design. They placed a cell phone in a custom holder that was curved to fit the shape of the user's hand while he or she held the phone. The five actuators were embedded in the holder so that they were isolated from each other and were in direct contact with the skin of the user's palm and fingers. The actuator locations corresponded to top, bottom, left, right, and center of the device. In a user study, the task was to distinguish vibrotactile patterns that were either positional (top, bottom, left, right, and center), linear (bottom-top, top-bottom, left-right, and right-left), or circular (clockwise and counter-clockwise). The results showed that participants could distinguish the positional, linear, and circular patterns

with mean success rates of 90%, 90%, and 75%, respectively. Yatani and Truong also proposed several applications for presenting information with the design. These included a numerical keyboard, music player, calendar, games, navigation aids, and interfaces for the visually impaired.

4.4 SUMMARY

A number of different parameters can be varied to code information with tactile stimulation. Of the possible parameters, spatial location, duration, and rhythm have been identified as particularly suitable for creating stimuli that are easy for users to distinguish. These parameters were also used in the studies reported in this thesis. The choice of tactile actuator type is also important when designing interfaces that use the tactile channel. For instance, voice coil actuators allow for precise control of physical actuation but can be difficult to fit in mobile devices. Piezoelectric actuators, on the other hand, can be extremely small and therefore easy to embed in devices with different shapes and sizes.

Several studies exist on using a single actuator to present alerts and feedback of GUI elements with touchscreen devices. However, less research has been carried out to study whether touchscreen devices and tactile stimulation could be used to present alphabetical information. By sensing the spatial location of user input, it could be possible to provide location-dependent tactile stimulation even with a single actuator. This was the topic of Study I, which aimed at developing a tactile method for reading letters based on the Braille coding. The prior work reported in this chapter also informed the design of Study II. Existing device prototypes stimulating the user's palm and fingers have mainly used actuators that create high-frequency vibrotactile stimulation. This can lead to a situation where the vibration disperses, making it difficult for a user to localize the stimulation source. Because of this, Study II explored the use of linear actuators that would stimulate only a localized area of the user's palm.

5 Touch in Interpersonal Communication

Touch between people is an integral part of human life. This is already evident during the first months of newborn babies. According to Montagu (1986), touch is the first sense to develop and also the first medium of communication. Touch has several important functions in the life of an infant such as regulating physiological states and helping in normal biological and social development (Montagu, 1986). Hertenstein, Verkamp, Kerestes, and Holmes (2006) state that because of its importance in early life, touch may establish the foundation of all other forms of human communication. Even though the frequency of touch contact decreases after early childhood, interpersonal touch is equally important in adulthood. Humans need to touch and be touched throughout their adult years (Jones & Yarbrough, 1985). Touch has common meanings in all cultures, and fundamental uses include communication of comfort, attachment, and aggression (Hertenstein, Verkamp, et al., 2006). This chapter concentrates on the communicative use of touch in adulthood. Special emphasis is put on the use of touch in emotional communication between people.

5.1 MEANINGS OF TOUCH IN SOCIAL INTERACTION

Studying the meanings of interpersonal touch is challenging. Hertenstein, Verkamp, et al. (2006) wrote that a major part of touch communication takes place in private settings, thus making it difficult to study. Also, touch is difficult to measure because it can differ in a number of ways. Touch can vary in its action (e.g., stroking, rubbing, and squeezing), intensity, velocity, abruptness, temperature, location, frequency, duration,

and extent of surface area touched (Hertenstein, 2002). Issues such as the privacy and diversity of interpersonal touch can be taken into account by utilizing different methodological approaches. Thayer (1986) divided prior studies into three categories based on the use of self-report, observational, and experimental methods.

In one of the most comprehensive self-report studies to date, Jones and Yarbrough (1985) asked participants to report all instances of touch that took place in both public and private interaction. The participants were students, and they received detailed instructions on how to record events of them touching someone or of someone else touching them. The results revealed 12 distinct meanings of touch: support, appreciation, inclusion, sexual interest or intent, affection, playful affection, playful aggression, compliance, attention-getting, announcing a response, greetings, and departure. There were also other categories of touch with more ambiguous or hybrid meanings. Overall, the breadth of different meanings was larger than what was expected based on prior work. Also, when excluding ritualistic touches (e.g., handshakes when greeting or departing), significant parts of the reported meanings of touch were related to expression of positive affect. These included support, appreciation, inclusion, sexual interest or intent, and affection. The use of touch for expressing positive affect was evident especially between people in close relationships.

In an observational study by McDaniel and Andersen (1998), the use of interpersonal touch was examined in a public setting to see whether the relationship type or cultural background of people affected their use of touch. The study took place in an airport terminal where people were observed unobtrusively and then interviewed briefly. The results indicated that individuals from Northeast Asia used touch less (i.e., the number of touched body areas was lower) than individuals from Southeast Asia, Caribbean-Latin nations, Northern Europe, and the United States. Furthermore, regardless of the cultural background, individuals who considered themselves friends or lovers used touch significantly more as compared with those who were family members, spouses, strangers, or acquaintances. This finding is in line with other work suggesting that public touch is generally less frequent in casual relationships and initial relationship stages, most extensive among close friends and lovers, and reduced among spouses and family members (Hertenstein, Verkamp, et al., 2006; Willis & Briggs, 1992).

Even though touch is typically used the most between people in close relationships, it has been shown that touch can communicate distinct emotions even between strangers. In an experimental laboratory study by Hertenstein, Keltner, et al. (2006), the task of participant pairs was to communicate 12 distinct emotions using only touch. One participant was

instructed to convey each of the emotions by touching the hand of another blindfolded participant. The study results showed that anger, fear, disgust, love, gratitude, and sympathy were communicated with above chance success rates. Happiness, sadness, surprise, embarrassment, envy, and pride, on the other hand, could not be communicated with above chance rates. In later work, Hertenstein et al. (2009) revised the methodology by allowing touches to other body locations than only the hand and by reducing the number of studied distinct emotions to eight. Surprise, embarrassment, envy, and pride were not included in the second study. The results indicated that this time all the emotions—anger, fear, happiness, sadness, disgust, love, gratitude, and sympathy—could be communicated at above chance rates. The mean success rates for communicating each of the emotions ranged between 50 and 70%. The findings of these two studies suggested that touch can communicate distinct emotions between people.

Furthermore, the work of Hertenstein, Verkamp, et al. (2006) and Hertenstein et al. (2009) revealed that participants used different touch gestures in communicating the intended emotions. For example, anger was most commonly expressed with shaking, pushing, and squeezing. Love, on the contrary, was typically communicated with hugging, patting, and stroking. Also, the durations and intensities of touches were different depending on the communicated emotion (Hertenstein et al., 2009). For instance, sadness elicited light-intensity touch with moderate duration, whereas anger was characterized by strong- to moderate-intensity touch with shorter duration. These findings indicate that differences in the physical contact alone can convey the meaning of interpersonal touch. On the other hand, in some cases one type of physical contact can be assigned different meanings. This is known as the principle of equipotentiality (Hertenstein, Verkamp, et al., 2006). Placing an arm around one's shoulders can be interpreted differently depending on the communication partners and their relationship.

In conclusion, research with different methodological approaches has indicated that interpersonal touch has a role in emotional communication between people, and this is evident especially with people in close relationships. The communicative capabilities of human touch result from the number of different touch gestures that people use in interacting with each other. Thus far, we have discussed communication where two people are situated in a shared physical space. This has traditionally been the inherent limitation of touch; to be able to touch something, one needs to be close to it. However, this limitation can be partly circumvented by using haptic technology to mediate interpersonal touch.

5.2 Mediated Social Touch

Because touch communication research has shown that physical touch is an integral part of human life, researchers in the fields of haptics and HCI have started to investigate whether some of the effects of physical touch could be replicated by using technical devices to mediate touch between people. A central concept in this field is *mediated social touch*, which has been defined as "the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology" (Haans & IJsselsteijn, 2006). This section focuses on tactile feedback technology suitable for mobile settings.

Partial support exists for the assumption that touch mediated via tactile technology can have similar effects to physical touch. Haans et al. (2007) investigated response similarities between mediated and non-mediated touch by considering gender differences. The authors hypothesized that if mediated social touch resembles non-mediated touch, then participants would evaluate mediated touch from the opposite sex as more pleasant than mediated touch from the same sex. To study this, a vest and two arm straps were used for presenting vibrotactile patterns, and the participants were led to believe that the patterns were created by either a male or a female stranger. The results did not show a significant gender effect. However, an effect of body location of touch was found. Similarly to a non-mediated touch, a mediated touch on the stomach was perceived as more unpleasant than a mediated touch on the upper arm. In addition, Haans and IJsselsteijn (2009) investigated whether mediated social touch could increase people's altruistic behavior and willingness to comply with a request similarly to a non-mediated touch. This is also known as the Midas touch phenomenon. To imitate touch, the researchers had the participants wear on their upper arm a strap equipped with six vibrotactile actuators. A comparison with prior work indicated that the strength of the Midas touch in the mediated setting was comparable with the Midas touch in the non-mediated setting.

The findings of Haans et al. (2007) and Haans and IJsselsteijn (2009) are promising considering that a large number of studies exist on enabling emotional communication via mediated social touch (e.g., Bonanni, Lieberman, Vaucelle, & Zuckerman, 2006; Mueller et al., 2005; Park et al., 2010). The recurring theme in these studies has been to develop mobile and wearable research prototypes that could be used for communicating emotions between users. The following subsections provide an overview of these studies. The first study (Chang et al., 2002) did not focus on emotional communication, but it is included here because the presented tactile technology is of interest regarding the emotional use of mediated social touch. In general, the reviewed prior work was chosen on the basis of either guiding the original studies presented in this thesis or being

similar to them. For further information on mediated social touch, the reader should see an extensive review by Haans and IJsselsteijn (2006).

ComTouch

One of the first studies on this topic was carried out by Chang et al. (2002), who introduced ComTouch, an interface that augmented remote speech communication with a tactile channel. The idea was to convert finger pressure of one user to vibrotactile stimulation felt on the finger of another user. This was achieved by using force-sensing resistors to measure the pressure and small vibrotactile actuators to present stimulation. In practice, the users placed their hands on a custom plate so that they used their index fingers for both initiating touch and feeling the vibration.

In a user study, the task of participant pairs was to use the tactile channel the way they saw fit during a free-form discussion and a negotiation scenario. The results indicated that the tactile stimulation was used mainly for signaling emphasis, turn-taking, and mimicry. For instance, the participants emphasized a phrase by synchronizing the tactile signal with their speech or signaled that they were about to start speaking. In the case of mimicry, the participants echoed back tactile patterns that they received. Although the ComTouch had distinct uses, the participants did notice limitations with the design. They commented that even though the intensity of finger pressure was mapped to the intensity of vibrotactile stimulation, the difference was hard to recognize. Also, the participants would have liked to use multiple fingers instead of only their index fingers.

Hug Over a Distance

Mueller et al. (2005) introduced Hug Over a Distance, an air-inflatable vest that was designed for communication of intimate and emotional content for people in close relationships. The vest covering the user's upper body torso included air compartments that could be filled using an air compressor. This resulted in a sensation of light pressure that could resemble a physical hug. The artificial hug could be triggered remotely by another user.

The results indicated that participants could not see themselves using the vest. One explanation for this was the fact that the air compressor generated audible noise that was hard to separate from the tactile sensation. In addition, the participants commented that giving a hug is a two-way interaction, and during the study only a single vest was available for use. To date, no formal user studies have been reported on evaluating the capability of the Hug Over a Distance to communicate intimacy or emotions between people.

TapTap

TapTap was a haptic wearable designed for conveying the emotional and physical benefits of human touch using tactile stimulation (Bonanni et al., 2006). The main goal was to use TapTap for emotional touch therapy so that predefined touch patterns could be broadcasted to multiple users. The first prototype was based on an idea of presenting four types of touch gestures: tap, press, stroke, and contact. For this purpose, vibration motors, linear solenoids, pneumatic air bladders, and thermal Peltier elements were considered. However, the air bladders and Peltier elements were soon discarded because of their bulkiness and mechanical failure, respectively. The vibration motors and solenoids were arranged in groups of eight so that an illusion of movement could be created by driving them in a sequence. The actuators were attached to a neoprene brace that the users wore over their shoulder blade.

Participants in a pilot study perceived the brace as too constraining. The second prototype utilized a scarf-like form factor so that users could more easily choose when and how to wear it. Even though no formal communication experiments were conducted with TapTap, the pilot study did elicit some interesting comments. Women and men perceived the stimulation of vibration motors and solenoids differently. Women preferred the vibration motors that provided gentle stimulation, whereas men preferred the solenoids that created more intense stimulation.

CheekTouch

Park et al. (2010) presented CheekTouch for enabling affective touch-based interaction while speaking on the phone. Their design was based on a 4 × 3 array of vibrotactile actuators attached to the backside of a touchscreen device. The backside with the actuators was held against the cheek, while the touchscreen facing outwards could be touched with the index and middle fingers. The aim was to imitate touch gestures of pat, slap, pinch, stroke, kiss, and tickle by detecting the touch input and by triggering predefined tactile patterns corresponding to each of the gestures.

The results of a user study showed that participants could recognize the tactile patterns with mean success rates of 50–100%. However, they also expressed a desire for free-form touch that would not be limited to the six predefined gestures. In a later study, Park, Bae, and Nam (2012) refined the design by moving to a 3 × 3 actuator array and by allowing free-form gestures that were detected in real time and mapped to vibrotactile stimulation. Using the refined prototype, the authors conducted a user study where couples used the devices for 20 minutes per day for 5 consecutive days. The aim was to find out how they would utilize CheekTouch during phone conversations. By analyzing the gesture data, the authors found a number of use cases such as comforting, conveying

status and presence, expressing numerical count, emphasizing emotions, and calling for attention.

Pressages

Pressages, or pressure-based messages, were introduced by Hoggan et al. (2012), who used squeezing of the side of a mobile device to create vibration on a recipient's phone. For detecting squeezing, they attached a force-sensing resistor to the side of a Nokia N900 phone. The phone's standard ERM motor was used to present tactile stimulation. The authors chose four discrete pressure levels that were mapped to four different tactile textures. The textures were composed by varying the intensity and duration of stimulation.

To evaluate the concept, Hoggan et al. (2012) ran a longitudinal study with three couples in long-distance relationships. The couples were asked to use the force-sensing phones instead of their normal phones for a period of 1 month. The users could create tactile stimulation by squeezing the phone while speaking. The results indicated that the couples used the tactile stimulation for three main purposes: to emphasize speech, to express affection and presence, and to playfully surprise each other. Emphasis was added, for example, to greetings. In expressing affection, some participants commented that the use of tactile stimulation resembled stroking their partner. The stimulation was used less for expressing anger, and the participants commented that strong vibrations could make the receiver angry, too. In playful use, the stimulation was used to surprise or make the other person laugh.

TaSST

The Tactile Sleeve for Social Touch (TaSST) was developed for studying different types of touch gestures in mediated social touch (Huisman, Darriba Frederiks, Van Dijk, Heylen, & Kröse, 2013). The device was wrapped around the user's forearm, and it used two different layers for sensing input and presenting output. Conductive wool pads were positioned in a 4 × 3 grid for sensing touch input. Under the sensing layer, a corresponding grid of ERM actuators was used for stimulating the skin of the forearm.

In a user study, the participants' task was to sense stimulation recorded by the experimenters and to replicate the sensed stimulation by touching the TaSST. The experimenters had recorded three types of gestures: simple (poke and hit), protracted (press and squeeze), and dynamic (rub and stroke). The results indicated that dynamic touches were the most difficult to replicate. On the basis of the findings, the authors improved the design by manufacturing a thinner input layer to facilitate dynamic touches and by making the vibration more spatially localized (see Figure 11).
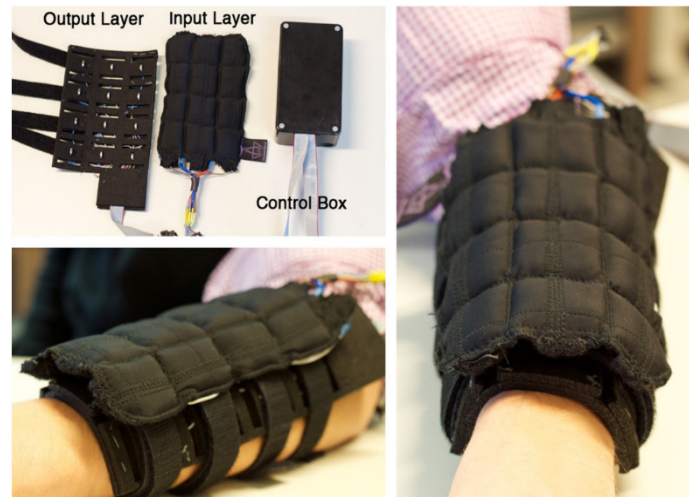
Figure 11. The improved version of the TaSST with input and output layers shown in top-left (Huisman et al., 2013, Figure 4, © IEEE 2013).

In a later study, Huisman and Darriba Frederiks (2013) investigated how users interacted with the TaSST when asked to express eight distinct emotions. The task was to record tactile stimulation that would best represent anger, fear, happiness, sadness, disgust, love, gratitude, and sympathy. The authors analyzed parameters such as area of touch contact and average duration to find possible differences between the expressions of the eight emotions. They concluded that the participants did vary their expressions to some extent. However, no studies have been reported to date on evaluating the TaSST in mediated communication between users.

Limitation of Prior Studies

The potential of mediated social touch in emotional communication has been explored in a number of studies (Bonanni et al., 2006; Hoggan et al., 2012; Huisman et al., 2013; Huisman & Darriba Frederiks, 2013; Mueller et al., 2005; Park et al., 2010, 2012). However, as Haans and IJsselsteijn (2006) wrote, "very few studies are available that report on empirical system validations beyond the level of anecdotal descriptions of user experiences." This is very much the case with emotional use of mediated social touch, even though in their review Haans and IJsselsteijn discussed mediated social touch research in general.

There is a lack of research on studying whether touch mediated via tactile technology can indeed communicate emotions between two people the way they intended. The intended emotion and the participants' capability to successfully communicate it need to be defined and measured in a systematic manner. This leads us to theories of emotions that could provide a theoretical foundation for empirical studies. The following section introduces the two main theories together with prior examples of applying them in haptics research.

5.3 THEORIES OF EMOTIONS

The two prevalent theoretical approaches to emotions are the differential and dimensional theories. The differential theory of emotions suggests that there exists a set of discrete emotions that are also often referred to as basic emotions (e.g., Ekman, 1992; Izard, 1977; Johnson-Laird & Oatley, 1989). The theory suggests that all basic emotions have their own neural and physiological background, and all other emotions are derived from the basic emotions. According to Ekman (1992), the six basic emotions are anger, fear, sadness, enjoyment, disgust, and surprise. The list of basic emotions varies between different researchers (e.g., Johnson-Laird & Oatley, 1989), but the set introduced by Ekman is widely recognized as one of the most influential. For an emotion to be classified as a basic emotion, it must meet a number of requirements. For instance, each basic emotion has a distinctive, universal facial expression (Ekman, 1994).

In previous haptics research, the differential theory of emotions has been used by Bailenson, Yee, Brave, Merget, and Koslow (2007) for studying communication of emotions using a force-feedback device. The device resembled a joystick and allowed movement similar to a handshake with two degrees of freedom. The task of one group of participants was to use the device for expressing seven different emotions: anger, disgust, fear, interest, joy, sadness, and surprise. The participants' interaction with the device was recorded and played back to a second group of participants who attempted to recognize the seven emotions. The emotions were listed on a sheet of paper, and each emotion could be chosen only once. The results showed that the emotions were recognized with a mean success rate of 33% when the chance level was 14%. A control experiment where participants attempted to express the same emotions using non-mediated, physical handshakes showed that the corresponding success rate was 51%. Thus, the participants were capable of recognizing emotions via mediated social touch with an above chance success rate, but the rate was still lower than that for non-mediated touch. In addition, Smith and MacLean (2007) used four emotion words—angry, delighted, relaxed, and unhappy—in studying communication of emotions via one-degree-of-freedom haptic devices. One participant moved his or her device, while the other attempted to recognize the intended emotion via a second device. The results showed that the pairs could communicate the emotions with a mean success rate of 54% (chance level 25%).

The dimensional theory of emotions organizes emotions along a set of dimensions (e.g., Bradley & Lang, 1994; Russell, 1980; Russell, Weiss, & Mendelsohn, 1989; Schlosberg, 1954). Each emotion is a combination of these dimensions rather than an independent emotion. A model by Bradley and Lang (1994) consists of three dimensions: valence (from unpleasant to pleasant), arousal (from relaxed or calm to arousing), and dominance (from the feeling of the stimulus being in control to the feeling

of the user being in control). One established method to measure changes and responses in the dimensions is to use bipolar rating scales. Bradley and Lang (1994) presented the self-assessment manikin for non-verbal pictorial assessment. The technique uses a paper sheet with pictures for assessing the valence, arousal, and dominance. For example, valence is represented with a set of five figures that range from a frowning face to a pleasant face. Participants can check any of the figures or alternatively place a mark between two figures. This results in a nine-point rating scale.

Salminen et al. (2008) used the dimensional theory of emotions in studying emotional experiences evoked by vibrotactile stimulation. A friction-based prototype device was used to stimulate the participant's fingertip with rotational movement. The task was to sense the stimuli and rate them using nine-point bipolar scales for valence, arousal, dominance, and approachability. The results revealed significant differences between the ratings of stimuli. For instance, continuous stimulation without temporal intervals was rated as more unpleasant, arousing, dominating, and avoidable than discontinuous stimulation with temporal intervals. In a later study, Salminen et al. (2009) used the same methodology to evaluate the effect of use context on emotional experiences evoked by vibrotactile stimuli. A touchscreen device with a piezoelectric actuator presented stimuli that participants rated both in a laboratory and in a moving bus. The results indicated that the stimuli were rated as more pleasant, less arousing, and less dominant in the moving bus. It should be noted that in the studies of Salminen et al. (2008, 2009), the stimuli were defined beforehand and no interpersonal communication setting was included. To adapt the methodology to communication of emotional intention, it would be possible to ask one participant to intentionally create a stimulus that represents a particular position in the dimensional space. Then, a second participant would rate the felt stimulus using the bipolar rating scales. This would provide a way to assess the similarity of the intended and experienced emotions between communication partners.

Even though the differential and dimensional theories seem to be separate approaches to emotion research, they do share some similarities and can in fact be regarded as complementary rather than opposite. Both theories can be used in haptics research to assess the experienced emotionality of touch stimulation. The differential theory provides a predefined set of possible emotions, whereas the dimensional theory allows more freedom in positioning an emotional experience to the multidimensional space. Smith and MacLean (2007) and Bailenson et al. (2007) chose an approach closer to the differential theory because the communicated distinct emotions were chosen from a list. Although the given emotions could be conveyed with above chance success rates in both studies, the findings cannot be directly translated to mobile settings because the used devices created force feedback rather than tactile stimulation. Salminen et al. (2008,

2009) chose the dimensional theory for their studies and showed that bipolar rating scales can be used to measure differences in emotional experiences evoked by tactile stimulation. The research reported in this thesis followed the methodology of Salminen et al. (2008, 2009). Communication of emotional intention was evaluated using bipolar rating scales for valence and arousal.

5.4 SUMMARY

Touch has an important role in interaction between adults. This chapter concentrated on the emotional use of touch in interpersonal communication that is particularly common between people in close relationships. Different touch gestures have been shown to be capable of communicating distinct emotions between people who are in a shared physical space. This has resulted in an increased interest in developing technology that could mediate social touch between people who are physically apart.

It has been hypothesized that mediated social touch could communicate emotions similarly to non-mediated, physical touch. However, few studies have reported results of empirical experiments to assess this hypothesis. The last three studies reported in this thesis (Studies III–V) aimed at contributing to this field of research. Study III was motivated by the different touch gestures that people use in touch interaction. The goal was to imitate certain characteristics of touch gestures by transferring them to vibrotactile stimulation created using spatial actuators. Study IV evaluated the touch gestures in communicating emotional intention between two users. The dimensional theory of emotions was adopted for this purpose. Finally, Study V expanded the use context from tactile-only to audio-tactile communication where participants could use the gestures while speaking.
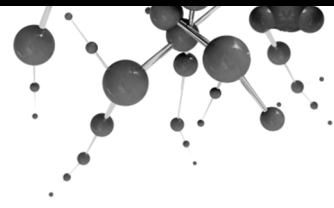
6 Methodology

The research reported in this thesis was constructive and empirical. Functioning prototypes were used in laboratory experiments to evaluate how the implemented methods performed in presenting information. Volunteer participants were recruited for this purpose. The evaluated methods were non-invasive, and each participant read and signed an informed consent form before proceeding to the experiment. If an explicit ethical permission was needed to run an experiment, the permission was acquired. The experiment reported in Study IV was conducted at Stanford University with an approval from the Stanford Institutional Review Board. Data from all experiments were kept in a safe place, and the anonymity of individual participants was protected when reporting the results.

6.1 CONSTRUCTIVE APPROACH

Our choice to use a constructive approach was due to several reasons. The use of touch stimulation is a new medium of communication for the majority of people. It would be difficult to estimate the potential of different methods using only higher level measures such as interviews and focus groups. In addition, tools such as paper prototyping are feasible with visual information but difficult to reproduce in the case of tactile stimulation. The choice was also partly dictated by our interest in measuring the usability of the proposed tactile interaction methods. This could be estimated only with functioning prototypes that stimulate the user's skin.

The research question of each study guided the selection of the prototype device that had to meet certain input/output requirements. The work reported in this thesis was conducted as a part of several research projects

that provided access to existing prototype devices (Studies I and III–V) and to tools for manufacturing novel ones (Study II). The selection of a device was followed by development of the tactile interaction methods. C, Java, and Pure Data programming environments were used for this purpose. The methods were developed in an iterative manner so that the current author and project colleagues first evaluated the use informally and then made required modifications to ensure the general feasibility of the methods. This phase included, for example, setting the overall intensity level of tactile stimulation.

6.2 EMPIRICAL EVALUATION

Our general aim was to evaluate the usability of the developed tactile interaction methods in presenting information to users. According to the ISO 9241-11 (1998) definition, usability is defined in HCI as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use." First, *effectiveness* refers to the accuracy and completeness with which users achieve specified goals. In the current context, this can be understood to be related to the successfulness of communicating specified information content.

In prior work on tactile communication, a key quantitative measure in evaluating the effectiveness has been the success rate (or accuracy) of communication (Bailenson et al., 2007; Bliss et al., 1970; Brown et al., 2005; Brown & Kaaresoja, 2006; Hoggan & Brewster, 2007; Levesque et al., 2007; Smith & MacLean, 2007). A success rate of 100% would be ideal because it indicates that information coded in different stimuli was interpreted by a user without any mistakes. The advantage of using the success rate as a measure is that it can be easily calculated based on experimental data, and it is also easy to interpret. Furthermore, it can be used to estimate communication of different types of information such as alerts (Brown et al., 2005; Brown & Kaaresoja, 2006), letters (Levesque et al., 2007), and emotional intention (Bailenson et al., 2007; Smith & MacLean, 2007). In this thesis, the success rate was used in three studies (I, II, and IV) that included specific communicative goals. In Study IV, the success rates were derived from subjective ratings of valence and arousal that were gathered using nine-point rating scales.

Even though the success rate of communication is a widely accepted measure, it does have limitations. Success rates are difficult to generalize across other types of communication tasks or tactile technologies (Tan, Reed, & Durlach, 2010). An alternative is to use an information transmission (IT) rate that is less dependent on a particular experimental setting (Tan, 1996; Tan et al., 2010). IT rates are measured in bits per second, which takes into account the presentation speed of tactile stimuli

(and, subsequently, information as well). Therefore, IT rates are particularly useful in optimizing the speed of information presentation in applications where fast reading rates are valuable (e.g., reading several pages of text). This is related to *efficiency*, which is the second aspect of studying the usability of HCI. Although we measured the time used for acquiring information in Study I, the emphasis was not on optimizing presentation rates across several types of tactile devices; therefore, IT rates were not reported. Instead, the reading speeds in Study I were reported in characters per second (cps) and words per minute (wpm), which are established measures of input and output speed (MacKenzie & Soukoreff, 2002). The length of one word is five characters when using words per minute.

The third aspect, *satisfaction*, was evaluated qualitatively to reveal participants' subjective impressions of the devices and overall interaction. For example, it is not desirable to use stimulation that is perceived as unpleasant, even if information could be communicated successfully. One way to gain insight of participants' subjective impressions is to conduct interviews after the experiment. We carried out unstructured interviews in Studies I and III, where participants were first asked to comment on certain predefined themes. After that, they could also give other general comments on the use. In Studies IV and V, we used semi-structured interviews (DiCicco-Bloom & Crabtree, 2006) where a set of predefined questions was presented to the participants. The interviewer asked clarifying questions in case the participants needed to explain their answers further.

In addition to measuring the effectiveness, efficiency, and satisfaction, we also wanted to understand how participants interacted with the prototype devices. For this purpose, we analyzed features such as the intensity and duration of touch by logging data of touch input (Studies III and IV), by using video recordings of interaction (Studies I and III), and by unobtrusively observing the interaction while it took place (Studies I and III–V). We hypothesized that such data could help in understanding whether the interaction methods were used in a manner that we expected. If not, the data could help in developing the methods further to take into account the other emerged use practices.

7 Introduction to the Studies

The overarching theme in the individual studies of this thesis was to evaluate how spatial touch input and/or output could be used in presenting information. To demonstrate the input/output division of each study, Figure 12 shows the studies positioned to the interaction space of spatial touch introduced in Chapter 1. Study I focused mainly on spatial input. Different input locations were mapped to vibrotactile output created using a single actuator. Study II explored the use of spatial output. Four actuators were used for presenting directional tactile patterns to the user's palm, and no user input was required because the patterns were triggered automatically. Studies III–V concentrated on combining spatial input and spatial output. A device was used that sensed multiple touch gestures and transferred them to vibrotactile stimulation presented with either one or four actuators.
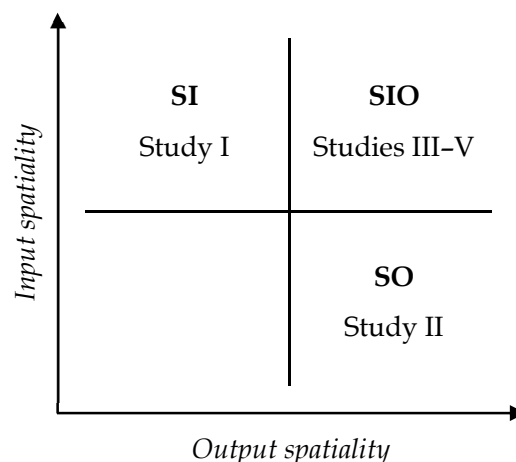

Figure 12. The individual studies of this thesis situated in the interaction space of spatial touch.

A second way to classify the five studies is to represent them in a continuum based on their application type that ranged from individual to shared (Figure 13). Because Study I aimed at presenting letters to a single user, it was positioned to the left end of the continuum. In Studies II and III, the applications were designed primarily for communication between two remote users. However, the experiments included no interpersonal communication tasks; the applications were evaluated by a single user at a time. Because of this, the studies were positioned to the middle of the continuum. Studies IV and V focused on emotional communication using a shared application, and the application was also evaluated in practice by participant dyads in our experiments. Thus, these studies were positioned to the right end of the continuum.

Study I	Studies II & III	Studies IV & V
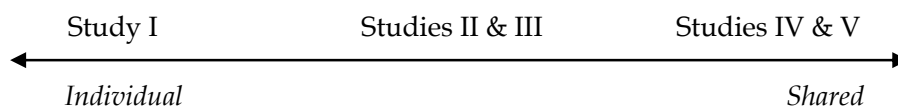
Individual   *Shared*

Figure 13. The studies organized along a continuum ranging between applications designed for individual or shared use.

The following sections introduce each of the five original studies. The aims and used methodologies of each study are presented along with the main results and discussion. The purpose of these sections is to provide an overview of the conducted research so that the findings can be discussed in a more general level in Chapter 8.

7.1 STUDY I: BRAILLE WITH VIBROTACTILE STIMULATION

Reference

Rantala, J., Raisamo, R., Lylykangas, J., Surakka, V., Raisamo, J., Salminen, K., Pakkanen, T., & Hippula, A. (2009). Methods for presenting Braille characters on a mobile device with a touchscreen and tactile feedback. *IEEE Transactions on Haptics*, 2(1), 28–39. doi:10.1109/TOH.2009.3

Objective and Methods

Our aim was to study whether Braille characters could be presented successfully to blind users by utilizing vibrotactile stimulation on a touchscreen device. We identified this as a potential application to study spatial touch input because touchscreens offer a relatively large input area but virtually no information of its use for the blind. We used a prototype version of the Nokia 770 Internet Tablet that had a piezoelectric actuator embedded under its touchscreen. The actuator vibrated the entire screen, but an illusion of spatial output could be provided by triggering different tactile stimuli depending on the user's input location on the screen. We used two stimuli with varying amplitudes and durations for presenting the raised and lowered Braille dots.

We developed three methods to access the dots. The first two methods used spatiotemporal coding to present the six dots of a letter. In the first method, scan, the dots were positioned spatially on the screen according to the traditional Braille cell layout of two columns and three rows. The six dots were read one by one by gliding a stylus or finger over the columns. In the second method, sweep, the dots were arranged horizontally so that they could be read using a single stroke from left to right or vice versa. The third method, rhythm, relied solely on temporal coding. The dots were presented with predefined time intervals once the stylus or finger touched any screen location.

To evaluate the effectiveness of the methods, we conducted two separate experiments with five blind participants who were experienced readers of Braille. In the first experiment, all three methods were tested in reading single letters of the Finnish alphabet. All 29 letters were presented in a randomized order using each method. In the second experiment, the presentation speed of the rhythm was increased to study whether this affected the success rates of reading. In both experiments, the participants' task was to indicate which letter they thought was presented.

Results and Discussion

The results of the first experiment showed that all three methods were feasible in presenting information, for the participants read single letters correctly with mean success rates of 91–97%. The average times spent for reading a letter varied between 3.7 and 5.7 seconds. The reading times for the scan and sweep methods were longer than for the rhythm method because the scan and sweep methods required lateral movement to feel the dots. In addition, the participants tended to rate the subjective experience of using the rhythm more positively as compared with the other two methods. The second experiment showed that the reading speeds of the rhythm method could be further improved by increasing the presentation speed (i.e., decreasing the intervals between dots). When the presentation speeds were 2.45, 1.85, and 1.25 seconds per letter, the participants read letters successfully with mean success rates of 83%, 84%, and 70%, respectively. As could be expected, interpreting the information became more difficult when the presentation speed increased.

Our findings showed that alphabetical information can be conveyed by presenting different tactile stimuli depending on the location of spatial input. Blind participants were able to read letters correctly in over 9 of 10 cases. We also learned that spatiotemporal coding is less efficient than temporal coding in terms of reading speeds. The rhythm method was the most efficient of the three methods. Still, the fastest reading speeds of 9.6 wpm with the rhythm method were notably slower as compared with 100 wpm reported for printed Braille (Warren, 1978). Furthermore, several participants commented that the methods required intensive

concentration, suggesting that the cognitive requirements of the new temporal representations were higher than those of traditional Braille.

7.2 STUDY II: STIMULATION WITH LINEAR ACTUATORS

Reference

Rantala, J., Myllymaa, K., Raisamo, R., Lylykangas, J., Surakka, V., Shull, P., & Cutkosky, M. (2011). Presenting spatial tactile messages with a hand-held device. In *Proceedings of IEEE World Haptics Conference 2011 (WHC '11)*, 101–106. Washington, DC, USA: IEEE. doi:10.1109/WHC.2011.5945469

Objective and Methods

In the second study, we began to explore the use of multiple actuators for spatial output. The aim was to find out whether distinguishing the location of spatial stimulation on the hand could be made easier by using stimulation other than vibration. Our motivation was that the typically used high-frequency vibration propagates along the skin (Sofia & Jones, 2013) and therefore activates Pacinian corpuscles farther from the point of stimulation. This makes it difficult for a user to tell the exact spatial location of touch, which in turn affects the presentation of information.

To address this, we implemented a device that stimulated the user's palm with linear actuation. The actuation resembled tapping one's hand with the blunt end of a pen. We chose this because low-frequency (15 Hz) tapping is sensed via Merkel receptors and Meissner corpuscles that can detect fine spatial differences (Gardner et al., 2000). We embedded four linear actuators to the device with an intertactor spacing of 3 cm that was well above the spatial resolution of the hand (Johnson & Phillips, 1981; Weinstein, 1968).

We conducted an experiment to evaluate the effectiveness of presenting different tactile stimuli with the device. The stimuli were adapted from Yatani and Truong (2009), who used a set of positional, linear, and circular stimuli. Positional stimuli activated only a single actuator. Linear stimuli activated either two or four actuators so that an illusion of movement was perceived, for example, from left to right. Circular stimuli activated all four actuators, creating clockwise or counter-clockwise movement. Each stimulus was presented twice with two durations (i.e., 1 and 2 seconds) and two device configurations (i.e., square and diamond). Thus, a total of 80 stimuli were presented per participant. The participants' task was to indicate which stimulus they felt.

Results and Discussion

The results showed that recognizing the stimuli was an easy task for the participants. The mean success rates for positional, linear, and circular stimuli were 99%, 97%, and 90%, respectively. The stimulus duration and

device configuration had no effect on the rates. We compared these results with prior work on using high-frequency vibration. In a study by Yatani and Truong (2009), participants recognized similar circular stimuli with a mean success rate of 75% when presented with vibration. It should be noted that we could not compare the success rates of positional and linear stimuli because Yatani and Truong utilized five actuators to present them. Nevertheless, this partial comparison suggested that stimuli moving in a circular manner were easier for people to distinguish when using linear actuation. Thus, tactile technology capable of providing linear actuation with low frequencies could be useful if accurate localization is needed. The downside of the current technical solution was that the actuators moved properly only when the device was held in an upright position, suggesting that further development would be needed before practical use.

In this study, we did not assign the stimuli with any explicit information content (cf. letters in Study I) because the aim was simply to find out how well users performed in localizing the spatial locations of stimulation. However, the main application field considered when planning and running Study II was mediated social touch. Being able to stimulate different parts of the user's hand is a requirement for replicating touch gestures such as stroking. This could be done by driving several actuators in a sequence. The next study pursued this idea by incorporating touch sensing into a device so that physical gestures could be detected and replicated with tactile stimulation.

7.3 STUDY III: TOUCH GESTURES IN INTERPERSONAL COMMUNICATION

Reference

Rantala, J., Raisamo, R., Lylykangas, J., Ahmaniemi, T., Raisamo, J., Rantala, J., Mäkelä, K., Salminen, K., & Surakka, V. (2011). The role of gesture types and spatial feedback in haptic communication. *IEEE Transactions on Haptics*, 4(4), 295–306. doi:10.1109/TOH.2011.4

Objective and Methods

The focus of the third study was on combining spatial input and spatial output in mediated social touch applications. We wanted to find out what touch gestures would be feasible for providing input as well as to understand whether users preferred multiple spatial actuators in feeling the resulting vibration. We assessed the whole interaction from sensing a gesture to presenting it with tactile stimulation, whereas prior work has focused more on using predefined stimulation (Bonanni et al., 2006; Huisman et al., 2013; Mueller et al., 2005; Park et al., 2010). We expected that with this approach we could get a more realistic understanding of the ways people use and perceive mediated social touch.

For this study, we needed a device capable of detecting different gestures. Thus, we could not utilize the device from Study II. We used another device that detected three touch gesture types: moving, squeezing, and stroking. These gestures that are common in everyday touch interaction were selected based on the findings of a prior study (Heikkinen et al., 2009). The device detected moving with gyroscopes, squeezing with force-sensing resistors, and stroking with a capacitive touchpad. The spatiality of tactile stimulation was varied by using two actuator types. Four linear vibration motors were embedded in the sides of the device for providing stimulation that followed the spatial location of touch input. In addition, one larger actuator was placed inside the device to vibrate its whole body. The intensity and duration of touch gestures were mapped to the amplitude and duration of tactile stimulation, respectively.

To understand which input and output method users preferred, we carried out an experiment where participants were asked to create tactile messages with the device. The participants were given four example communication scenarios (e.g., send a nice haptic message to a loved one) and instructed to create stimulation that they found suitable for the scenarios. Each scenario was presented six times to evaluate all the possible input method (i.e., moving, squeezing, and stroking) and output method (i.e., one or four actuators) combinations. We did not measure actual communication between users. Instead, each participant was instructed to imagine that another person would feel the created messages. After each scenario, the participants used nine-point rating scales to evaluate the applicability, easiness, expressiveness, reasonability, and pleasantness of the particular input–output method combination.

Results and Discussion

The results of the subjective ratings and post-experimental interviews showed that the participants tended to prefer squeezing and stroking to moving. Squeezing was perceived as a significantly more reasonable input method than moving. Also, the participants commented that squeezing and stroking were generally easy to use, whereas moving required more training. We believe that one reason for these different preferences could be that moving the device in midair mainly resembled pointing, which is not directly related to interpersonal touch. When the participants squeezed or stroked the device, on the other hand, the device could be understood to be a metaphor of the recipient. In addition, the participants perceived the four spatial actuators as significantly more expressive and applicable than a single actuator. Spatial stimulation was beneficial especially when using stroking gestures that included lateral movement. Some of the participants commented that spatial stimulation felt more natural and facilitated the expression of nuances.

In conclusion, we found some hints suggesting that supporting the spatial features of touch could prove useful in mediated social touch applications. Squeezing and stroking could be mimicked more accurately with tactile stimulation from four spatial actuators. The participants of Study III envisioned that mediated social touch would be useful in relatively simple use case scenarios such as emphasizing words or expressing comfort. However, the limitation of Study III was that no interpersonal communication took place; thus, we could not evaluate whether the gestures could convey information between people. This was the topic of the following study, which focused on communication of emotional intention.

7.4 STUDY IV: GESTURES IN COMMUNICATING EMOTIONAL INTENTION

Reference

Rantala, J., Salminen, K., Raisamo, R., & Surakka, V. (2013). Touch gestures in communicating emotional intention via vibrotactile stimulation. *International Journal of Human-Computer Studies*, *71*(6), 679–690. doi:10.1016/j.ijhcs.2013.02.004

Objective and Methods

The aim in this study was to evaluate whether vibrotactile stimulation that represents squeeze and finger touch (e.g., stroking) gestures could convey intended emotions from one person to another. Squeeze and finger touch gestures were selected based on the findings of Study III, and we also used the device from Study III with the four spatial actuators. When one person squeezed the device or touched it with finger(s), another person felt corresponding stimulation on his or her device simultaneously.

We conducted an experiment with participant dyads who were either intimate couples or friends. The two participants were assigned with the roles of a sender and a receiver, and they were situated in different laboratory rooms so that they could interact only via the tactile device. The dyads attempted to communicate variations in the affective dimensions of valence and arousal. The sender's task was to convey unpleasant, pleasant, relaxed, or aroused emotional intention to the receiver by creating suitable stimulation. The experiment consisted of eight trials (two gestures × four intended emotions).

After each trial, both the sender and receiver rated the stimulation using nine-point scales for valence and arousal so that we could measure the match between the sender's intended emotion and the receiver's interpretation. The receiver was neither aware of the sender's goal of communicating the four emotions nor told which gesture the sender used.

Results and Discussion

The results showed that the match between the senders' and receivers' ratings depended on the used touch gesture. Squeeze was suitable for communicating unpleasant and aroused emotional intention, whereas finger touch was more suitable for conveying pleasant and relaxed intention. With these gestures, the mean success rates for communicating variations in valence and arousal were 75% and 79%, respectively (chance level 50%). In other words, when the more suitable gesture was used, the participants perceived the emotionality of mediated touch similarly in roughly three of four cases. The success rates were closer to chance level if the effect of touch gesture was not taken into account. The overall success rates calculated over both gestures for valence and arousal were 49% and 69%, respectively.

We believe that the different emotional interpretations of the touch gestures could be explained by considering the parameters of the vibrotactile stimulation. Stimulation created with squeeze typically had higher amplitude, whereas finger touch resulted in more spatial variation between the four actuators. Furthermore, we found some similarities between our results and those of previous studies on non-mediated touch. Hertenstein et al. (2009) reported that squeeze was often used for expressing anger and fear, which are associated with unpleasantness and arousal in the dimensional space used in our study. Finger touch gestures such as stroking and patting, on the contrary, communicated mainly positive emotions in the non-mediated setting (Hertenstein et al., 2009) and pleasant and relaxed emotional intention in our study. These similarities can be seen as partial evidence for the assumption that mediated touch could communicate emotional intention between people.

Because we focused solely on the tactile modality in Study IV, the participants could not utilize the gestures in more natural, multimodal communication. Thus, the next step was to evaluate the use of the gestures together with speech.

7.5 STUDY V: GESTURES IN AUDIO-TACTILE COMMUNICATION

Reference

Rantala, J., & Raisamo, R. (2014). Preferences for touch gestures in audio-tactile communication. In *Proceedings of IEEE Haptics Symposium 2014 (HAPTICS '14)*, 247–250. Washington, DC, USA: IEEE. doi:10.1109/HAPTICS.2014.6775462

Objective and Methods

The final study evaluated the squeeze and finger touch gestures during conversations between two participants. Our goals were to assess how much and for what purposes the gestures were used and to find out

whether the conversation topic or participant gender affected the use. The participants wore audio headsets that enabled speech communication. We modified the tactile stimulation design from Studies III and IV in an attempt to make the two gestures distinguishable. Squeeze was presented with a modulated sine wave symbolizing a heartbeat, and finger touch was presented with a mixed sine wave imitating contact with a surface. The tactile communication was bi-directional so that both participants could send and receive mediated touches.

In an experiment, the task of the participant dyads was to use the two gestures the way they saw fit during three conversations that varied in their emotional topics. The three topics were chosen so that they would elicit conversations with positive, neutral, and negative emotional themes. We logged the durations of touch gesture use to analyze how frequently squeeze and finger touch were utilized during the conversations. After each conversation, both participants evaluated how suitable the gestures were for the particular emotional theme. Also, the participants filled in questionnaires to describe how and for what purposes they used the gestures.

Results and Discussion

The results indicated that the participants used squeeze more than finger touch regardless of the emotional conversation topic. In an average conversation lasting 7 minutes, each participant spent 92 seconds for interacting via squeeze and 40 seconds for interacting via finger touch. The preference for squeeze could be due to several reasons. Squeeze supported one-handed use, whereas finger touch required both hands to initiate a mediated touch. Also, some participants commented that they had to divide their attention between the auditory and haptic modalities and therefore could not always distinguish which gesture their pair had used. It is possible that the participants opted for squeeze because it was quicker to use and finger touch did not provide enough additional benefit to compensate for the extra effort.

In addition, we found differences in the perceived suitableness of the gestures between genders. Male participants considered squeeze to be more suitable than finger touch, whereas female participants considered them equally suitable. This was an interesting result because gender differences in touch gesture use have been reported in non-mediated touch communication. When participants were asked to communicate intended emotions by touching another participant, male and female participants preferred different touch gestures (Hertenstein et al., 2009). Even though we evaluated only two alternative gestures in the current study, our findings suggest that gender differences can also take place in mediated touch communication.

8 Discussion

The research question of this thesis was to find out how spatial touch could be better supported in presenting information to mobile device users. This was accomplished by building interactive prototypes that aimed at presenting information in new or more effective ways. The practical work was guided by a goal to take into account the different areas of the interaction space of spatial touch. This was reflected in the individual studies that varied in how they emphasized spatial input or spatial output or both. Thus, it seems fitting to begin by discussing the findings in the level of these three interaction space areas.

Study I focused primarily on spatial input (SI). The main finding was that alphabetical information can be read successfully by sensing tactile stimulation while moving the hand or stylus spatially on a touchscreen. In prior studies with touchscreen devices, the input location has been mapped to tactile stimulation to provide feedback of virtual buttons (Fukumoto & Sugimura, 2001; Hoggan et al., 2008) and other GUI elements (Kaaresoja et al., 2006; Leung et al., 2007). These applications have used tactile stimulation to enhance the visual feedback provided by the interface. Our current approach differed from the prior applications because the methods for reading Braille were designed for use by the blind. The results showed that experienced Braille readers could interpret single letters successfully in over 9 of 10 cases. Thus, it was possible to locate spatially mapped stimulation points on a touchscreen without any visual cues. However, the use of spatial hand movements in the scan and sweep methods did limit the achievable reading speeds. The rhythm method that presented the dots with fixed time intervals required no spatial movement and, consequently, enabled the fastest reading speeds. Compared with standard Braille reading where one cell is read at a time, the current methods were rather slow because Braille was read one dot a

time. The reading speeds measured with the rhythm method were roughly 10 times slower than those measured for printed Braille. This indicates that the methods would not likely be suited for reading long texts. Instead, it is possible that they could be used for accessing limited amounts of information such as alphabetical cues of menu options or short words.

Study II concentrated on spatial output (SO). The main outcome was that for stimulating the user's hand so that it is easy to localize, it may be worthwhile to use linear actuators providing movement perpendicular to the skin. Participants using a device with four linear actuators recognized different spatial stimuli with a mean success rate of over 90%. The relatively high success rates could partly be anticipated based on prior knowledge of tactile perception and skin mechanoreceptors. According to Goldstein (1999), tapping the skin with low frequencies (1–40 Hz) activates different mechanoreceptors compared with vibrating it with high frequencies (>100 Hz). The current study was one of the first to demonstrate this in practice by stimulating the user's palm. The lack of prior efforts in this area could partly be due to the requirement of enabling direct contact between the actuator and the user's skin. Our solution was to use small holes in the body of the handheld device so that the actuators could protrude and directly touch the user's palm. This also prevented the actuation from propagating across the whole device. Incorporating similar solutions to consumer products could prove more difficult because mobile phones and other similar devices typically utilize solid covers. Also, the linear actuators that we used were too large to fit inside mobile devices. Assuming that more miniaturized solutions can be developed in the future, linear stimulation could have practical value in presenting information with mobile devices. In addition to mimicking interpersonal touch such as the location of taps, spatial stimulation could be used, for example, for providing navigation cues to the user's hand. To date, navigation cues have been presented mainly to the user's torso (van Erp, 2005b) and waist (van Erp, van Veen, Jansen, & Dobbins, 2005).

Studies III–V evaluated the combined use of spatial input and output (SIO). The main finding was that converting the spatial features of touch gestures to tactile stimulation facilitated communication of information. The studies were based on a previously suggested idea of simulating interpersonal touch by driving multiple spatial actuators in a sequence (Bonanni et al., 2006; Haans & IJsselsteijn, 2009; Huisman et al., 2013; Mueller et al., 2005; Park et al., 2010). This creates an illusion of apparent motion that feels as if another person would be touching the skin. The main difference between the prior work and our studies was that in our studies the tactile stimulation, and, thus, the apparent motion, was modified in real time based on the user's touch input. The findings of Study III suggested that squeezing and stroking gestures resembling

interpersonal touch were preferred to more abstract movements. Also, it was found advantageous to use four spatial actuators over a single actuator to mimic the gestures. This is a rather intuitive finding; the spatial features of touch input gestures cannot be conveyed without spatial output technology. For example, moving one's finger spatially on top of the device resulted in a vibration following the touch input location. The results of Study IV showed that these spatial variations, along with amplitude changes, defined how people interpreted the gestures. Stimulation resulting from squeeze input typically had little spatial variation and high amplitudes, whereas finger touch elicited more spatial variation and low amplitudes. Thus, the current way of mapping physical touch gestures to spatial stimulation did have a role in mediating information. In audio-tactile communication, on the other hand, the role of the spatial stimulation was less important. The findings of Study V indicated that the users preferred squeezing to moving regardless of the conversation topic. One possible explanation for this could be that the users had to divide their attention between the auditory and haptic modalities, and therefore the spatial characteristics of the tactile stimulation were more difficult to perceive.

To summarize the main findings, non-spatial input and non-spatial output were efficient when presenting alphabetical information to an individual (Study I), whereas spatial input and spatial output were more suitable when presenting emotional information using a shared interface (Studies III–V). This suggests that the application type may affect how useful the spatial features of touch input and output are in presenting information. At the same time, we must be cautious in making such conclusions because in this thesis we evaluated the application types only with certain input and output combinations. For instance, we did not assess the presentation of alphabetical information with multiple spatial actuators even though this would have been possible using a different study setup. Instead, we utilized multiple spatial actuators in the context of mediated social touch because we hypothesized that the spatial stimulation could provide more additional value to this application field. Therefore, it could be advantageous to discuss the findings more closely from the viewpoints of alphabetical and emotional information.

Our effort to present alphabetical information for visually impaired users combined previous knowledge of sensory substitution systems, Braille displays, and piezoelectric actuators. The developed Braille reading methods based on a single actuator and temporal presentation differed significantly from the normal method of reading whole Braille cells. Regardless of the differences, the proposed methods were shown to be feasible because experienced Braille users could utilize their existing skills in parsing letters from the individual dots. The users required very little training before being able to recognize letters based on the tactile

stimulation. The downside of the methods was that reading with the new and unfamiliar Braille representations required additional cognitive effort from the users. Similar findings have been reported by Levesque et al. (2007), who stated that reading Braille using lateral skin deformation demanded great concentration from the users. In our study, the required additional effort could have resulted from the need to remember the first dots of a character while still reading the remaining ones. It is plausible that this cognitive load would decrease over time when users learn the methods better and gain more experience of the use. However, this cannot be determined based on the results of the current work. Further experiments with more than three sessions would be needed to evaluate the possible effects.

From a technical viewpoint, the design of Study I was relatively simple because we used a single piezoelectric actuator to present Braille. This differs from prior studies on alternative Braille displays that have proposed more complex implementations. Levesque et al. (2007) used 60 piezoelectric actuators to stimulate the user's fingertip with lateral skin deformation, and Roberts et al. (2000) proposed rotating wheels with refreshable pin positions. The simplicity of our approach could be an advantage when considering the potential usefulness of the findings in mobile settings. We chose piezoelectric actuators because the technology allowed for very accurate control of stimulation amplitude and duration. However, it is conceivable that a regular mobile phone with an ERM motor could be used as well, provided that the motor has an adequate response time (i.e., time required to ramp up the rotating mass). In addition, the rhythm method is not dependent on a touchscreen device. It would be possible to start the presentation of Braille dots by pressing a hardware key, and the vibration would be felt through the body of the device while holding it. Essentially, the new reading methods can be regarded as alternatives to screen readers and speech synthesizers, which are currently the dominant non-visual methods of acquiring information from mobile devices. The limitation of using speech output is that it can be difficult to hear in noisy environments, and sometimes the user might not want everyone else around to hear the information. For example, reading a short private message via touch could be more convenient if there are other people nearby.

The studies on communicating emotional information between users were founded on the research fields of interpersonal touch communication, emotions, and mediated social touch. The main contribution was that in Study IV mediated squeeze and finger touch gestures evoked different emotional interpretations in the people who received them. Squeeze was better at communicating unpleasant and aroused emotional intention, and finger touch was more suitable for communicating pleasant and relaxed emotional intention. A possible way to evaluate our findings on mediated

touch is to compare them with the use of non-mediated touch. The results of Hertenstein et al. (2009) showed that the communicative functions of non-mediated squeeze and finger touch (e.g., stroke and pat) generally resembled the ones we observed for mediated touch in Study IV. Furthermore, Hertenstein et al. observed that men and women preferred different touch gestures when communicating via non-mediated touch. In a similar fashion, we found in Study V that men preferred mediated squeeze to finger touch, whereas women perceived the gestures similarly. Thus, there tend to be similarities between our findings and those of Hertenstein et al. At the same time, we must emphasize that these similarities should be interpreted with care because we did not empirically compare mediated and non-mediated touch in our own studies. Acknowledging this limitation, it could be argued that we found partial support for the assumption that the use of mediated touch could have similar effects to non-mediated touch. This conclusion is in line with the results of other researchers. Haans et al. (2007) showed that similarly to a non-mediated touch, a mediated touch on the stomach was perceived as more unpleasant than a mediated touch on the upper arm. In another study, Haans and IJsselsteijn (2009) reported that the strength of the Midas touch phenomenon in a mediated setting was comparable with the strength of the Midas touch in a non-mediated setting.

Our experiments in Studies IV and V complemented prior mediated social touch research that can be roughly divided into empirical studies on comparing mediated and non-mediated touch (Haans et al., 2007; Haans & IJsselsteijn, 2009) and studies on presenting prototypes for emotional use of mediated social touch (e.g., Bonanni et al., 2006; Huisman et al., 2013; Mueller et al., 2005; Park et al., 2010). Our work introduced one more prototype into this field, but the central aim was to empirically assess its capabilities in communicating emotional intention between people. Previously, this has been measured mainly using larger force-feedback devices that are not applicable in mobile settings (e.g., Bailenson et al., 2007; Smith & MacLean, 2007). The current results demonstrated that relatively simple vibrotactile technology can mediate emotional intention between two users. The practical value of this finding is that it might be possible to mediate emotional information between users via touch if devices such as smart phones would provide similar functionality. Squeezing could be detected by introducing touch-sensitive device borders, and finger touch gestures can already be tracked using existing touchscreen technology. For example, similarly to a non-mediated setting, a user holding his or her mobile device could use a stroking gesture to express pleasant or relaxed feelings to a communication partner. The partner would feel vibration travelling on the hand in a similar fashion to a physical stroking gesture. Such interaction could partially help in bridging the gap between mediated and non-mediated communication. Modern communication between people relies more and more on

computer interfaces that lack the subtleties of physical communication. The findings of this thesis indicate that at least some of the subtleties related to emotional communication could be brought back with the help of haptic technology.

The choice of tactile stimulation parameters in the individual studies of this thesis was informed by prior research on tactons and sensory substitution systems. We identified spatial location, duration, and rhythm as the most promising parameters. Spatial location and duration were used in all five studies, and rhythm was utilized in Study I. We used a maximum of four different spatial locations in the studies to ensure adequate intertactor spacing and accurate localization. In addition, we varied the amplitude of stimulation in Studies I and III–V. One limitation on its use was found in Study I, where we initially used high amplitude for coding raised Braille dots and low amplitude for coding lowered Braille dots. This led to difficulties in telling whether the very first dot of a character was raised or lowered, for there was no reference point before sensing a dot with the other amplitude. To differentiate the dots better, we chose to use duration as a second parameter. In terms of frequency, we used fixed values in all studies so that amplitude and frequency variations would not get mixed (Geldard, 1957). We also experimented with the use of waveform as a stimulation parameter in Study V, where it was varied in an attempt to distinguish the two gestures. Our results of the use of waveform were somewhat inconclusive. In the practice phase, the users typically reported that they could distinguish the gestures based on the different stimulation. During speech communication, on the other hand, it was more difficult to tell which gesture their pair had used at a given time. This could be because the users' cognitive resources had to be divided between the two modalities or because the waveform designs were not distinguishable enough. These findings accord with earlier studies reporting mixed results of the usefulness of waveform as a stimulation parameter (e.g., Brown et al., 2005; Hoggan & Brewster, 2007).

We recognize that there were some limitations in the studies. All the user experiments were conducted in a laboratory environment, and therefore one could argue the external validity to be low because it would be difficult to generalize the results to real use. We decided to focus on controlled experiments because we were mainly interested in the usability of the methods in presenting information. Measuring this was more convenient in a controlled setting where it was possible to present specific tasks to the users and observe their interaction while they completed the tasks. A fitting method to get more generalizable results would be to conduct field studies where a device or interaction method is evaluated in everyday contexts over a longer period of time (e.g., Hoggan et al., 2012). One prerequisite for such studies is that the device to be evaluated should be robust enough to be taken outside the laboratory. The prototypes used

in this thesis work were still in a more experimental phase because they required wired connections and computers for control. We consider longitudinal studies in more realistic settings as a potential way to continue this research.

Moreover, the results reported in this thesis depended on various factors related to the used tactile technology such as the chosen actuator type, stimulation parameters, and device form factor. This is a general challenge in the field of haptics research because replicating the technical implementations tends to be difficult. The effect can be mitigated to some extent by describing the implementations as accurately as possible. We strived for this when explaining the technical settings in the individual papers. A complementary method could be to repeat the experimental tasks, for instance, with different types of tactile actuators. In Studies III–V on mediated social touch, we used high-frequency vibrotactile actuation to stimulate the user's palm and fingers. It would have been beneficial to run the same experiments with the device of Study II that utilized linear actuation to create tapping movement. It is possible that the users' emotional interpretations of mediated social touch would have differed from the ones we reported now. Unfortunately, we did not succeed in incorporating touch input sensing to the device of Study II in the course of this thesis research. This is another apparent path for future research.

This work was positioned in the intersection of various research fields, including haptics, HCI, sensory substitution, emotions, and interpersonal touch communication. Currently, touch is used in HCI predominantly as an input channel; we tap, swipe, and tilt mobile devices to receive information via visual and auditory modalities. The use of touch as an information transmission channel has been limited. The present research indicated that touch has unused potential also as an output channel. Tactile stimulation can offer an alternative way of acquiring information when visual information is not accessible and the auditory channel is not preferred or available. This is relevant to people with visual impairments who can utilize tactile stimulation for reading information via tactile stimulation. Furthermore, tactile stimulation can provide a rough simulation of interpersonal touch. This can be utilized in communicating emotional information between people who are physically apart. By supporting different touch gestures, it could be possible to mediate different emotional information with each gesture.

The main outcomes of this research were to demonstrate that humans can quite accurately perceive which location of their hand is being stimulated, and that the location of touch is an effective parameter in conveying different types of information. Ultimately, the wider acceptance and adoption of these findings depends on researchers, users, and technology manufacturers alike. We, along with other researchers, have demonstrated

that utilizing the sense of touch is a viable method to present information to mobile device users. However, the additional benefit of incorporating new touch-based interaction methods to consumer devices such as smart phones should be high enough so that technology manufacturers would adopt them. We believe that the current work can partly motivate attempts to introduce more expressive, spatially located actuators to mobile devices.

9 Conclusions

In summary, this thesis reported research on designing, implementing, and evaluating techniques to utilize the spatiality of touch in presenting information with handheld mobile devices. The research was divided into five individual studies that focused on different areas of the interaction space of spatial touch. The following conclusions can be drawn from each of these studies:

- Combining spatial touch input with tactile stimulation on a mobile touchscreen device enables the presentation of single letters based on the Braille coding. Faster reading rates can be achieved by using a temporal representation where the finger is placed on the screen to feel stimulation presented with fixed time intervals (Study I).

- Distinguishing the spatial location of tactile stimulation on the hand can be made easier for users by adopting low-frequency linear actuation instead of high-frequency vibrotactile actuation. This reduces propagation of the tactile stimulation and activates skin mechanoreceptors capable of discriminating fine spatial differences (Study II).

- People prefer squeezing and stroking gestures to moving when using a tactile communication device. In addition, using multiple actuators in presenting the gestures with tactile stimulation is more expressive than using a single actuator (Study III).

- Squeeze and finger touch (e.g., stroking) gestures communicate different emotional information between people when mediated in vibrotactile form. Squeezing is generally perceived as unpleasant

and arousing, whereas finger touch is perceived as more pleasant and relaxing (Study IV).

- When squeeze and finger touch gestures are used in remote communication along with speech, squeeze gestures are preferred over finger touch gestures. Also, men perceive finger touch gestures as less suitable than do women (Study V).

These conclusions can be used in further haptics and HCI research aiming at supporting the use of touch with mobile devices. In particular, the present conclusions can inform the development of methods for presenting information to visually impaired users and for creating mediated social touch applications that enable emotional communication between people in close relationships.
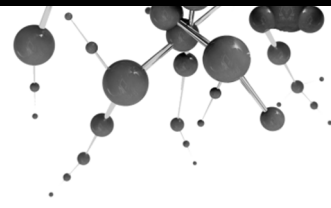
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Paper I

Rantala, J., Raisamo, R., Lylykangas, J., Surakka, V., Raisamo, J., Salminen, K., Pakkanen, T., & Hippula, A. (2009). Methods for presenting Braille characters on a mobile device with a touchscreen and tactile feedback. *IEEE Transactions on Haptics, 2*(1), 28–39.

Methods for Presenting Braille Characters on a Mobile Device with a Touchscreen and Tactile Feedback

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Abstract—Three novel interaction methods were designed for reading six-dot Braille characters from the touchscreen of a mobile device. A prototype device with a piezoelectric actuator embedded under the touchscreen was used to create tactile feedback. The three interaction methods, scan, sweep, and rhythm, enabled users to read Braille characters one at a time either by exploring the characters dot by dot or by sensing a rhythmic pattern presented on the screen. The methods were tested with five blind Braille readers as a proof of concept. The results of the first experiment showed that all three methods can be used to convey information as the participants could accurately (91-97 percent) recognize individual characters. In the second experiment, the presentation rate of the most efficient and preferred method, the rhythm, was varied. A mean recognition accuracy of 70 percent was found when the speed of presenting a single character was nearly doubled from the first experiment. The results showed that temporal tactile feedback and Braille coding can be used to transmit single-character information while further studies are still needed to evaluate the presentation of serial information, i.e., multiple Braille characters.

Index Terms—Assistive technologies for persons with disabilities, haptic I/O, input devices and strategies, interaction styles.

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1 INTRODUCTION

INTERACTING with mobile devices is challenging for the visually impaired. Getting proper feedback and information on the state of the device is especially problematic as the use of devices is currently based mainly on visual information. Recently, as the computational power of mobile devices has increased, screen readers coupled with speech synthesizers, e.g., [1], [2], have become available for a limited number of devices. However, speech output is not a private medium if used without headphones. In certain situations, such as public spaces, synthesized speech may be inconvenient or even impossible to listen to. The use of synthesized speech also causes disturbance to the environment. Headphones, on the other hand, may prevent one from hearing what is happening around, making it hard to observe the environment.

1.1 Braille Displays

Many blind mobile device users are accustomed to using their tactile sense for reading Braille; for them, it is one of the most common ways of acquiring information. Braille is a reading and writing system which transliterates traditional written letters into tactile characters. In six-dot Braille, each character consists of a rectangular array of two columns and three rows where individual dots are either raised or lowered (Fig. 1).

Braille is read by gliding the fingers over the dots forming the characters. Shapes outlined by individual dots are used for mentally constructing a geometric model of the layout of the Braille characters [3]. It has also been claimed that the reading of Braille is mainly based on variations in dot spacing and density [4]. This is the case especially when longer texts are read instead of individual characters.

Nowadays, mechanical Braille displays are used alongside traditional Braille, which is embossed on paper. Braille displays are devices that usually have up to 80 Braille cells. Each cell typically has six pins controlled by individual electromechanical actuators. Textual information, for example, in a document or in a menu, is transmitted via screen reader software to a Braille display. Although current Braille displays are widely used, two major drawbacks hinder the use of these devices in everyday life: their price and poor portability.

According to Roberts et al. [3], Levesque et al. [5], and Ramstein [6], the price of current Braille displays is a major obstacle for potential users. A standard Braille display for desktop computers typically costs between 5,000 and 15,000 USD. For this reason, there has been research on alternative approaches to cut down the cost of such devices. One common way has been to reduce the number of actuators. Instead of placing individual actuators for each dot, displays with fewer electromechanical parts have been built.

Roberts et al. [3] simplified the mechanical design by creating a Braille display which was based on a rotating wheel with the characters molded around its surface. Users
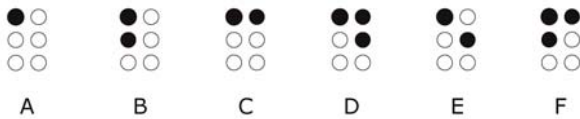

Fig. 1. Examples of six-dot Braille characters where black dots represent raised dots.

placed their fingers against the wheel and thereby received an impression of a continuous line of Braille characters without actually moving their fingers. In another approach, Levesque et al. [5] created a virtual Braille display by applying lateral skin deformation to the fingertip. By creating an impression of objects sliding on the skin, pairs of two Braille dots could be presented at a time. In a later study, Levesque et al. [7] extended their work to present six-dot Braille by applying lateral skin deformation two dimensionally. This presentation technique was shown to be legible as participants read 69 percent of meaningful five-letter words correctly with an average duration of 9 seconds per word. When reading meaningless strings of five letters, reading accuracy of 57 percent and average duration of 12 seconds per string were measured.

However, these less expensive alternatives to traditional Braille displays, e.g., [3], [5], [7], require custom-built devices and cannot be easily miniaturized for mobile use. Nonetheless, the portability of Braille reading devices has lately become an important factor as the use of technical devices shifts toward mobile contexts: there is a growing need to acquire information by using touch regardless of the user's location. Manufacturers have become aware of this, and more compact Braille displays for mobile use, e.g., [8], [9], [10], have already been developed. These displays are typically equipped with 12-40 Braille cells and have a wireless connection to mobile phones or handheld devices.

Although this has been a major step forward, external Braille displays for mobile devices may be inconvenient to use if the amount of information is limited. In mobile use, this is often the case when users would like, for example, to browse their contacts or read a short text message. If these few characters and words could be read without first having to attach external displays, the usability of mobile devices would improve significantly. Moreover, any external appliances shorten the already limited battery life of the host device even more. Therefore, we believe that it is important to investigate alternative solutions to transmit information based on Braille coding without using additional and expensive aids.

1.2 Tactile Actuators for Mobile Devices

Recently, there has been a major increase in the number of solutions available for producing tactile feedback for mobile devices. Earlier, virtually only vibration motors with eccentric rotating weights were used in devices such as mobile phones to provide coarse vibrotactile feedback to the user. It is characteristic of this actuator type that the vibration resonates through the entire device and that it has a very limited capacity to modify the feedback. In addition, making the rotating weight both speed up and slow down causes notable latencies in presenting the feedback, thereby

making the actuator inappropriate for certain purposes where accurate and varying feedback is required.

Better actuators capable of producing more fine-grained tactile feedback have lately been used. Among the first were Fukumoto and Sugimura [11] who placed a voice coil actuator on the back panel of a handheld device. Because of the low latency of the actuator, the impression of manipulating real buttons on the screen was strong [12]. The downside of using voice coils is their limited frequency and amplitude range, which make it difficult to create complex feedback patterns.

Luk et al. [13] and Pasquero et al. [14] introduced a handheld device with a small tactile display based on piezoelectric actuators. A vertically aligned line of eight piezoelectric bending actuators was used for applying lateral skin stretch to the user's thumb. Similar actuators are used, for example, in most current Braille displays in horizontal orientation to raise the pins. The thumb display is a more portable, compact, and lightweight version of its predecessor, the virtual Braille display, by Levesque et al. [5]. In the handheld prototype, the tactile display was mounted on a slider located on the left side of the device. The slider was pressure sensitive and thus could also be used as an input device.

Moreover, Poupyrev et al. [12] created a tactile display using a piezoelectric actuator. Tactile feedback was provided to the hand holding the device through the back panel. In a later study, Poupyrev and Maruyama [15] embedded the piezoelectric actuator right underneath the screen of a handheld device to create a direct tactile display where the feedback was felt right under the current contact point on the display. Similar direct feedback displays based on piezoelectric actuators have been used successfully in several other studies, e.g., [16], [17], [18], and have proven to be particularly suitable for mobile devices. This is due to their durability and their ability to offer efficient and versatile actuation [18].

The actuators introduced above provide new opportunities to create more robust and localized tactile feedback. This promotes the use of haptic feedback for communicating complex information on mobile devices (e.g., characters and geometric forms) as the stimuli patterns can be made more distinguishable and mapped spatially when used together with a touchscreen.

1.3 Toward Vibrotactile Braille Presentation

Looking for a novel and widely usable way to convey information in tactile form, we started to investigate whether Braille characters could be presented in mobile devices. We propose a different approach from the expensive and external Braille displays: to utilize tactile actuators not specifically designed to present Braille. This research was motivated by an initial user requirement study carried out among the visually impaired, revealing the need for a way to read Braille characters without additional displays. The respondents suggested that Braille could be used in mobile devices, for example, to provide numerical or alphabetical cues to make the user more confident when navigating in complex menu structures. In addition, single Braille characters could be used for choosing any kind of options in the software. Thus, the amount of information that needs to be read via haptics is not

Fig. 2. Nokia 770 internet tablet.

Fig. 3. An illustration of pulse shapes and durations of tactile feedback for presenting raised (broken line) and lowered (solid line) Braille dots.

necessarily large, but the option would nevertheless be very helpful. Currently, most mobile devices provide the visually impaired with only little or no information at all on the state of the device.

The aim of this study was to make it possible to read single Braille characters using a piezoelectric actuator solution embedded under the touchscreen of a mobile device. Users read characters dot by dot, either by exploring the dots based on traditional character layouts or by sensing the dots via a tactile rhythm at the point of contact on the screen. In all three methods, the Braille characters were placed on the screen in relation to the location where the user first touched the screen. For raised dots, tactile feedback representing a bump was produced. Lowered dots were represented with less powerful vibration-like tactile patterns to indicate blank space.

Although traditional Braille is based on reading multiple characters consecutively, the focus in this paper is on presenting single characters. Our main goal was to investigate whether it was possible for blind users to recognize Braille characters using only a touchscreen augmented with temporal tactile feedback. The use of single characters was chosen for this purpose.

We start by describing the design and implementation process of our Braille reading methods where each of the three methods and their use are introduced in detail. We then report the results of two experiments conducted with five blind participants. Finally, we conclude by discussing the findings and future plans in light of the present work.

2 PRESENTATION METHODS

We developed the Braille presentation methods using a prototype device based on the Nokia 770 Internet Tablet (Fig. 2; http://europe.nokia.com/770). Nokia 770 is a handheld tablet which has a large touchscreen (800 pixels × 480 pixels or 90 mm × 55 mm). The prototype was equipped with a piezoelectric actuator solution which was embedded under the touchscreen of the device. By utilizing this actuator technology, we were able to produce tactile feedback on the touchscreen with various pulse shapes and displacement amplitudes. The sharpness of the feedback pulses was controlled by the current fed to the piezoelectric actuator and the displacement amplitude by the driving voltage [19]. This control method expanded the variability of the tactile stimuli enabling much more freedom for haptic stimuli design compared to the actuator solutions (e.g., vibration motors) commonly used in mobile devices [16]. For
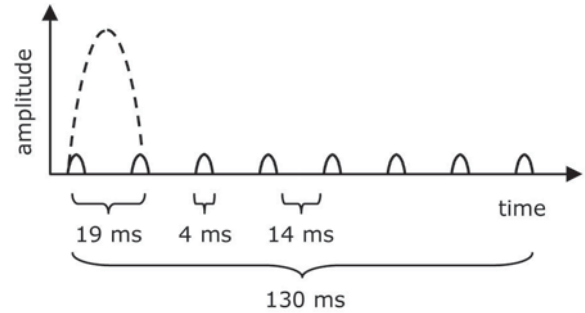
a more detailed description of the piezoelectric actuator solution, see earlier research by Laitinen and Mäenpää [16] and Tikka and Laitinen [18].

The tactile feedback created by the device cannot be targeted at any specific location on the screen. As the entire display vibrates, the traditional layout of six simultaneously presented physical dots could not be used. Instead, Braille characters were read by perceiving each dot individually. This created an impression of localized feedback: When a user touched the screen, the feedback was felt to be located right under the contact point. Thus, we could effectively produce location-specific tactile feedback to provide spatiotemporal information.

2.1 Design of the Tactile Feedback

We used the piezoelectric actuator for creating tactile feedback for raised and lowered Braille dots. We designed the feedback in an iterative process and validated the designs by pilot testing with sighted users. Initially, we tried to create the feedback by varying only the amplitude of the stimuli. It was immediately found that the feedback for raised and lowered dots could not be reliably differentiated in this way. It was especially difficult for the users to recognize if the first dot of a character was raised or lowered before being able to compare it with the feedback of the other dots.

In the next design, we strove for more differentiable feedback. The tactile feedback for raised dots (broken line in Fig. 3) consisted of a single pulse, which was set to be as noticeable as possible using the maximum amplitude of 30 μm. The duration of this feedback was 19 ms. The lowered dots were composed of separate lower amplitude pulses (solid line in Fig. 3). Eight individual pulses with a duration of 4 ms were separated using intervals of 14 ms. Thus, the overall duration of the feedback for lowered dots was approximately 130 ms. This was chosen to be the final design as the feedback was recognized accurately by our pilot users.

After having designed the feedback, we carried out iterative constructive research on a successful presentation method. First, we divided the screen area roughly into six blocks representing the distribution of the six Braille dots in a 2 × 3 matrix. Users could freely explore the matrix of Braille dots and tactile feedback was provided when touch input was detected in one of the six areas. As the sizes of the areas (i.e., individual dots) were very large, it soon became apparent that it would be neither easy nor practical to read
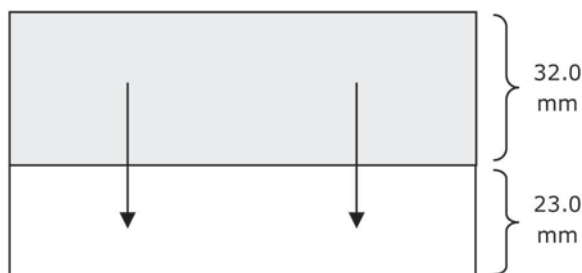
Fig. 4. Examples of allowed scan gestures starting from the gray activation area (55 mm × 32 mm or 800 pixels × 280 pixels).
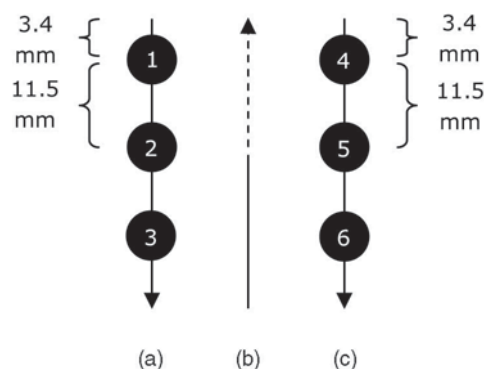

Fig. 5. The use of the scan method. After (a) reading the first three dots, the (b) stylus was moved at least one step upward to (c) read the last three dots.

characters by explicitly pointing the fixed areas one at a time. We decided to make the characters smaller and benefit from the large screen area by adjusting the dots according to the initial point of contact on the screen. This iterative research phase led to a set of three separate presentation methods. In our later implementations, the screen could be touched at any desired location assuming that the method-specific boundary conditions were met. Either a stylus or finger could be used with the methods. For simplicity, we use stylus in the following subsections where the methods and their limitations are explained in more detail.

2.2 Braille Scan

The Braille scan method used the traditional six-dot Braille layout where the dots are placed in a 2 × 3 matrix. Characters were read by moving a stylus on the screen from dot to dot starting from dot 1 in the top left corner of the character. The standard numbering of Braille dots is presented in Fig. 5. The dots were available for reading from the moment the stylus was placed on the screen until it was lifted off. Because of this the six dots must be read with a single gesture. On the following touches, the dot positions were readjusted.

The reading was started by placing the stylus at a random point on the upper part of the screen (Fig. 4). The allowed starting region was defined as a rectangle of dimensions 90 mm × 32 mm (800 pixels × 280 pixels). Braille characters were positioned downward from the touch location, and a minimum downward movement of 23.0 mm (200 pixels) was needed to read all three dots in a column. Tactile feedback was produced only once for each dot. Thus, it was not possible to move backward but the whole character had to be read again.

In the initial version of the scan method, the first dot was presented as soon as the screen was touched. After the first column had been read by moving downward, the stylus had to be moved upward until it reached the vertical height of the first dot. After that, the fourth dot was again immediately presented. In addition to moving upward, the stylus had to be moved a minimum of one pixel to the right to symbolize the change of column after the third dot. However, in the pilot tests, we found problems in moving the stylus in the designed manner. The change of columns between the third and the fourth dots particularly seemed to cause difficulties. Besides, as the feedback was produced immediately when a touch was recognized, users felt that they were not yet prepared and in many cases, they

completely missed the first dot. This applied to the first dot in the second column (dot 4) as well.

Based on the findings, we optimized the scan method to make it more usable. Fig. 5 illustrates the final version of the scan method. The stylus had to be moved 3.4 mm (30 pixels) downward from the initial point of contact before the first dot was presented (Fig. 5a). The two following dots were read by moving downward two 11.5 mm (100 pixels) steps. After reading the left column, the stylus was moved upward at least one step 11.5 mm (100 pixels) from the level of dot 3 (Fig. 5b). Horizontal movement was no longer needed to access the second column of dots. The application recognized when the upward movement stopped and placed the fourth dot 3.4 mm (30 pixels) below this turning point (Fig. 5c). In this way, the feedback of the fourth dot did not come unexpectedly and users had more control over reading. The fifth and the sixth dots were read by moving two steps downward.

The pilot studies showed that the standard Braille dimensions where the dots are placed in a grid defined by a 2.5 mm distance would be virtually impossible to use. This was due to the fact that the reading gestures could not be made precise enough to differentiate between individual dots. During piloting with different dimensions, we found the dot density to be suitable when the normal dot distance was multiplied by 4.6, thus making the gaps between dots 11.5 mm long.

2.3 Braille Sweep

In the Braille sweep method, the dots were laid out horizontally instead of the standard matrix. The layout was adopted from Braille writers using a similar six-key layout to form characters. On the keyboard, the left-hand controls dots 3, 2, and 1 (corresponding to ring finger, middle finger, and index finger, respectively) and the right-hand controls dots 4, 5, and 6 (index finger, middle finger, and ring finger, respectively). It was an open question how this representation of inputting Braille would transfer to reading the characters.

The reading direction in the sweep method was determined depending on whether the gesture was started inside the left or the right activation area, namely, 35.5 mm × 55 mm (310 pixels × 480 pixels) in dimensions (Fig. 6).
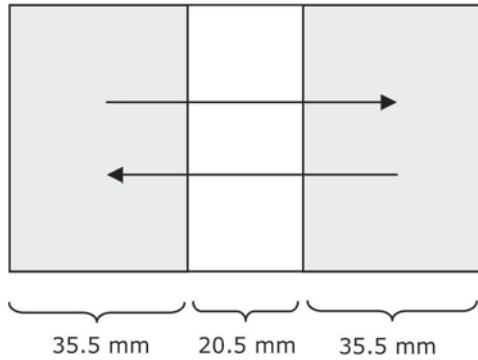
35.5 mm   20.5 mm   35.5 mm

Fig. 6. Examples of allowed sweep gestures starting from the gray activation areas (35.5 mm × 55 mm or 310 pixels × 480 pixels).

To read the six dots, a minimum of 56 mm (490 pixels) of screen space was required in the horizontal direction. Fig. 7 illustrates the sweep gesture where a character is read from left to right. Similar to the scan method, the dots were lined up so that the first dot (dot 3) was placed horizontally 3.5 mm (30 pixels) away from the initial point of contact. The next two dots (dots 2 and 1) were placed to the right in 9.2 mm (80 pixels) steps. After the third dot, the next one (dot 4) was placed 16.1 mm (140 pixels) to the right to divide the dots into two groups as in Braille writers. The fifth and the sixth dots were located two smaller steps to the right. The distances between dots were decided upon after several iterations with different dot spacing.

Compared to the scan method, the stylus movements were easier in the sweep method as all the dots could be read with a simple horizontal gesture from left to right or vice versa. The vertical dimension did not affect the reading, and diagonal movements were also possible.

2.4 Braille Rhythm

The Braille rhythm method enabled reading Braille characters as temporal tactile patterns by holding the stylus on the screen. Here, characters were composed of consecutively produced tactile pulses where Braille dots were presented in a numerical order (i.e., different from the order used with the sweep method). Reading was accomplished by touching the screen at any location to start the feedback and by keeping the stylus on the screen until feedback for all six dots was presented. The rhythm was selected as one method because of some promising earlier results on tactile perception of rhythmic patterns (e.g., [20], [21], and [22]). However, it was unclear how such temporal patterns could be used and understood in coding character-based information.
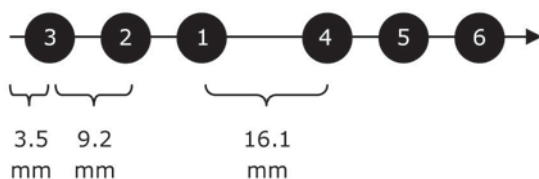

3.5   9.2   16.1
mm   mm   mm

Fig. 7. The use of the sweep method for reading horizontally aligned Braille dots.

19 /   130 /   130 /   19 /   130 /   130 /
341   230   815   341   230   230

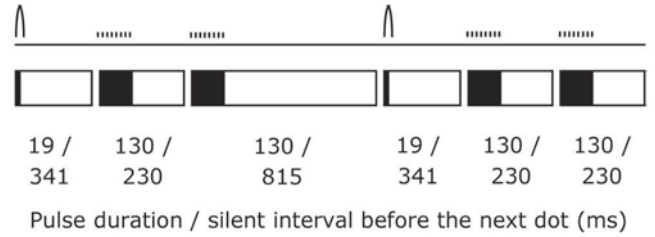Pulse duration / silent interval before the next dot (ms)

Fig. 8. The feedback pattern for letter "c" which is represented by dots 1 and 4 in Braille. The first and the fourth dots are raised (higher pulse shapes) and the other four lowered (lower pulse shapes).

Fig. 8 shows the feedback provided for letter "c" using the rhythm method. To avoid the problem caused by the first dot being felt immediately after contact, an onset delay of 360 ms was defined. The same value was used as an interval between the feedback onsets of two successive dots. Thus, the 19 ms feedback for the raised dot was followed by a silent interval of 341 ms. For the 130 ms feedback of the lowered dot, the silent interval was 230 ms. The same formula was applied to the remaining dots with the exception that the interval was 2.6 times longer (945 ms) between the third and the fourth dots. Again, this was done to divide the dots into two groups to make it easier to distinguish the dot columns.

The rhythm method was not based on any of the traditional, spatial Braille representations such as the standard 2 × 3 matrix in the scan method or the horizontal Braille writer layout in the sweep method. Instead, all the dots were felt at the same location and temporal coding was used to separate them. Consequently, users could not control the presentation rate of the feedback by movement but it was provided with fixed intervals. These intervals were determined on the basis of pilot studies where usable values between dots and columns were found. With interval values of 360 and 945 ms, the total duration of a character was either 2,404 or 2,515 ms depending on whether the last dot was raised or lowered.

3 EXPERIMENT 1

The purpose of Experiment 1 was to find out whether readers of Braille can recognize single characters using the three presentation methods. We used three sessions in the experiment to monitor the possible improvements of performance over a short period of time as well as the stability of the presentation methods.

3.1 Methods

3.1.1 Participants

Six volunteers (three females and three males) participated in the experiment (mean age 35 years, range 26-50). All of the participants were blind and had no additional impairments. The participants were experienced Braille readers (mean number of years reading Braille was 24, range 19-39). All six participants had previous experience of Braille writers or note takers using six horizontally aligned keys to input Braille characters. One of the participants was left handed and five of them were right handed by their own report. One right-handed female participant was excluded

Fig. 9. Experimental settings of Experiment 1 consisting of the prototype device, hearing protector headphones, experimenter's Bluetooth keyboard, and microphone.

from the analysis due to misunderstanding of instructions. Thus, the results are based on data from five participants.

3.1.2 Technical Settings

The prototype device based on the Nokia 770 Internet Tablet was used in the experiment. The device was on a table top during the experiment. To avoid accidental presses of hardware buttons located on the left side of the device (see Fig. 2), a piece of cardboard was attached to the device. The touchscreen of the device was used with a stylus. The stylus was chosen for Experiment 1 because the use of fingers was observed to cause interruptions and skips in the gestural touch input due to friction. The participants were instructed to use their dominant hand to hold the stylus and their nondominant hand to hold the device on the table top (Fig. 9).

In order to block the noise of the piezoelectric actuator, the participants listened to pink noise via hearing protector headphones. A microphone was used for giving instructions and verbal feedback to the participants through the headphones. The experimenter used a Bluetooth keyboard for logging verbal answers. The character presentation was controlled by an application written in C programming language and run on the Linux environment of the device. Reading times of individual characters were measured from stylus down to stylus up events. Thus, the results did not contain the reaction time of the experimenter.

3.1.3 Stimuli

The six-dot Braille characters used in the experiment were letters of the Finnish alphabet. In each block, the participants were presented with all 29 letters once in a random order. The participants read a total of 87 (3×29) characters in one session and 261 (3×87) characters in three sessions. In the scan and sweep methods, the duration of a character was determined by the speed of the reading gesture. In the rhythm method, the duration of a character was fixed so that the interval between the feedback onsets of two successive dots was 360 ms.

3.1.4 Procedure

The experiment was a 3×3 (session $\times$ presentation method) within-subject repeated measures design consisting of three separate sessions. Each session was divided into three blocks according to the three presentation methods. The order of the blocks was balanced between the participants so that each participant used the methods in a different order. In each block, the task was to recognize single Braille characters.

The first session began with an instruction phase where the participants explored the dimensions of the device and its display with their hands. After this, the stylus was picked up and held on the touchscreen while the experimenter presented the feedback twice for both raised and lowered dots.

Each block started off with practice trials using the given method. The participants read a specific training character (dots 1, 2, and 3 were lowered and dots 4, 5, and 6 were raised) ten times at their own pace. After practicing, the participants continued to the character recognition task which proceeded as follows: the participants heard a beep sound via the headphones signaling that the first character could be read. Each character could be read either one or two times. If the stylus was accidentally raised from the touchscreen during a reading gesture, the failed gesture was not counted and the reading could be repeated. The participants gave their answers verbally. There was no time limit set for answering. If the participants could not recognize the character, they were instructed to say "next letter." After each answer, the experimenter told the participant which character the device had presented. When an answer was logged, the next character was initiated after a 3 second interval followed by the beep sound.

There was a short break between the blocks during which the participants could take the headphones off and rest. The same procedure including the training trials and the character recognition task was applied to the following two blocks. After completing all three blocks, the participants were asked to rate their subjective experiences of the presentation methods using six nine-point bipolar scales ranging from -4 to $+4$. These subjective evaluations were collected only after the first and the third sessions. Ratings were requested for the following scales: general evaluation (bad-good), easiness (difficult-easy), speed (slow-fast), accuracy (inaccurate-accurate), pleasantness (unpleasant-pleasant), and efficiency (inefficient-efficient). On each of the scales, the middle of the scale represented neutral experience (e.g., neither bad nor good).

3.1.5 Data Analysis

Repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Pairwise Bonferroni corrected t-tests were used for post hoc tests. Both correct and incorrect responses were included in the reading time analysis. The rhythm method was not included in the reading time analysis because the feedback was provided at a fixed speed. Thus, the time from stylus down to stylus up was practically constant.
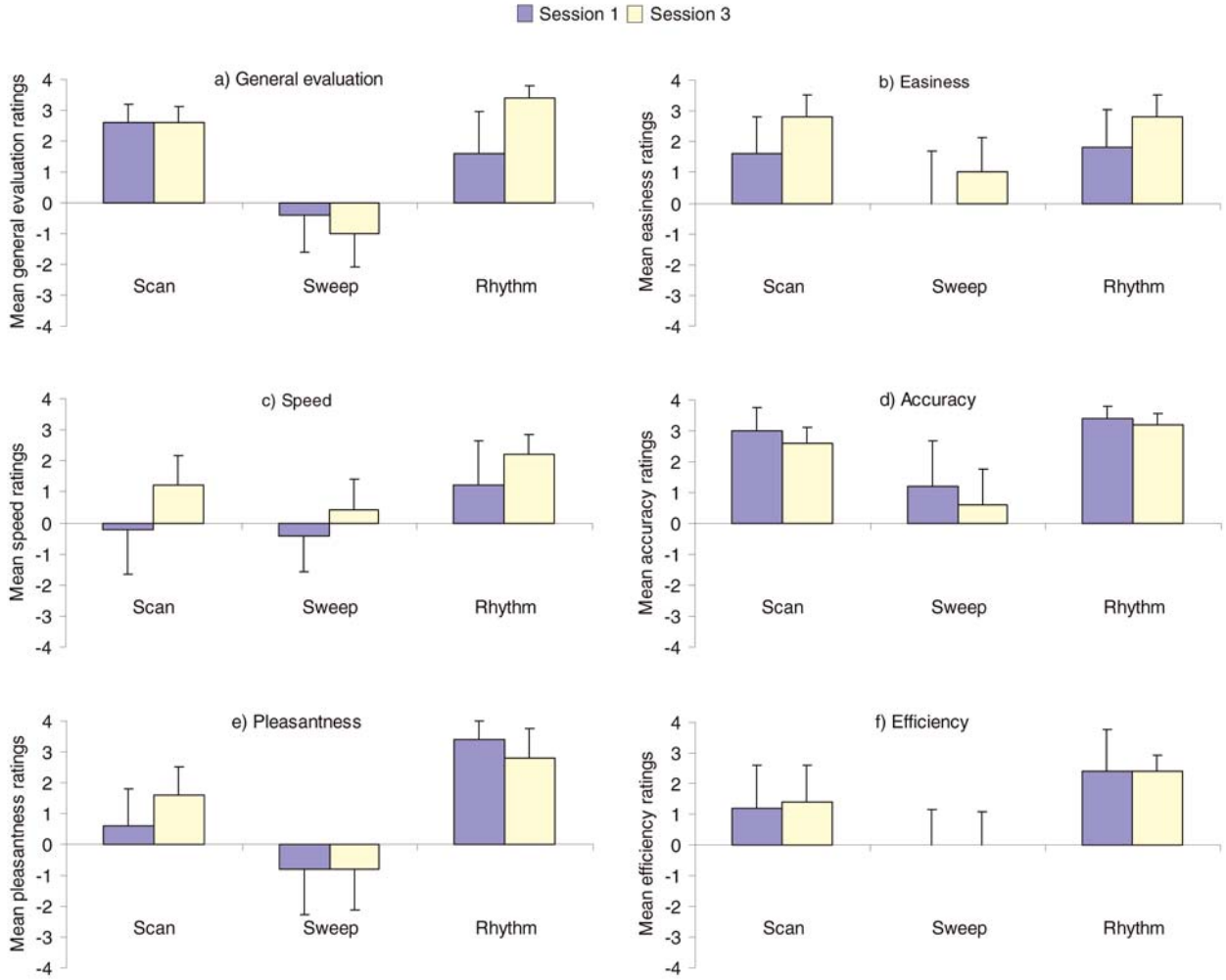
Fig. 10. Mean ratings and SEMs for the subjective evaluations of the presentation methods after sessions 1 and 3.

3.2 Results

3.2.1 Subjective Ratings

Mean subjective ratings and standard error of the means (SEMs) are presented in Fig. 10. Nine separate two-way 2×3 (session $\times$ presentation method) ANOVAs did not show significant main effects or interaction effects of the main effects for the ratings of general evaluation, easiness, speed, accuracy, pleasantness, and efficiency (see Fig. 10).

3.2.2 Recognition Accuracy

For the recognition accuracy (see Fig. 11), a two-way 3×3 (session $\times$ presentation method) ANOVA showed a statistically significant main effect of the session $F(2, 8) = 5.0, p \leq 0.05$. However, post hoc pairwise comparisons did not show significant differences between the sessions. The main effect of the presentation method and the interaction of the main effects were not statistically significant.

3.2.3 Reading Time

For the reading time (see Fig. 12), a two-way 3×2 (session $\times$ presentation method) ANOVA did not show significant main effects or interaction effects of the main effects.

3.3 Discussion

Mean recognition accuracies after three sessions were 97 percent for the scan, 91 percent for the sweep, and 92 percent for the rhythm method. In practice, over 9 out of 10 characters were recognized with two reading gestures. Although there were no statistically significant results between different presentation methods and sessions, an improving trend for recognition accuracy and reading time
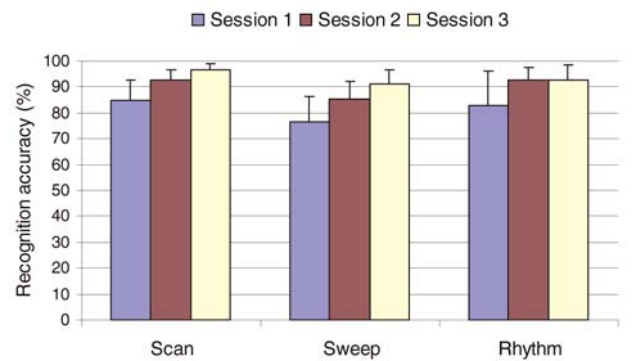

Fig. 11. Mean recognition accuracies and SEMs of Braille characters by presentation method and session.
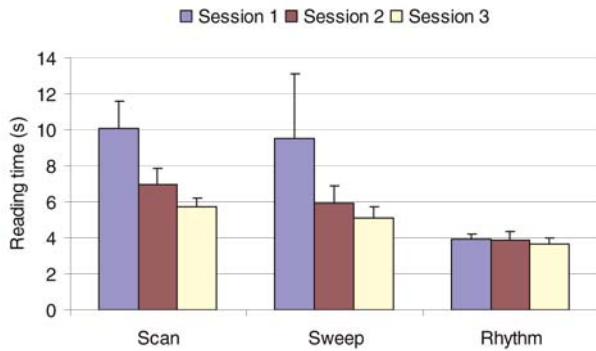
Fig. 12. Mean reading times and SEMs of Braille characters by presentation method and session. The rhythm method was excluded from the statistical analysis due to its different nature.

was observed. The initial performance in the first session was already at a relatively high level as mean recognition accuracies of 76-85 percent were measured. The results indicate that single Braille characters could be recognized by experienced Braille readers without extensive practicing. Furthermore, although the three methods required translation between temporal and traditional spatial representation of Braille, information could still be conveyed. A note of caution must, however, be made due to the fact that the number of experimental participants was relatively low. Handedness of the participants had no noticeable effect on the reading as the one left-handed participant performed just as well as the others.

After three sessions, the mean reading times (from stylus down to stylus up) for single characters were as follows: 5.7 seconds for the scan, 5.1 seconds for the sweep, and 3.7 seconds for the rhythm method. Translated into characters per second (cps), the measured speeds were as follows: 0.18 cps for the scan, 0.20 cps for the sweep, and 0.27 cps for the rhythm method. It should be noted, however, that the reading time of the rhythm method was constant as the dots were presented using a fixed interval.

In comparison to reading printed Braille or using speech synthesizers, the reading speeds measured for the three methods were considerably slow. The average reading speed using printed Braille has been reported to be around 5.8 cps or 70 words per minute (wpm) [23]. Furthermore, in a study by Legge et al. [24], reading speeds between 5.4 cps (65 wpm) and 15.4 cps (185 wpm) were found. Default listening rates for speech synthesizers are usually around 15 cps (180 wpm) although those accustomed to speech synthesis can use listening rates three times the default rate [25]. However, to the best of our knowledge, there are no previous investigations on reading Braille dot by dot or by using solely temporal tactile feedback. Due to the interaction methods being original innovations [26] intended for mobile use with touchscreens, comparisons with earlier studies are not feasible.

Although the differences were not statistically significant, subjective ratings indicated that the participants tended to evaluate the scan and the rhythm methods more positively than the sweep method. The ratings remained fairly constant throughout the sessions. In the postexperimental interview, the participants reported that the horizontal reading gesture in the sweep method was easy to

use as the movement required was simple. On the other hand, the order of the dots (3-2-1-4-5-6 from left to right) caused difficulties for some participants, suggesting that the transformation of the representation from inputting to reading was not entirely straightforward. Despite the initial challenges, the results of the sweep method were positive, as the recognition accuracy was comparable to the other presentation methods.

In contrast, the dot layout in the scan method was the closest to the standard Braille dot layout, which might explain the relatively positive subjective evaluations. The main drawback of the scan method was partially caused by the use of the stylus. The participants felt that the stylus was unnatural and clumsy. Especially in the first session, the stylus movements were not steady, and therefore reading was inconvenient. The participants commented that they had to press the stylus quite heavily on the touchscreen, which caused stress on the reading hand.

Four out of five participants would have chosen the rhythm method for their personal use. This may be due to the fact that there was no need to concentrate on moving the stylus from dot to dot on the screen. Although the rhythm method was found to be the fastest of the three, the participants proposed higher presentation rates. Furthermore, the rhythm method was found to be the most suitable for use without a stylus as the friction caused by fingers would not be an issue from the technical point of view.

4 EXPERIMENT 2

In light of the encouraging results of the first experiment, we conducted a follow-up experiment with the rhythm method. The rhythm method was shown to be the most efficient as well as the most positively received of the three methods by our users. Furthermore, it became evident that the presentation rate of the rhythm method could be increased by adjusting the intervals between individual dots. The character duration used in the first experiment was not optimized in terms of presentation rate but to ensure that it was suitable for all the participants. Our main goal in the second experiment was therefore to evaluate how the participants performed when the character duration was shorter than in Experiment 1.

4.1 Methods

4.1.1 Participants
The five volunteers from Experiment 1 also took part in the second experiment. We decided to continue with the same participants; due to their previous experience in using the methods, they could effortlessly try the rhythm with faster presentation rates.

4.1.2 Technical Settings
The technical settings were otherwise identical to those in Experiment 1 but the participants used the index finger of their preferred Braille reading hand instead of a stylus. This change was made as the first experiment proved the stylus to be unnatural for this purpose. In addition, the rhythm method could be used with bare fingers because it required no movement between dots on the touchscreen, thus avoiding problems in losing touch contact.
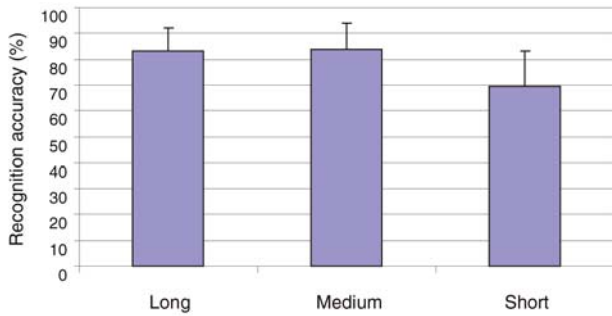
Fig. 13. Mean recognition accuracies and SEMs of Braille characters by character duration.

Fig. 14. Mean recognition accuracies of Braille characters by participant and character duration.

4.1.3 Stimuli

The character durations in the rhythm method varied in each block. The original character duration from Experiment 1, 2.45 seconds, was used as a starting point. This duration was measured from the onset of the first dot to the offset of the last dot. The other two respective durations were 1.85 and 1.25 seconds. The durations were selected based on preliminary evaluations with one blind pilot participant. The same letters of the Finnish alphabet were used but now the total number of letters presented to one participant was 87 (3 × 29).

4.1.4 Procedure

There were four differences from Experiment 1 in the procedure. First, only one test session was used. Second, in each of the three blocks, the participants used different character durations of the rhythm method instead of the three different methods. Third, the order of test blocks was not randomized but was the same for all participants; each one started with the longest and ended with the shortest character duration, making the task progressively more difficult. Fourth, the participants were allowed to read each character only once before answering.

4.1.5 Data Analysis

A repeated measures ANOVA was used for statistical analysis.

4.2 Results

Mean recognition accuracies and SEMs are presented in Fig. 13. For the recognition accuracy, a one-way ANOVA did not show a statistically significant effect of the stimulus duration $F(2, 8) = 3.68$, $p = 0.074$.

4.3 Discussion

The mean recognition accuracies for different character durations were as follows: 83 percent for the long (2.45 seconds per character), 84 percent for the medium (1.85 seconds per character), and 70 percent for the short (1.25 seconds per character) duration. The mean recognition accuracy for the long duration was 9 percent lower than in the last session of the first experiment. This could be because some months elapsed between the experiments. In addition, the participants were allowed to read each character only once. The option to read each character twice was removed to simplify the experimental setup and data analysis.
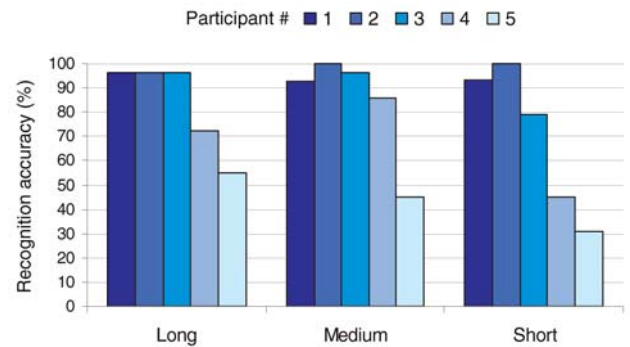
Interestingly, there were practically no differences in mean recognition accuracies between the long and medium character durations. This implies that the standard presentation rate of the rhythm method could be increased without affecting character recognition. A 14 percent drop in mean recognition accuracy was measured with the short character duration compared to the medium duration. Taking into consideration that the short duration is approximately half of the long duration, the decrease in recognition accuracy is quite moderate. This promotes the view that the rhythm method has potential in terms of shorter reading times compared to the other two presentation methods. A hypothetical reading speed of 0.8 cps can be calculated using a character duration of 1.25 seconds. Even though this is still far from those of normal Braille reading, in mobile contexts where the amount of information to be acquired is limited (e.g., single characters, words, and short messages), the current speed could well be adequate.

Fig. 14 shows that there were wide variations in recognition accuracies between participants. When using the short character duration, mean recognition accuracies of 31-100 percent were measured. Encouragingly, three of the participants also performed particularly well (79-100 percent) with the shortest duration, suggesting that 1.25 seconds per character may not necessarily be the minimum value of understandable rhythmic presentation. For some of the users, even shorter character durations could be recognizable. In practical use, the character duration should be adjustable so that all readers could use their own preferences and start with lower presentation rates if necessary.

Four out of the five participants preferred using the index finger to the stylus. It was more natural and thus less of a strain on the reading hand. Only one participant preferred the stylus because he was able to sense the raised dots more accurately through the plastic pen in the first experiment. Several of the participants commented that the tactile feedback could be slightly stronger. We used the highest possible amplitude of the piezoelectric actuator but as the presentation methods are not limited to a specific hardware solution, alternative and stronger tactile feedback could also be used. In general, the participants stated that efficient use of the rhythm method would be possible through learning.

5 APPLICABILITY OF THE RESULTS

We have shown that single Braille characters can be presented in a mobile device using spatiotemporal (i.e., scan and sweep) and temporal (i.e., rhythm) tactile feedback. We used an approach different from those based on building nonportable mechanical devices, e.g., [3], [6], [7], to overcome the problem of expensive Braille readers. Our current aim was to make it possible for visually impaired people to read single characters one at a time without an additional Braille device. The findings of Experiment 1 revealed that experienced Braille readers recognized characters accurately (91-97 percent) without prior experience. Further, reading time analysis showed that the use especially of the scan and the sweep methods is time-consuming compared to reading printed Braille or using normal Braille displays. It took over 5 seconds on average to read a character. On the other hand, in Experiment 2, where the rhythm method was used with a character duration of 1.25 seconds, the participants were still able to recognize 70 percent of the characters correctly.

In generalizing the findings, we found that the rhythm method was the most promising of the three in terms of reading time and user satisfaction when reading single-character data. In a real context of use, the rhythm method could provide single numerical or alphabetical cues while accessing information on a mobile device. When using a menu, the user could automatically receive the first letter of each menu option to make navigation more fluent. Furthermore, short words or number sequences could be read one character at a time, for example, to make sure that a phone number has been typed in correctly. Alternatively, the user could confirm private information such as a PIN number in a more secure way compared to using speech. What is noteworthy while considering the use contexts for the findings is that Braille code has undergone continuous modification over the years. One of the results of this progress is abbreviations for common words (e.g., afternoon = afn, necessary = nec). If the rhythm method were adopted for reading words, shorter representations common in modern messaging could be used to create informative expressions with only a few characters, thereby improving the efficiency of use.

We experimented with two alternative ways to use the touchscreen; the stylus was found to be feasible for the scan and sweep methods because of the better contact on the touchscreen, whereas in the rhythm, the index finger was preferred. This study showed that the use of bare fingers is preferred by visually impaired people for sensing tactile feedback. It would also be possible to use the palm of the hand for reading as the rhythm method does not necessarily require the device to be equipped with a touchscreen. In general, any sufficiently precise tactile actuators capable of creating distinguishable feedback could be used to provide the Braille coding to the body of a device. Instead of touching the screen to start the feedback, a hardware button could be used.

Each of the participants in our experiments reported that the use of the presentation methods required intensive concentration on the reading task. Because of the nature of the new temporal Braille representation, users need to parse Braille characters one dot at a time. The cognitive requirements for remembering dot positions and mentally forming characters out of individual feedback were different from

standard Braille reading. Similar to our finding, Levesque et al. [7] reported that reading using nonfamiliar Braille representation demanded great concentration from the readers. Further studies would be needed in order to find out how practical experience in using the methods affects reading and whether the required level of concentration declines while learning.

In extreme simplification, it can be stated that tactile-specific sensory memory and working memory have a crucial role in comparing the series of individual vibrations with the internal model for reading traditional Braille characters stored in long-term memory. One of the participants commented that while reading, he was constantly anticipating the next dot on the basis of dots already presented. This suggests that experienced readers were able to hold dots in their working memory and thus facilitate reading by limiting the number of possible characters. Tan [27] reported a similar finding with letters when studying tactual and auditory reception of Morse code.

Our results show that visually impaired people could utilize their prior skills in reading Braille although the representation used in this study was different. This suggests that the new reading methods suit the preexisting models in long-term memory for reading traditional Braille. What kinds of cognitive processes were required to recode the vibrotactile patterns to match with the representation of traditional Braille cannot, however, be explained through these series of experiments. Although an interesting research question, the psychological processes were not the main focus of the present study. Even so, the results demonstrated the flexibility and potential of the human brain which could be utilized in providing new haptic interaction methods for visually impaired people. We therefore believe that it is valuable to investigate more versatile and mobile alternatives to traditional Braille to improve the nonvisual accessibility of mobile devices.

Looking from the perspective of traditional Braille reading, we cannot yet draw definite conclusions on how these methods would perform in reading multiple consecutive Braille characters. However, when considering the findings of this study as well as the technological development of different actuator solutions, the possibilities are obvious. As we were successful in showing that characters can be read via temporal tactile feedback and Braille coding, there are various paths that can be taken to enable the use of these methods in reading multiple Braille characters. The next step for us will include thorough research on how the present results could be utilized for accessing serial information as well as user evaluations of the new implementations. One possible direction in which to proceed on this topic would be to use the touchscreen for moving between multiple characters and to present characters with the rhythm method when a touch input is detected in a certain location.

Interestingly, when discussing the representation used in the rhythm method on a more general level, we can identify similarities to Morse code, which uses two elements to form characters. Although traditionally transmitted through auditory senses, there has been research on using Morse via a tactile channel. In a study by Tan [27], four participants recognized over 95 percent of single letters correctly using vibrotactile Morse at a presentation rate of 1.3 cps (16 wpm). Thus, due to the similar nature of these two tactual representations, commonalities might also be possible in

terms of efficiency. A longitudinal study should be conducted in order to measure the efficiency levels of expert readers using the rhythm method.

We have proposed three alternative presentation methods to external Braille displays for cases where these displays are either impractical or not available at all. The novel presentation methods based on temporal Braille coding showed promise in accessing limited amounts of information (i.e., single characters) on mobile devices. As research on different tactile actuators has resulted in viable solutions, e.g., [12], [13], [14], [15], [16], [18], the use of alternative Braille presentation methods on mobile devices can also become a reality in consumer products. In this respect, the rhythm method especially has potential as it can be used with devices with no touchscreen. Furthermore, in future, the rhythm method can be utilized in reading serial information based on Braille coding. Compared to mounting physical Braille cells in a limited number of mobile devices, tactile actuators coupled with Braille reading software is a reasonable choice in terms of cost-effectiveness and universal access with any compliant device.

6   SUMMARY

In this paper, we have introduced and studied three novel methods for presenting six-dot Braille characters using only a touchscreen augmented with tactile feedback. To the best of our knowledge, there were no previous solutions for reading Braille without additional displays attached to mobile devices. The results of the first experiment proved that experienced Braille readers could accurately recognize characters using all three methods, although reading speeds were slow compared to normal Braille reading. In the second experiment, the reading speed using the rhythm method approached 1 second per character, while the recognition accuracy remained at a usable level. In light of the insights gained through this study, we recommend the rhythm method to be used for providing a low-cost and portable way to read small amounts of information using mobile devices with precise enough tactile actuators. As the findings of this first study proved the new representation of Braille to be practicable, the next step will be to enable the rhythm method to be used for reading multiple Braille characters consecutively.

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Paper II

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Presenting Spatial Tactile Messages with a Hand-Held Device

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ABSTRACT

This paper introduces a multi-actuator tactile device designed for remote touch communication. While closely-spaced high-frequency vibrotactile actuators can be difficult to distinguish, our system utilized four linear DC motors for presenting spatial tactile messages through low-frequency actuation. An experiment was conducted to determine accuracy for recognizing stimuli presented on the palm of the hand. Participants were asked to identify 10 predefined stimulus patterns created from the four linear actuators positioned in either a diamond or square configuration. Results showed that positional, linear, and circular stimuli were recognized with mean response accuracies of 98.8, 96.5, and 90.2 %, respectively. No statistically significant differences were found between the actuator configurations. These findings can be utilized in developing a remote communication channel that supports the transfer of spatial aspects of touch such as mapping the location of finger touch of one user to tactile sensation on the palm of another user.

KEYWORDS: Haptics, tactile communication, tactile stimulation, spatial feedback.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1   INTRODUCTION

Touch is an essential part of social interaction between people. It is used in our daily lives for expressing, for example, support and compliance [9]. Due to the inherent requirement of a shared physical space, interaction via the sense of touch has traditionally been limited to face-to-face situations. Recently, there has been a range of research on developing a remote touch communication channel. The studies have strived for simulating a human touch by using artificial haptic stimulation. Encouragingly, partial support has been found for the assumption that mediated social touch and real touch are perceived similarly [5]. Also, it has been argued that emotional content can be transferred between two users via haptics [18].

In several previous studies, the user's hand has been used as a site for presenting remotely created tactile feedback (i.e., touch messages). The hand is an area that is classified as a non-vulnerable body part in terms of acceptability of touch [9] and is highly sensitive to touch stimulation [12]. The fingertip, in particular, has been widely utilized in tactile displays (e.g., [13][22]) due to its superior tactile sensitivity. However, from the point of view of interpersonal touch communication, the available skin area of the fingertip is not large enough for presenting multi-dimensional touches in their original scale (e.g., sensation caused by stroking). The palm has larger stimulation area and sufficient spatial resolution as two contact points are perceived as separate when they are positioned at least 10 mm apart [20]. Also, when carrying a mobile device, the palm is usually in contact with the back of the device body. Despite the available stimulation area, most hand-held tactile communication devices have utilized a single actuator [2][6]. This limits the expressiveness of the device as no directional information on touches (e.g., direction of finger stroke) can be presented. With multiple actuators, it is possible to simulate these spatial features by creating apparent tactile movement that is perceived as a single moving sensation instead of several discrete stimuli [17]. This illusion can also be achieved by controlling feedback intensities between actuator locations [16][23]. A recent study showed that users preferred multiple actuators and spatial stimulation to a single actuator when evaluating a hand-held tactile communication device [14].

The dominant solution to stimulate the user's hand has been to use vibrotactile actuators (e.g., [4][6][14]) that are usually designed to be driven with frequencies from 200 to 300 Hz. Although vibrotactile actuators are small, inexpensive, and provide relatively efficient feedback, they have certain characteristics that hinder their usefulness in presenting spatial tactile messages to the user's palm. Firstly, of the four mechanoreceptors found in the glabrous skin of the human hand, previous vibrotactile communication devices have primarily stimulated the Pacinian corpuscles. Due to the fact that these receptors are located in the deeper layers of the skin and have large receptive fields [8], they do not have central role in tactile perception of spatial features [11]. Therefore, when several vibrotactile actuators are stimulating the palm, it is possible that a single receptor field responds to multiple stimulation sources. In such a case, it can be hard for a user to reliably distinguish the spatial features of the feedback.

Moreover, attaching several actuators to a lightweight, non-grounded device is challenging. Concurrent feedback signals can disperse and get mixed, which results in feedback that is felt across the whole device body. The very purpose of some vibrotactile actuators such as motors with eccentric rotating weights is to create non-localized and rough vibration (e.g., vibration alert when one receives a phone call). Thus, using the same actuators for creating localized sensations is not advisable. For instance, in an earlier study [15], six vibrotactile actuators were attached to the sides of a rigid mobile device mockup. The low accuracy for locating a single actuator (36 %) can be due to mixed feedback signals. There have been attempts to isolate the vibrating actuators from the rest of the device body [14][21]. Also, the dispersion effect can be attenuated by placing actuators in soft materials [23].

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The process of implementing a communication device for spatial touch stimulation should be guided by the knowledge of the properties of the skin. The fine spatial sensitivity of glabrous skin in the hand is accounted for by the superficial Merkel disks and Meissner corpuscles [19]. In everyday touch interaction, these mechanoreceptors respond to a wide range of touch stimuli such as tapping, motion, flutter, skin indentation, and pressure, while the Pacinian corpuscles respond mainly to tickling [10]. The Merkel disks and Meissner corpuscles are known to be most sensitive to low-frequency stimulation of 7-40 Hz [10].

To create tactile feedback suitable for activating these receptors, one alternative is to use linear actuators that operate perpendicularly to the skin. Stimulation caused by linear indentation is highly localized by its nature. Small linear actuators have been used widely in developing miniature pin-array displays that stimulate the user's fingertip (e.g., [22]). In haptic communication research, multiple linear solenoid actuators have been used in a haptic scarf to simulate a stroking sensation from a continuous series of short pokes [1]. The resulting sensation was interpreted as tapping by users.

The present study sought to address the above challenges of standard vibration by using low-frequency linear actuation. A tactile communication device prototype was implemented for this purpose. The device utilized four linear DC motor actuators that were in direct contact with the user's palm. To assess the suitableness of the device for sensing tactile messages, an experiment was conducted where participants recognized predefined stimuli. The stimuli were adapted from an earlier study where vibrotactile feedback was used for supporting interaction with a mobile touchscreen device [23]. In addition, we wanted to investigate whether the configuration of actuators on the palm affects response accuracy. Thus, we used two actuator configurations – diamond and square. Also, we varied the stimulus duration to see whether longer presentation times facilitate the recognition of multi-actuator tactile messages.

2 METHODS

2.1 Participants

A total of 14 participants volunteered to take part in the study (mean age 24.5, range 19-31 years). All participants signed informed consent forms and were either students or employees at Stanford University. Seven of the participants were male and seven female. Each participant reported holding mobile touchscreen devices in their left hand in everyday use.

2.2 Apparatus

A hand-held tactile device was used in the experiment (Figures 1 and 2). The device was designed so that it could be held comfortably in one's hand. In order to create contact all across the
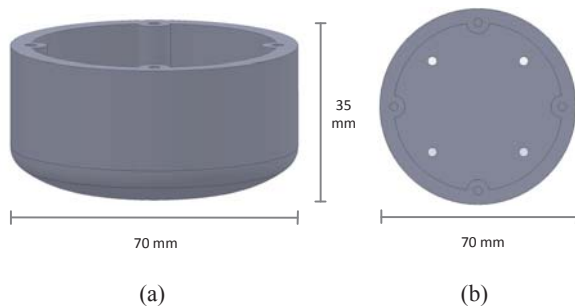

Figure 1. The 3D model of the prototype device shown from the side (a) and top (b).
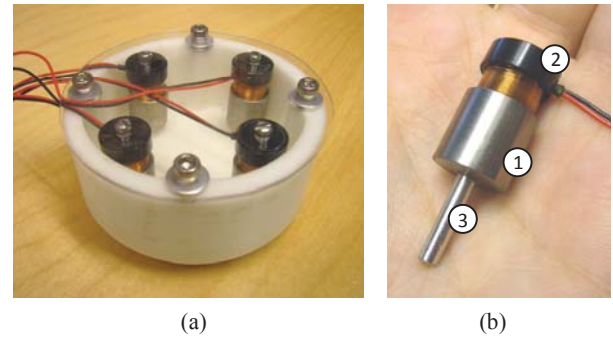

Figure 2. The prototype device with actuators and lid attached (a). The linear actuator (b) with magnetic housing (1), coil (2), and end-effector pin (3).

user's palm, the bottom half of the device was rounded (Figures 1a and 2a). The overall dimensions of the polymer form were 70×35 mm (diameter $\times$ height). Four linear DC motors (LVCM-013-013-02 from MotiCont) were used in the device. Before assembly, the actuators consisted of two separate parts: the magnetic housing and the coil (Figure 2b). At mid-stroke position (as shown in Figure 2b), dimensions of the two combined parts were 13×20 mm (diameter $\times$ height). These actuators were chosen as they provided strong feedback and a sufficient stroke length of 6.4 mm. Four actuators were used because it was the minimum number that could present the four main directions of movement (i.e., left, right, forward, and backward).

In order to create localized touch sensations, end-effector pins were screwed to the magnetic housings (Figure 2b). The diameter and length of the pins were 3.18 and 15 mm, respectively. Four holes were drilled to the bottom of the device (Figure 1b) so that the pins made direct contact with the user's palm. A transparent lid was placed on top of the device for rigidly attaching the non-moving coil parts (Figure 2a). When the device was held in the hand without applying a driving signal, the pins pushed gently against the palm and caused the magnetic housings to retract to the mid-stroke position. The four pins formed a square where the length of a side and, thus, the distance between contact points was 30 mm. This distance was well above the two-point discrimination threshold of 10 mm [20].

A Java application controlled the experimental procedure and provided an answering mechanism to the participants. The actuators were driven using audio signals. The signals were created using Pure Data (PD) audio synthesizer software. The Java and PD applications communicated via a socket connection. The created signals were fed to two external Gigaport HD USB sound cards for amplification. Amplified signals were forwarded to the four actuators.

2.3 Design and Stimuli

The experiment was a within-subject repeated measures design. The stimuli in the experiment were varied by pattern, actuator configuration, and duration. A total of 10 different patterns were used. The patterns adapted from a previous study [23] were divided into three categories (Tables 1 and 2). First, positional patterns activated a single actuator. Second, depending on the actuator configuration, linear patterns activated either two or four actuators so that the resulting sensation represented a linear movement. Third, circular patterns activated all four actuators creating either a clockwise or counter-clockwise movement. The used actuator configurations were diamond (Table 1) and square (Table 2). To change between the configurations, the device was rotated 45°. Two values were chosen for varying the stimulus duration. Pilot tests suggested that the initial duration of one

Table 1. Patterns for the diamond configuration.

Table 2. Patterns for the square configuration.

second might be too short for recognizing stimuli that utilized all four actuators. Therefore, both one and two second long stimuli were used. The total duration of a stimulus was fixed regardless of the number of used actuators. For example, a second long circular stimulus consisted of four separate activations of 250 milli-seconds.

The audio signal used for driving the actuators was a 15 Hz sine wave. The frequency fell in the sensitivity range of the superficial skin receptors (i.e., 7-40 Hz). The actuators were driven with an output power of 0.06 W. No funneling was used to modify the illusory movement between actuators as in some previous studies with vibrotactile feedback [3][16][23]. That is, the amplitude of the sine wave was constant throughout actuator activation.

2.4   Procedure

Participants were told that the purpose of the experiment was to evaluate a hand-held device that provided tactile stimulation. The device was held so that the four actuators were always in contact with the participant's palm. The participant was advised to let the device rest on the palm instead of squeezing or gripping it (Figure 3a). The device was held in the hand that the participant normally used for holding a mobile touchscreen device (i.e., left hand for all
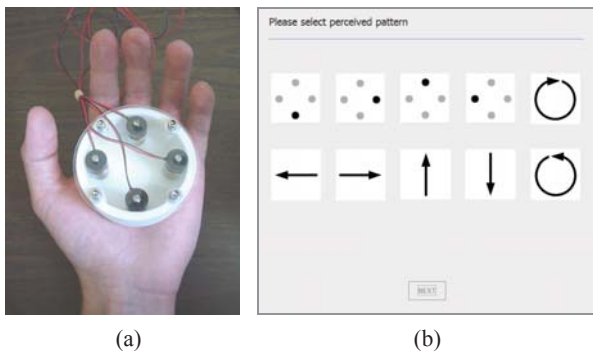

Figure 3. Prototype device (a) held in the diamond configuration (rotating 45º made the square configuration). The experimental interface (b) showing the response options for the diamond configuration.

participants). Noise-blocking headphones were used to ensure that audio created by actuation was not perceived. In addition, a piece of cardboard was attached on top of the device in order to prevent the participant from obtaining visual cues of actuation. Soft foam was placed under the participant's hand to prevent fatigue when holding the device.

The experiment was divided into two blocks based on the two actuator configurations. The order of the blocks was counter-balanced so that successive participants started with different actuator configurations. The participant's task was to sense and recognize predefined stimuli. Available response icons (Figure 3b) were shown and described verbally to the participant before starting the experiment. Response icons for the positional patterns were configuration-specific, whereas for the linear and circular patterns the same response icons were used.

In the beginning of the first block, the current actuator configuration (i.e., diamond or square) was introduced to the participant. Then, a practice session of eight trials started. The practice stimuli were different than the ones used in the actual test session. The participant used a computer mouse with his/her other hand to initiate the first practice stimulus. The stimulus started after a four second delay. After the stimulus was presented, response icons appeared on the screen of a laptop PC.

The participant had to click on an icon to proceed to the next trial. The actual test session proceeded similarly to the practice session. After finishing the first test block, a short break was taken before continuing to the second block. Each pattern was presented twice during both blocks in a randomized order. Thus, a total of 80 stimuli (10 patterns × 2 durations × 2 configurations × 2 repeats) were presented to each participant. The entire experiment took approximately 30 minutes.

2.5   Data analysis

The frequencies of correct responses were first analyzed with Friedman tests. Wilcoxon signed-ranks tests were used for pairwise comparisons.

3   RESULTS

Mean response accuracies for positional (i.e., bottom, top, left, and right), linear (i.e., bottom-top, top-bottom, left-right, and right-left), and circular (i.e., clockwise and counter-clockwise) stimuli with the diamond configuration were 97.9, 94.7, and 89.3 %, respectively. For the square configuration, the corresponding accuracies were 99.6, 98.2, and 91.1 %. The combined mean accuracies of both configurations were 98.8, 96.5, and 90.2 %. That is, the accuracy of recognizing an arbitrary stimulus was 95.1 %. Participants' mean response times from the offset of a stimulus to the click of a response icon were 3.3 seconds for both actuator configurations.

Two separate analyses were conducted for the response accuracies of positional stimuli as the response icons were different for the two configurations. For the positional diamond stimuli, the Friedman test showed a statistically significant effect of response accuracy $X^2 = 15.2$, $p < 0.05$. However, Wilcoxon signed-rank tests did not show significant differences between stimulus pairs. For the positional square stimuli, the Friedman test did not show a significant effect. Similarly, two further Friedman tests did not show significant effects for the linear or circular stimuli. The confusion matrices for the diamond and square stimuli are shown in Tables 3 and 4, respectively. In order to simplify the matrices, and especially since Wilcoxon signed-rank tests did not show significant differences between one and two second long stimuli, responses were summed over duration.

Table 3. Confusion matrix for the diamond stimuli. The numbers in bold font represent the number of correct user responses. The numbers in parentheses represent the distribution of user responses in percentages.

	User Response										
	Bottom	Top	Left	Right	Bottom-Top	Top-Bottom	Left-Right	Right-Left	Clockwise	Counter-clockwise	Total
Bottom	**55** (98.2)		1 (1.8)								56
Top		**56** (100)									56
Left			**56** (100)								56
Right			2 (3.6)	**52** (92.9)			2 (3.6)				56
Bottom-Top					**55** (98.2)				1 (1.8)		56
Top-Bottom						**56** (100)					56
Left-Right			4 (7.1)	1 (1.8)			**51** (91.1)				56
Right-Left		1 (1.8)	3 (5.3)	1 (1.8)				**50** (89.3)	1 (1.8)		56
Clockwise									**49** (87.5)	7 (12.5)	56
Counter-clockwise									5 (8.9)	**51** (91.1)	56
Total	55	57	66	54	55	56	53	50	56	58	560

Table 4. Confusion matrix for the square stimuli. The numbers in bold font represent the number of correct user responses. The numbers in parentheses represent the distribution of user responses in percentages.

	User Response										
	Top left	Top right	Bottom left	Bottom right	Bottom-Top	Top-Bottom	Left-Right	Right-Left	Clockwise	Counter-clockwise	Total
Top left	**56** (100)										56
Top right		**56** (100)									56
Bottom left	1 (1.8)		**55** (98.2)								56
Bottom right				**56** (100)							56
Bottom-Top					**56** (100)						56
Top-Bottom						**56** (100)					56
Left-Right							**54** (96.4)		2 (3.6)		56
Right-Left					2 (3.6)			**54** (96.4)			56
Clockwise								1 (1.8)	**52** (92.9)	3 (5.4)	56
Counter-clockwise									6 (10.7)	**50** (89.3)	56
Total	57	56	55	56	58	56	54	55	60	53	560

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4 DISCUSSION

The results showed that the participants could recognize spatial tactile stimuli presented to the palm in a robust fashion (i.e., with a mean accuracy of 95.1 %). The positional stimuli were recognized almost perfectly as 448 trials resulted in only four incorrect answers (see Tables 3 and 4). The mean response accuracies for the linear stimuli were comparable despite the different pattern designs in square and diamond configurations. In the square configuration, all four actuators were used, whereas in the diamond configuration only two actuators were active. The results showed that two actuators were sufficient for creating distinguishable linear stimuli. There was a tendency to recognize anteroposterior stimuli (i.e., top-bottom and bottom-top) better than the mediolateral ones (i.e., left-right and right-left). However, no statistically significant effect was found between the dimensions. The mean response accuracies for the circular stimuli were on average 7.6 % lower compared to the positional and linear stimuli. All but one of the incorrect answers were caused by confusion about the direction of circular movement (i.e., clockwise patterns were perceived as counter-clockwise and vice versa). This indicated that the circular stimuli were highly distinctive in relation to the other stimuli.

Overall, the results showed no statistically significant differences between the two actuator configurations. Similarities between the configurations were also demonstrated by the participants' mean response times that were identical for both configurations. In terms of the two stimulus durations, no statistically significant differences were found. Thus, the results showed that also the shortest activations of 250 milliseconds in circular stimuli were long enough for recognizing the actuator locations.

A partial comparison can be made between the current results and earlier work conducted with vibrotactile actuators [23]. In the earlier study by Yatani and Truong, an actuator setting was used that was otherwise similar to the diamond configuration, but had a fifth actuator placed in the middle of the four. Therefore, it is not meaningful to compare the positional patterns as the number of response options was different. For the linear patterns, on the other hand, a general comparison is feasible as the same four main directions of movement were used in both studies. Also, the designs of circular patterns were identical in both studies. That is, four actuators were driven sequentially starting from the top one. In the earlier study, mean response accuracies of 90.2 and 74.6 % were reported for the linear and circular patterns, respectively. When compared to the corresponding mean (diamond) accuracies of 94.7 and 89.3 % of the current study, we can see that recognizing the patterns was easier with linear actuation. In particular, the current mean response accuracies for counter-clockwise patterns were noticeably higher compared to the earlier study (i.e., 91.1 and 65.8 %). Although there were certain differences in the setups of these two studies, the above comparison suggests that the current device design using linear actuation performed better in presenting spatial tactile messages to the user's hand.

Our first aim in implementing the prototype device was to minimize the actuation effect on the device body and, thus, create highly localized tactile sensations. The linear DC motors were suitable in this respect as the free movement of the magnetic housing directed practically all actuation energy to the user's palm. With this actuator solution, we were able to avoid the dispersion of actuation energy to the device body that complicates the recognition of multiple actuation sources [15]. The second aim was to present spatial messages reliably instead of maximizing the resolution of the tactile display. It should be noted that a range of research has been carried out to optimize the dimensions and information transfer capabilities of miniature linear displays (e.g.,

[22]). The current decision to incorporate four actuators seemed justified as the participants could distinguish the different messages with high accuracy. The ceiling effect (i.e., 100 % response accuracy) observed with some stimuli suggests that the device would have supported more complex stimulus designs. The chosen actuator count proved to be flexible in that the recognition of tactile messages was not dependent on a specific actuator configuration. One limitation with the current implementation was the fact that the two-part DC motors functioned properly only in an upright position. Tilting the device more than 90° caused the magnetic housing to slide inside the coil part which prevented actuation. This could be resolved by attaching appropriate stoppers between the parts.

It can be argued that the evaluated linear stimulation method supported the presentation of spatial tactile messages with a hand-held device. As reviewed in the introduction, previous multi-actuator solutions have mainly utilized high-frequency vibrotactile stimulation despite the challenges in differentiating the different actuator sources. The current results suggest that linear actuators are preferable when multi-actuator tactile messages are desired on the palm area. From the point of view of everyday touch interaction, linear stimulation has potential to mimic several touch types. For example, tapping, patting, and stroking are tactile behaviors that could possibly be represented using linear actuators. At the same time, it should be noted that the human tactile system is extremely complex. In addition to the tactile behaviors, touch can vary in its intensity, velocity, abruptness, temperature, location, and duration [7]. Therefore, replicating all the characteristics of a real touch is a challenging if not impossible task with today's actuator technology. Acknowledging this general limitation, this work evaluated a stimulation method that was founded on the capabilities and everyday use of the cutaneous sense.

In reflecting our results in the light of tactile communication research, this study showed that linear, low-frequency actuation is a feasible technology for presenting the spatial aspects of tactile messages. With a spatial actuation solution, tactile communication devices could present users' real tactile behaviors in a more precise manner. Although the current study was limited in the sense that the participants perceived predefined messages passively, we wanted to take this as a first step and evaluate the prototype in a controlled fashion. In future work, a sensing mechanism will be added to the top of the device so that users can compose their own tactile messages using finger strokes similarly to a previous study [14]. The location of touch input will be mapped to the locations of the four actuators on the bottom of the device. Thus, when two devices are connected, a touch of one user will result in a tactile sensation on the palm of another user. The fact that the simple tactile messages were recognized in a robust fashion is encouraging as the user-created messages would in practice be combinations of the very same patterns. In addition, further research is needed to determine whether users perceive linear actuation as more touch-like than vibrotactile feedback.

5 CONCLUSION

This research sought to improve the design of hand-held tactile communication devices by using four linear actuators to provide spatial messages to the user's palm. Experimental results showed that participants recognized predefined stimuli with a mean accuracy of 95.1 % when varying the stimulus pattern, actuator configuration, and duration. The contribution of this study is that it introduced linear actuation as a more spatially accurate alternative to high-frequency vibrotactile stimulation that is traditionally used in hand-held tactile communication devices. Spatiality plays an essential role in supporting the transfer of touches with directional information (e.g., direction of a finger

stroke) between remote users. In addition, from the perspective of cutaneous sensing, linear low-frequency actuation has potential to deliver touch-like tactile sensations with remote communication devices. Further research needs to be conducted to determine the value of linear actuation in an actual remote communication setting.

6   ACKNOWLEDGMENTS

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Paper III

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The Role of Gesture Types and Spatial Feedback in Haptic Communication

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Abstract—The sense of touch is a fundamental part of social interaction as even a short touch from another person can elicit emotional experiences. Previous studies on haptic communication indicate that the benefits of interpersonal touch exist even when touch is artificially mediated between people that are physically apart. In the current study an evaluation of three input gestures (i.e., moving, squeezing, and stroking) was conducted to identify preferred methods for creating haptic messages using a hand-held device. Furthermore, two output methods (i.e., one or four haptic actuators) were investigated in order to determine whether representing spatial properties of input gestures haptically provides additional benefit for communication. Participants created haptic messages in four example communication scenarios. The results of subjective ratings, postexperimental interviews, and observations showed that squeezing and stroking were the preferred ways to interact with the device. Squeezing was an unobtrusive and quick way to create haptic content. Stroking, on the other hand, enabled crafting of more detailed haptic messages. Spatial haptic output was appreciated especially when using the stroking method. These findings can help in designing haptic communication methods for hand-held devices.

Index Terms—Haptic I/O, input devices and strategies, interaction styles, mobile communication systems.

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1 INTRODUCTION

THE haptic modality plays an essential role in our everyday lives. Many tasks such as examining textures and holding objects depend on information received via touching. Touch is particularly important in social interaction. A short touch from another person can elicit strong emotional experiences [1]. It has been demonstrated that touch can communicate distinct emotions even when touching an unacquainted person [2]. Jones and Yarbrough [3] found several meanings of touch such as support, affection, and compliance. Usually interpersonal interaction via the sense of touch is limited to face-to-face situations where one can reach and touch the other. Consequently, devices supporting remote communication have relied mainly on spoken messages and vision.

Lately there has been a growing interest in research on haptic communication. It has been shown that even simple vibrotactile stimulation can carry emotional information in human-computer interaction [4], [5]. The latest findings indicate that emotional content can also be transferred between two users via haptics. Smith and MacLean [6]

argued that emotion-related information can be communicated successfully between two persons using 1-degree of freedom haptic knobs. Moreover, Haans et al. [7] found partial support for the assumption that mediated social touch (i.e., touching each other over a distance by means of haptic technology) and real touch are perceived similarly. In this respect, research on haptic communication is relevant and well justified as mediated social touch provides unique benefits compared to current communication technology dominated by hearing and vision.

A considerable number of prototype devices exist that allow users separated by distance to exchange information using the sense of touch. Such haptic communication devices have been used for enhancing textual, e.g., [8] and auditory interaction, e.g., [9], [10]. There are also several communication devices based only on haptic interaction, e.g., [11], [12], [13]. Because of the central role of touch as a way to convey emotional information, these prototypes have been mainly designed for enhancing the feeling of proximity while being physically apart.

Several factors affect the design of haptic communication devices. First, sensitivity of different body areas determine how accurately artificial touch can be perceived. It is known that lips, tongue, hands, feet, and genitals are considerably more sensitive than other parts of the human body [14]. The most common actuation areas used in previous haptic communication research have been hands [9], [10], [12], upper body torso [11], [13], and feet [15]. Second, there are notable differences in touch behavior between cultures. The most haptically active cultures are located in warmer climates where skin and other people are visible and available [16]. Third, different body areas have been classified based on their vulnerability to touch [3]. Nonvulnerable body parts include hands, arms, elbows, shoulders, and upper-middle back, while all other areas are considered vulnerable.

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In light of the previous knowledge, a hand-held device can be identified as a good candidate for further investigation. Hand is a highly sensitive, often visible and nonvulnerable body location. In addition, a hand-held device requires no fastening as it can simply be picked up when desired.

1.1 Creating Haptic Messages with Gestures

In a study by Heikkinen et al. [17] user expectations for haptic communication with a hand-held device were investigated. The results indicated that spontaneity of touch is an important factor when designing haptic communication devices, and unnecessary complexity in user interfaces (e.g., menus or multiple buttons) should be avoided. In addition, it was recommended to let users create and sense haptic messages in real time. In an ideal case, the use of a haptic device should not create any more cognitive load than creating a real touch. These issues have been addressed to some extent in previous research. Mueller et al. [13] created semantic congruency between physical input and affective haptic output by introducing a natural input method, hugging. Haans and IJsselsteijn [18] investigated the importance of morphological congruency in haptic communication. They found out that an input medium, that resembles the human body and allows for a one-to-one mapping between seen and felt touch, can improve the sense of telepresence and make mediated touches more touch-like.

Existing research suggests that use of a haptic communication device should resemble a real touch as closely as possible. However, virtually no systematic studies exist that cover the whole interaction of generating a touch input and feeling the resulting haptic output. Our first step in mapping this field was to observe users' natural gesturing methods [20]. A mock-up device was utilized because functional prototype devices tend to narrow down potential use affordances and thus affect users' understanding of the possible interaction methods. The participants were provided with a device supplied with imaginary and omnipotent haptic features. They were instructed to use it in the way they found natural in certain example communication scenarios.

Similarities between the contexts of users' inherent interaction methods [20] and unmediated touch [2], [21] were identified. Three particular types of behavior were recurring. First, shaking was a common behavior. With the omnipotent device, shaking was the most frequent gesture to express excitement, happiness, and agreeing. In the unmediated situations, it was used most frequently to express anger, fear, happiness, gratitude, embarrassment, and pride. Second, stroking using either a single finger or whole hand was used in both contexts. Stroking was the most frequent way to signal longing, comfort, and empathy with the omnipotent device. In the unmediated situations, stroking was used most frequently for expressing love and gratitude. Third, squeezing interaction was utilized in both contexts although not widely as the most frequent way. With the omnipotent device, squeezing was the second most frequent gesture when expressing excitement, happiness, and empathy. In the unmediated situations, squeezing was the most frequent behavior in expressing surprise and secondary in anger and fear.

Interestingly, some of the three touch gestures were used to convey various and even opposite emotions (e.g., shaking in unmediated situation). According to the principle of equipotentiality, same type of touch can have different meanings or consequences [21]. This suggests that other variables such as intensity and velocity are also important in determining the meaning of a touch.

In the second phase of our previous study [20] an initial experiment with shaking was conducted. The general idea of creating haptic messages from gesture data received acceptance. However, it was found that shaking gestures alone were not sufficient. The participants desired alternative input methods for expressing more versatile information and different emotions.

1.2 Presenting Haptic Messages Spatially

In addition, we were interested in studying how to represent dynamically created haptic messages so that characteristics of input gestures could be conveyed as accurately as possible. Some interesting actuation technologies have been introduced in previous haptic communication studies. These include an air compressor to inflate a vest [13] and a servomotor to simulate breathing [19]. However, such technology is not optimal for hand-held devices. Most existing prototypes, e.g., [8], [9], [10], [11], [12], have used vibrotactile feedback. This is mainly due to the fact that vibrotactile actuators are small, easy to mount, and provide relatively efficient feedback.

There has been prior work on mapping the design space of vibrotactile feedback, e.g., [22], [23]. Parameters such as frequency, amplitude, duration, and rhythm can be utilized to create distinctive haptic stimuli. Previous haptic communication prototypes have typically presented haptic messages with one vibrotactile actuator and have thus been limited to the above parameters. However, adding several actuators would enable spatial representation of haptic messages. This can be particularly advantageous when multidimensional physical gestures (e.g., finger strokes) are synthesized haptically. Instead of being able to transfer the intensity and duration of a touch, devices could also mediate spatial directions by driving multiple actuators sequentially.

Studies on a phenomenon called "sensory saltation" [24] indicate that directional tactile stimuli created with several actuators are generally intuitive and easy to perceive. Research has shown that specifically torso [25], [26], but also arm [23], [27], and wrist [28], are suitable body sites for presenting vibrotactile information using multiple actuators. The current study focused on determining and evaluating the spatial parameter for portable devices that are held in the user's palm.

In a study by Hoggan et al. [29], four vibrotactile actuators were attached to a hand-held PDA. Feedback was localized perfectly when two of the actuators were in contact with user's thumb and the other two with index and ring fingers. Furthermore, Sahami et al. [30] mounted six vibration motors inside the left and right side of a dummy mobile phone. Feedback locations in the four corners of the device were recognized with an average accuracy of 73 percent. However, two actuators located in the middle of the device were notably harder to recognize. It is likely that vibration from individual actuators dispersed so that it was felt across the whole body of the device. Yatani and Truong [31] improved the design by placing a mobile

device in a custom-built sleeve for creating better contact between actuators and the user's hand. The results showed that participants could recognize predefined patterns (i.e., positional, linear, and circular) created with five vibrotactile actuators with an average accuracy of 90 percent. These studies indicated that the palm and fingers could also be used successfully to present spatial movement.

In our previous study [20], a prototype device with four C2 actuators (Engineering Acoustics, Inc.) was used for creating haptic output based on real-time gesture data. The actuators were mounted in a 2×2 array so that the spatial aspects of input gestures could be rendered haptically. The results indicated that participants utilized the spatial parameter. However, the C2 actuators were not ideal on the palm area because of their large diameter. Moreover, we had limited understanding of whether the use of multiple actuators actually provided additional benefit.

1.3 Research Questions

Despite the fact that moving, stroking, and squeezing gestures seem to have a role in interpersonal communication, relatively little is known about how to introduce them into haptic communication devices. Also, it is not known whether the use of multiple actuators on a haptic communication device can provide additional value. Therefore, the research questions of the study were to find out:

1. Which input method (i.e., moving, stroking, or squeezing) is preferred?
2. Which output method (i.e., one or four actuators) is preferred?
3. How messages are created with the input and output methods?

In order to address these questions, an experiment was conducted where a hand-held haptic device enabled composition of messages by moving the whole device, stroking a touchpad, or squeezing buttons on the sides of the device. Four spatial actuators were located so that two were on the left and two on the right side of the device. One actuator was embedded inside to vibrate the whole device. Participants were to craft haptic messages for given communication scenarios. The device was used simultaneously both for creating and sensing the haptic messages.

Interaction with the device was analyzed using post-experimental interviews, video recordings, and subjective ratings. In terms of the ratings, dimensional affective space has been shown to be a viable method for assessing participants' emotional responses [32]. Bipolar rating scales have also been applied to haptics research, e.g., [4], [5], where scales for pleasantness, arousal, approachability, and dominance were used to study emotional responses evoked by haptic feedback. In the current study, we were interested in the pleasantness of use. Interaction with a communication device should be both pleasant and easy when unnecessary complexity has been minimized. Furthermore, to take specific aspects of haptic communication into account, additional scales for easiness, expressiveness, reasonability, and applicability were introduced. The scale of expressiveness was included to evaluate the value of multiple actuators. The scales of reasonability and applicability provided ratings for evaluating whether the methods were perceived as realistic.

Fig. 1. The haptic device on a tabletop (on the left) and upside down (on the right) showing the five actuator locations.

2 METHODS

The purpose of the experiment was to gather users' subjective experiences and evaluations of the input and output methods. Therefore, no actual interpersonal communication took place in the experiment.

2.1 Participants

Twelve participants volunteered to take part in the study (mean age 24.1, range 18-34 years). They were either students or employees in the University of Tampere, Finland. Eight of the participants were male and four female. All participants were right-handed by their own report. Eleven of the participants said that they held a mobile phone in their right hand and one held it in his left hand while speaking or typing a text message. All participants signed an informed consent form and thus agreed on the use of their video recordings for analysis.

2.2 Apparatus

A haptic device with multiple actuators and input sensors was used in the experiment (Fig. 1). The shape of the device with dimensions of $13.5 \times 5.5 \times 3.5$ cm (length $\times$ width $\times$ height) was such that it could be held comfortably in one's hand. There were two types of haptic actuators attached to the device. First, one C2 linear vibrotactile voice coil actuator (diameter 3.05 cm) was placed inside the bottom of the device (on the right in Fig. 1, dashed circle). The purpose of the C2 actuator was to provide feedback that would be felt on the whole device. Second, four Minebea Linear Vibration Motor actuators (LVM8, Matsushita Electric Industrial Co., Japan) with a diameter of 0.8 cm were attached to the device. Two actuators were located on the left and two on the right side of the device (on the right in Fig. 1, four ellipses). Due to their small size, the LVM8 actuators could be mounted inside separate buttons (on the left in Fig. 1). The buttons were isolated from the device body in order to localize vibration to the four specific areas on the sides of the device. A separate accelerometer (DE-ACCM3D) was used to analyze distribution of the vibration between different locations on the device. Accelerometer readings were recorded from the flat top of the device, four side buttons, and the round bottom of the device. When driving the four LVM8 actuators, the relative distribution between the top, side, and bottom was 0.11, 0.79, and 0.10, respectively. With the C2 actuator, the corresponding distribution was 0.50, 0.22, and 0.28. Both actuator types could be driven using audio signal which enabled modifying input with audio synthesis software.

Three different sensor types were used for gathering input data. Movement was detected using three 1-axis ADXRS300 gyroscopes that measured rotational motion
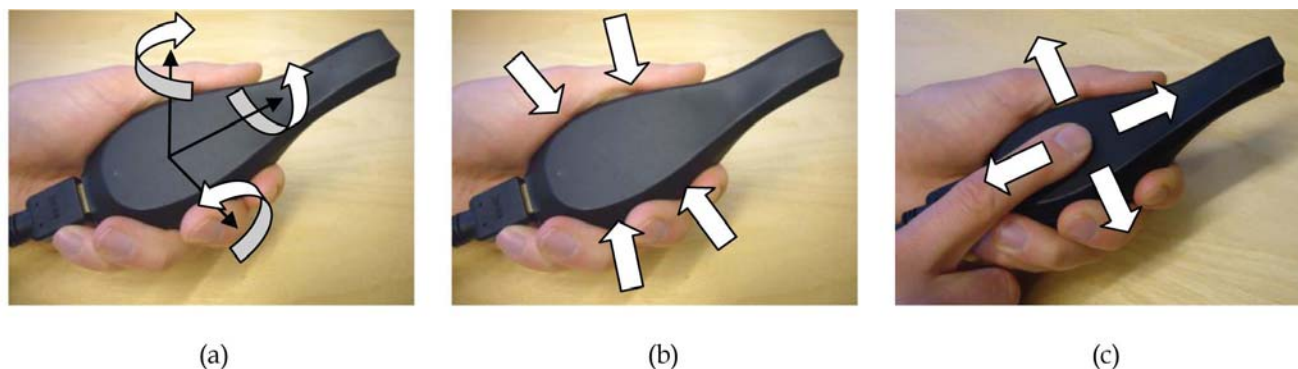
Fig. 2. Input methods of (a) moving, (b) squeezing, and (c) stroking.

(angular velocity) of the device (see Fig. 2a). Squeezing was measured with four force sensitive resistors (Model 400, Interlink electronics). The resistors were mounted inside the device so that they detected pressing of the four side buttons (see Fig. 2b). Each button reported separate pressure values. Stroking was measured with a custom built 15-channel capacitive touchpad. The touchpad was located under the flat area on top of the device (see Fig. 2c). Multitouch could be used as all 15 channels reported separate input values. All three sensor types were sampled with a frequency of 100 Hz.

In addition to the haptic device, an interface box was used in the experiment (Fig. 3). The box was an auxiliary device that connected the haptic device to a computer (Toshiba Portege R500). After collecting data from all sensors, a microcontroller in the device converted sensor values into ASCII characters for data transmission. The haptic device was connected to the box using a HDMI cable. Data transmission from the box to the computer was handled via serial communication. Pure Data audio synthesizer software (PD, http://puredata.info) read the input data and generated corresponding feedback signals for the haptic actuators. After the feedback synthesis, audio signals from PD were fed back to the box with an external Gigaport HD USB sound card. The box had separate 3.5 mm plugs for each audio signal. Finally, audio signals were amplified in the haptic device with a class-D audio amplifier (TPA2034 with a fixed 12 dB gain). PD was also used to log the created input data.
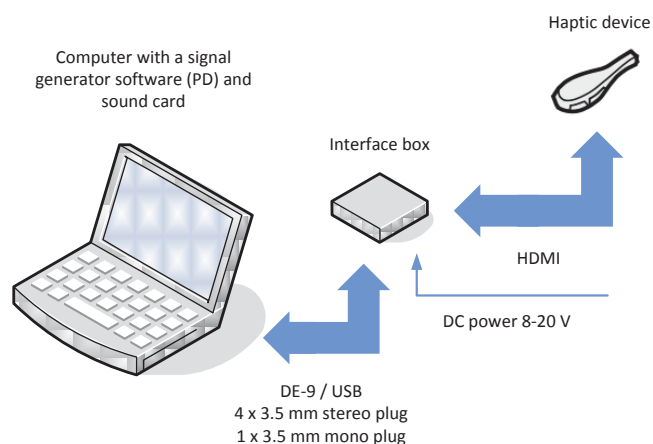
2.3 Feedback Synthesis

Our approach in the feedback synthesis design was to create a seamless mapping between physical input gestures and haptic actuators. Spatial parameter of input, such as tilting the device to a certain direction or stroking only one part of the touchpad, was represented haptically by driving different actuators independently. Intensity of input gestures (i.e., angular velocity of moving, pressure of squeezing, and force of stroking) was represented with different amplitude levels. Amplitude was chosen over frequency due to the fact that the participants in our previous study found subtle frequency changes to be relatively hard to recognize [20]. Moreover, controlling only the frequency of haptic feedback is challenging because different frequencies cause inherent amplitude variations.

A fixed resonant frequency of 160 Hz was used for both actuator types. The optimum frequencies for the C2 and LVM8 were 250 and 155 Hz, respectively. The lower frequency was chosen because the C2 has a wider usable frequency range than the LVM8. Thus, it was possible to drive the C2 with lower frequencies whereas the LVM8 could not be driven efficiently with a frequency of 250 Hz. Piloting showed that LVM8's optimum frequency of 155 Hz generated distracting audible noise and therefore a more silent 160 Hz was used.

An envelope signal was used to modulate the basic driving signal of 160 Hz sinusoid. Initial pilots with different signal shapes indicated that a constant sinusoid was perceived as too obtrusive. In addition, unevenness in the sinusoid shape was hypothesized to facilitate detection of small amplitude variations in the signal. In principle, the more variations users can recognize, the better is the expressiveness of the haptic messaging system. Fig. 4 depicts different phases of the feedback synthesis. First, input data were read and processed to get four separate
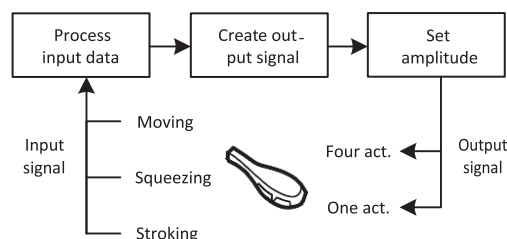

Fig. 3. Components and connections of the experimental setup.

Fig. 4. Interaction model of the device with feedback synthesis.
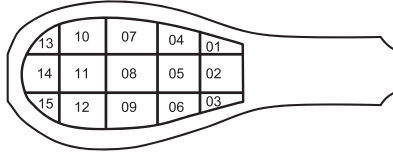
Fig. 5. Numbering of the 15 touchpad channels.

(a)   (b)   (c)

Fig. 6. (a) Envelope signal, (b) driving signal of 160 Hz sinusoid, and (c) final signal after mixing signals (a) and (b).

input intensity values. Second, the output signal was created using an envelope signal and a 160 Hz sinusoid. Third, the amplitude of the output signal was defined based on the intensity values and actuator type. These different steps are next described in more detail.

2.3.1 Processing Input Data

Raw data from the three sensor types were used to calculate separate input intensity values for the four side actuator locations (i.e., $Input_{frontleft}, Input_{backleft}, Input_{frontright}$, and $Input_{backright}$). These values were needed in order to create individual haptic output signals for each actuator. Squeezing input required no separate conversion as the pressure sensors were mounted in the buttons with their corresponding actuator (e.g., $Input_{frontleft} = Pressure_{frontleft}$).

Touch data were divided into four input locations by adding up values of several touchpad channels (see Fig. 5 for channel numbers). For example, channel values for the two left side actuators were calculated as follows:

$$Input_{frontleft} = Pad_{channel1} + Pad_{channel2} + Pad_{channel4}$$
$$+ Pad_{channel5} + Pad_{channel7},$$
$$Input_{backleft} = Pad_{channel7} + Pad_{channel10} + Pad_{channel11}$$
$$+ Pad_{channel13} + Pad_{channel14}.$$

The same approach was applied to the right side actuators. The middlemost channel 8 was not mapped to any of the four locations as the aim was to encourage users to touch or stroke the sides of the touchpad.

For moving input, the gyroscope's X- and Y-axis data were processed to separate four main directions of movement (i.e., $Gyro_{forward}, Gyro_{backward}, Gyro_{left}, Gyro_{right}$). Next, the directional values were converted into four input locations:

$$Input_{frontleft} = Gyro_{forward} + Gyro_{left},$$
$$Input_{backleft} = Gyro_{backward} + Gyro_{left},$$
$$Input_{frontright} = Gyro_{forward} + Gyro_{right}$$

and finally $Input_{backright} = Gyro_{backward} + Gyro_{right}$. Values for each of the four input locations ranged from 0 (no input) to 150 (maximum input intensity) regardless of the input method.

2.3.2 Creating Output Signals

First, an envelope signal was created by reading and looping an array where an envelope shape of half a period of sine wave was stored. The resulting envelope signal is depicted in Fig. 6a. Then, this envelope signal was mixed with a 160 Hz sinusoid (Fig. 6b). The final mixed signal (Fig. 6c) had irregularities in the signal shape to make the feedback feel more pleasant and facilitate recognition of subtle amplitude changes.
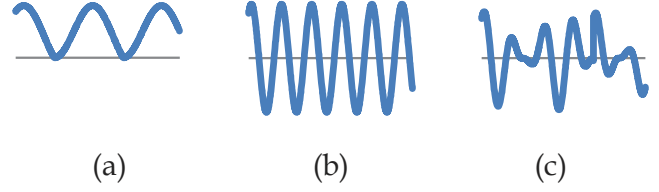
2.3.3 Setting Output Amplitude

Amplitude levels were calculated separately for the center and side actuators. First, amplitudes for the side actuators were determined using

$$Amplitude_{frontleft} = \left(\frac{Input_{frontleft}}{c}\right)^e, \qquad (1)$$

where $c = 15$ and $e = 0.7$. The same equation was applied to the other three side actuators. The constant c was hand-tuned during piloting to set a general amplitude level suitable for the side actuators. The exponent e was defined to make the amplitude modulation resemble a logarithmic function. In other words, it was possible to utilize noticeable amplitude levels with relatively low intensity input. Higher amplitude levels could be reached with sufficiently high input intensities. Amplitude for the center actuator was determined using

$$Amplitude_{center} = \left(\frac{Input_{sum}}{c}\right)^e, \qquad (2)$$

where variable $Input_{sum} = Input_{frontleft} + Input_{backleft} + Input_{frontright} + Input_{backright}, c = 238$, and $e = 0.7$.

The four input values were summed to get a total input value. The center actuator generated stronger vibrations than the smaller side actuators and therefore the constant c was modified accordingly to lower the amplitude.

Despite modifying the constant c, further equalization was needed to make the feedback of the two different actuator types comparable. A separate pilot experiment was conducted where a total of 10 participants (who did not take part in the actual experiment) adjusted the amplitude of the side actuators to be equal to the center actuator. The participants held the haptic device in one hand and used a computer mouse with the other. First, the participant felt a reference feedback from the center actuator. Then, an identical feedback was felt from the side actuators. At this point both amplitudes were set to be equal (i.e., the values were 1). The participant adjusted the intensity of the smaller side actuators to feel similar to the center actuator. This was done using a graphical slider implemented with PD. The participant was not aware that the adjusted parameter was amplitude. The procedure of sensing the feedback of both actuators and making adjustments was repeated a total of 10 times.

A mean amplitude level of 4.79 was calculated for the side actuators. This value was utilized in the actual experiment. That is, maximum input intensities with side and center actuators resulted in amplitudes of 4.79 and 1, respectively.

TABLE 1
Definitions of the Rating Scales

Scale	Definitions of scale extremes	
	-4	+4
Applicability	Inapplicable	Applicable
	(unsuitable, impractical)	(suitable, practical)
Easiness	Difficult	Easy
	(awkward, unnatural)	(effortless, natural)
Expressiveness	Weak	Strong
	(simple, similar)	(different, versatile)
Reasonability	Unreasonable	Reasonable
	(unrealistic, unlikely)	(realistic, likely)
Pleasantness	Unpleasant	Pleasant
	(uncomfortable,	(comfortable,
	inconvenient)	convenient)

2.4 Procedure

The participants were told that the purpose of the experiment was to study how information could be transmitted haptically using a mobile device. The participants were instructed to hold the device in a way that the two actuator areas on both sides would be in contact with the palm and fingers (see Fig. 2). The device was held in the same hand as the participant would hold a mobile phone while speaking or typing a text message.

The experiment was divided in six experimental blocks based on the input-output method combinations (3 input methods $\times 2$ output methods). The order of the blocks was counterbalanced so that the first input-output combination was different for every participant. In each block the participant's task was to create a haptic message in four different communication scenarios. The role of the scenarios was to act as stimuli for evaluating the different input and output methods. The most feasible scenarios for haptic communication were selected based on the previous study [20]. In scenario 1, the participant was to express excitement after meeting a new person. In scenario 2, the participant quickly agreed to a text message. In scenario 3, the task was to alert a friend who was talking during a lecture. In scenario 4, a nice haptic message was sent to a loved one. The order of the scenarios was Latin square counterbalanced.

In the beginning of each block, the current input-output combination was introduced to the participant. After a free-form training period, the participant heard a verbal description of a practice scenario and was asked to create a suitable message. The participant used one device both for creating and sensing the haptic feedback. Although no recipient was used in the experiment, the participant was asked to imagine that another user would hold a similar device and that he/she could feel the created message in real time. After coming up with a suitable message and rehearsing, the participant was asked to create the message once for logging purposes.

Then, the participant continued to complete the four test scenarios that proceeded similarly to the practice scenario. The test scenarios were followed by rating scales ranging from −4 to +4 (see Table 1). The participant was to rate the interaction (i.e., combined use of the current input and output methods) based on real-time use. That is, the created

messages were not played back for rating purposes. First, an applicability rating was asked for each of the scenarios. The scale was defined as follows: "−4 *(inapplicable) means that you were able to create an unsuitable and impractical message, while* +4 *(applicable) means that you were able to create a suitable and practical message using these methods.*"

Then, four additional ratings were given using the scales of easiness, pleasantness, expressiveness, and reasonability. No scenario-specific ratings were asked as we wanted to elicit more generalized ratings and urge the participants to consider how the specific methods would work in a real use context. The scale of easiness was defined as follows: "−4 *(difficult) means that it would be awkward and unnatural to create messages, while* +4 *(easy) means that it would be effortless and natural to create messages using these methods.*" The other three scales were defined similarly (see Table 1).

Once the participant had given the ratings, the next experimental block started. This procedure was repeated until all the six blocks had been carried out. The experimental tasks were followed by a nonstructured postexperimental interview. In the beginning of the interview, the participants were verbally guided to comment on 1) the interaction methods and 2) the concept of haptic communication in general. The test sessions were video recorded for observations analysis. Conducting the whole experiment took approximately 45 minutes.

2.5 Data Analysis

A repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Bonferroni corrected pairwise t-tests were used for posthoc tests.

The gathered interview data were first transcribed and then analyzed by categorizing and grouping based on main themes. Quotes that best represented the participants' general view or pointed out important challenges with the use were selected to the results section. The quotes were translated to English from Finnish. In observations analysis, each created message was coded from video using the following parameters: number of rehearsed gestures, time used for choosing a gesture, duration of a gesture, number of repeats in a gesture, type of touch/gesture, direction of a gesture, and intensity of a gesture. Analysis of the interview responses and video recordings was conducted by one coder.

3 RESULTS

3.1 Subjective Ratings

Figs. 7, 8, 9, 10, and 11 show the mean responses and standard error of the means (S.E.M.s) for the ratings of easiness, pleasantness, expressiveness, reasonability, and applicability.

3.1.1 Easiness

For the ratings of easiness (see Fig. 7), a two-way 2×3 (output method $\times$ input method) ANOVA did not show significant main effects or interaction of the main effects.

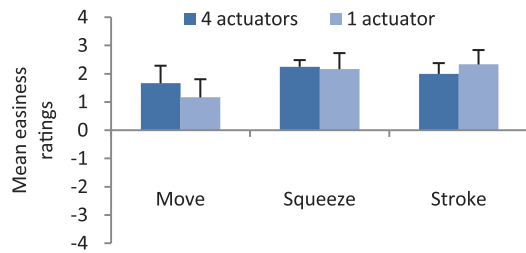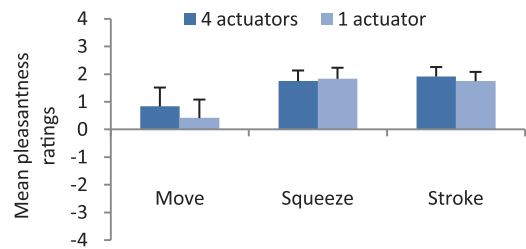Fig. 7. Mean ratings and S.E.M.s for the easiness by output and input methods.

Fig. 9. Mean ratings and S.E.M.s for the expressiveness by output and input methods.

Fig. 8. Mean ratings and S.E.M.s for the pleasantness by output and input methods.

Fig. 10. Mean ratings and S.E.M.s for the reasonability by output and input methods.

3.1.2 Pleasantness

For the ratings of pleasantness (see Fig. 8), a two-way 2×3 (output method $\times$ input method) ANOVA did not show significant main effects or interaction of the main effects.

3.1.3 Expressiveness

For the ratings of expressiveness (see Fig. 9), a two-way 2×3 (output method $\times$ input method) ANOVA showed a significant main effect of the output method $F(1, 11) = 6.4$, $p < 0.05$. Posthoc pairwise comparisons showed that the participants rated the output of four actuators as significantly more expressive than the output of one actuator $MD = 0.94, p < 0.05$. The main effect of the input method and the interaction of the main effects were not significant.

3.1.4 Reasonability

For the ratings of reasonability (see Fig. 10), a two-way 2×3 (output method $\times$ input method) ANOVA showed a significant main effect of the input method $F(2, 22) = 5.6$, $p < 0.05$. Posthoc pairwise comparisons showed that the participants rated the input by squeezing as significantly more reasonable than the input by moving $MD = 1.79$, $p < 0.05$. The other pairwise comparisons were not significant. The main effect of the output method and the interaction of the main effects were not significant.
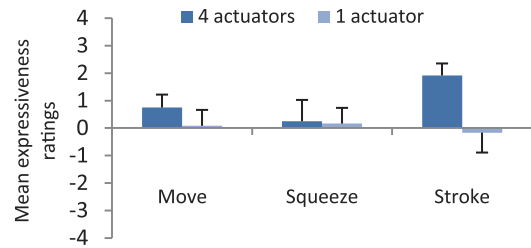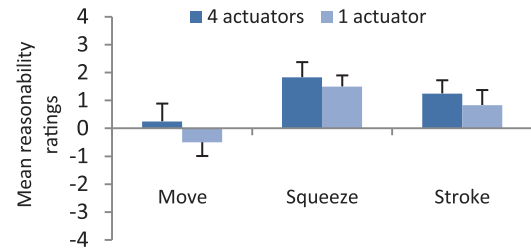
3.1.5 Applicability

For the ratings of applicability (see Fig. 11), a three-way $2 \times 3 \times 4$ (output method $\times$ input method $\times$ scenario) ANOVA showed significant main effects of the output method $F(1, 11) = 10.1$, $p < 0.01$ and scenario $F(3, 33) = 4.1$, $p < 0.05$. Posthoc pairwise comparisons showed that the output of four actuators was rated as significantly more applicable than the output of one actuator $MD = 0.42$, $p < 0.01$. The pairwise comparisons did not show significant differences between the scenarios. The main effect of the input method and the interactions of the main effects were not significant.

3.2 Postexperimental Interviews

3.2.1 Input Methods

Despite varying subjective preferences, stroking, and squeezing were the most preferred methods. When discussing the stroking method, one participant commented that it was practical and easy to learn. Also, he stated that it could be used either with one or four actuators. Related to the squeezing method, two participants expressed their preference by stating that squeezing "*was the easiest to use (female, 30)*" and "*fairly expressive in the end (male, 30).*" The participants also stated that squeezing was a nonintrusive and seamless way to create haptic content. One participant expressed his dislike of squeezing and considered it to be
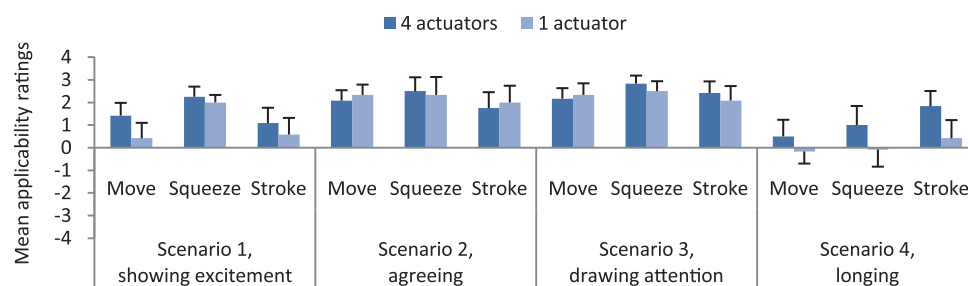

Fig. 11. Mean ratings and S.E.M.s for the applicability by output and input methods.

unnatural due to the fact that one had to squeeze physical buttons to create feedback. In terms of moving input, one participant commented that it "*requires more training than the other two … it was difficult for an inexperienced user (male, 31).*" Two participants desired more precise and responsive control. Also, one participant mentioned that "*it would feel weird to start shaking a phone outside [in a public place] (male, 30).*" Three participants noted that it would be optimal if one could utilize all three input methods at will and use different input styles in different situations.

3.2.2 Output Methods

Overall, four actuators were valued over one. One participant stated that "*it was nicer when you could feel [the feedback] in different buttons … it felt more natural in a way (male, 21).*" Another volunteer pointed out that it was easier to express nuances with four actuators. Different actuator locations had different meanings for some participants. It was commented that the feedback felt more intimate close to thumb and index finger. Also, fingertips were regarded as areas for both disagreement and excitement while the palm was used for comforting messages. One participant found it hard to distinguish the four vibrating locations when squeezing. For another volunteer the four actuators were advantageous especially when stroking.

Four users pointed out that they would have to hold the device at all times when using four actuators. As one of the four users put it, "*if a mobile phone would have such functionality, one's hand would have to constantly touch the phone because you could not feel the feedback location if the device was in a pocket (female, 20).*" Two volunteers were wondering if the recipient could open or replay the received haptic message afterward. One felt that if users would have to open the message, then it would make no difference whether the message was written or vibrating. Also, one participant thought that the feedback signal felt too weak. She also wondered how the feedback would feel like in the receiver's relaxed hand.

3.2.3 Communication Scenarios and Rules

The participants favored simple use scenarios. According to one comment, "*the best function for this [communication system] would be to replace short text messages or emphasize certain things with vibration instead of using other formatting (male, 19).*" Similarly, another user stated that one could replace short text messages with vibration. A third volunteer felt that vibration would be more suitable for getting the receiver's attention and stressing words than for communicating abstract information (e.g., agreement or disagreement). An example of using the device for emphasizing was given by one participant who stressed words "so cool" during an imaginary phone call. Another two participants regarded drawing attention as a particularly promising use scenario. They commented that "*I could very well imagine using 'shut up' [shaking the device] when someone is disturbing a lecture (male, 22)*" and that "*I think it was a really fun idea especially for the lecture or some sort of comforting (female, 20).*" Lastly, one volunteer said that all scenarios were feasible because one could understand the idea behind them.

Five of the users explicitly said that if such a haptic communication device was in real use, people would need to develop a lexicon for exchanging information. One saw that "*there should be some general rules in order to avoid confusion if using only touch messages (female, 18).*" Another volunteer continued that "*touch-based messaging could very well become a useful communication method provided that the lexicon is created in time (male, 31).*"

3.2.4 Acceptance

In terms of acceptance of the proposed haptic communication system, majority of the comments were supportive. One summarized that "*it felt utopist in the beginning but after time you got accustomed to it (male, 19).*" Another user got really excited about the idea and enquired when such functionality comes to mobile phones. According to the comments, it would be reasonable and interesting to have advanced haptic feedback functionalities in existing mobile devices. One volunteer concluded that "*the concept would have potential if implemented in the right way (male, 31).*" On the contrary, one of the users felt that "*[the use of the device] really is not easy (female, 34).*" She also mentioned that at times she had to close her eyes and really concentrate on sensing the feedback. Another user noted that if she would be walking in a hurry, it would be hard to sense and interpret touch messages. She would prefer to use the device in a more quiet setting.

3.3 Observations

After hearing the verbal description of a scenario, it took on average 15 seconds for the participants to come up with a suitable message. There were no notable differences in the crafting durations between different input and output methods. Two of the participants were quick in deciding the message and did not rehearse creating it at all. The rest tried different gestures and took their time in finding an optimal message.

The created 288 messages (3 input methods $\times$ 2 output methods $\times$ 4 scenarios $\times$ 12 participants) can be divided into three broad categories. Eighty two percent of the messages consisted of a single gesture design that was used either once or multiple times in a sequence (e.g., two identical forward nodding gestures). In 11 percent of the messages participants combined different parts (e.g., first making a stroke toward one's body and then tapping the touchpad once). In the rest random content was opted for (e.g., rapid sequential squeezes with different intensities).

With the stroking method, the participants used mainly their thumb, index finger, or index and middle fingers simultaneously in touching the surface. In 61 percent of the stroking messages only one touchpad location was utilized. The remaining messages consisted of spatial patterns such as moving one's finger lengthwise or drawing circular forms along the edges of the surface. One participant chose more abstract patterns by drawing the letter "z" (scenario 3) and a heart (scenario 4). The most common ways of gesturing with the moving method were tilting using wrist (56 percent), swinging using the whole hand (24 percent), and twisting or rotating in a circular manner (17 percent). Squeezing gestures were relatively subtle. In general, the

participants used all four buttons at the same time instead of applying pressure to separate locations.

The mean durations of messages created in the scenarios 1-4 were 3.6, 1.9, 3.2, and 4.9 seconds, respectively. A separate analysis of the mean durations showed that the durations did not depend on the input and output methods but on the different scenarios. That is, similar message durations were used regardless of the input and output methods.[1] Moreover, certain scenario-specific message parameters could be identified. In scenario 1, messages consisting of several parts with varying intensities and part durations were used to describe enthusiasm (e.g., four squeezes with varying durations and pressure levels). In scenario 2, a short and prompt message with one or two parts was the most common way to signal agreement (e.g., two short nods). In scenario 3, a message consisting of several intense parts was frequently chosen to draw the receiver's attention (e.g., three touches using multiple fingers at the same time). In scenario 4, longing was expressed with a calm gesture that had intensity variations in it (e.g., one or two long squeezes using ascending and descending pressure levels).

3.4 Discussion

The results showed that there was variance in how the different interaction methods were received. In terms of preferred input methods (i.e., research question 1), squeezing was evaluated as significantly more reasonable than moving. Also, the ratings of pleasantness and easiness were at the positive end of the scale although not significantly higher than for the other methods. According to the postexperimental interviews, the participants regarded squeezing as an easy and seamless method for creating haptic content. Because of this, the participants could very well imagine squeezing to be used, for example, for stressing certain words or sentences during a phone call. It is known that touch can emphasize, qualify, or contradict spoken words [33]. However, squeezing was not optimal for creating haptic messages with spatial properties as the ratings of expressiveness were quite neutral. This could be due to the fact that applying force to individual buttons was problematic as most participants squeezed all four buttons at the same time. In general, while squeezing an arbitrary object in one's hand, the force tends to distribute evenly making it hard to apply pressure to a particular location.

Stroking received generally positive ratings for easiness and pleasantness. In addition, although not statistically significant, the expressiveness ratings for stroking with four actuators were higher than for the other methods. The interview results were congruent with the ratings in that stroking was appreciated especially with four actuators. This could be partly caused by the fact that stroking was the only method that utilized two-handed interaction. The participants were instructed to use their other hand for touching the device as it was not ergonomically possible to simultaneously stroke the touchpad and keep contact with the actuator buttons using only one hand. Thus, the use of both hands likely facilitated creation of precise spatial movements. The participants did utilize a wide range of different message parameters such as number and position of fingers, touch location, and spatial pattern. In general, creating haptic messages using strokes can be argued to be well suited to situations where one can pay attention to gesturing and thus take advantage of the precise two-handed interaction.

When discussing the preferred output method (i.e., research question 2), we can note that output of four actuators was rated as significantly more expressive and applicable compared to using one actuator. The participants stated that the spatial output felt more natural and facilitated the expression of nuances. The preference for multiple actuators was not self-evident although previous studies implied that multiactuator patterns can be successfully presented on the palm area and fingers [29], [30], [31]. Gestures created in the current study utilized similar positional, linear, and circular patterns that were recognized with an average accuracy of 90 percent in a previous study [31]. This implies that it could also be possible to recognize dynamically crafted messages. One challenge for the use of spatial feedback was pointed out by several participants; it would be possible to sense the spatial patterns only when the device is being held in hand. For example, when carried in a pocket, only feedback parameters such as intensity and rhythm would be distinguishable. This issue could be addressed by using sensors to detect whether the recipient is holding the device and provide the sender with this information. In case the device was not held actively, a notification message could be sent to get the recipient's attention. Then, if further spatial properties were desired, the sender could craft a more detailed message.

Preference for squeezing and stroking can be attributed to several reasons. Both methods were based on active touch interaction with the device whereas moving used an alternative approach of free-form gestures. Profound differences can be identified between these input types. Moving supported mainly a use strategy where one pointed or poked with the device, as studied by Heikkinen et al. [17]. Conversely, when squeezing and stroking, the device could be understood to be a metaphor of the recipient. This could have affected the participants' subjective ratings as the metaphor strategy was closer to unmediated haptic communication. Furthermore, when rotating or shaking a passive object, kinesthetic and proprioceptive information from limb movements is dominant. It could be argued that because stroking and squeezing an object stimulates one's tactile senses (e.g., vibration caused by stroking with one's fingertip), these two manipulation types were preferred also with active vibrotactile feedback.

Moving was regarded as inconvenient to use because of the lack of precision in gesturing. There was no clear physical feedback of the interaction (cf., finger and palm contact when stroking and squeezing). Furthermore, users' comments about the moving method were in line with a previous study on social acceptability of gestures where it was found that people do not prefer large and noticeable gestures in a public setting [34]. Although most participants

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1. Also, mean input energies of created messages were not dependent on the used input and output methods as the highest mean energies were always measured in scenario 3 and the lowest in scenario 4.

moved the device unobtrusively using only their wrist, the interaction was nevertheless visible and more uncommon than stroking and squeezing.

Message parameters were found that defined how the participants interacted using the device (i.e., research question 3). The most notable parameter was the total duration of a message that was shown to be independent of input and output methods. It seems that a general message was often adapted to different input methods. Observations made during the experiment back up this view. For example, agreement (scenario 2) was often expressed by making a gesture consisting of one or two parts either by moving, stroking, or squeezing the device. Also, the number of parts that gestures consisted of varied somewhat coherently between the scenarios. Whereas agreement was expressed using one or two parts, showing excitement (scenario 1) and drawing attention (scenario 3) elicited gestures with multiple parts. Finally, highly emotional content was frequently coded using ascending and descending intensities. This was evident in expressing enthusiasm and longing whereas agreement and drawing attention were coded using more constant intensity levels.

4 GENERAL DISCUSSION

The goal of the present study was to identify recommended ways to interact with hand-held haptic communication devices by systematically evaluating potential input and output methods. The results indicated that squeezing and stroking were the preferred input methods while four haptic actuators were valued over one in terms of output. Also, each communication scenario elicited a typical message where parameters of message duration, number of parts in a message, and intensity were used to code information.

When looking at the findings from a wider perspective, support can be found for the view that interaction with haptic communication devices should resemble nonmediated interpersonal touch [17]. Squeezing and stroking are closer to this ideal as the object of touch (i.e., the haptic device) can be understood to represent the other person and particularly his/her hand. To put it simply, stroking and squeezing the hand of another person are more common behaviors than moving (or shaking or pointing with) it. This relates to the concept of semantic congruency where both the created gesture and resulting sensation should support a common interaction metaphor based on real touch (e.g., hugging [13]). It can be argued that the semantic congruency and spontaneity of touch were best supported with squeezing and stroking. Correspondingly, multiple actuators can express the spatial properties of a touch more vividly and therefore the use of four actuators makes the presentation more natural.

The concept of equipotentiality of touch [21] held true for the current results. The applicability ratings did not demonstrate any tendency to associate input methods with a specific meaning (i.e., scenario). Instead, a single input method was applicable to express varying meanings. It is encouraging in a sense that a haptic communication application does not necessarily need to incorporate several methods in order to support transfer of different information. The created haptic messages were relatively short as

the mean durations ranged from 1.9 to 4.9 seconds. Distinctive content was valued over continuous and long-lasting gestures. Also, the participants desired a common lexicon that would define the meanings of different messages. The prerequisite of a common symbolic meaning is essential for haptic communication to be successful [1]. As discussed by Brown and Williamson [9], it is possible that haptic messages could be regarded as gift-like items because of their personal nature. Some of the participants in the current study tried several message designs before making up their mind. Such messages could be appreciated by their recipients due to the time and effort put into the crafting phase.

It is acknowledged that there were certain limitations in the current study that affect the generalization of the results. First, no two-way communication took place. This was a conscious decision as the current focus was on evaluation of interaction methods instead of actual information transfer. Nevertheless, empirical studies on mediating information and emotions, e.g., [6], [7], are essential in establishing deeper understanding of the possibilities of remote haptic communication. Second, the participants gestured and felt the resulting feedback simultaneously. This approach was chosen because instant feedback of the physical input facilitated learning of the mapping. Furthermore, it was expected to be more natural than first creating a gesture and then replaying it afterward. It is likely that the perception of haptic output is different when one is holding the device in a relaxed hand instead of manipulating it actively. This might change the intended meaning of a message and thus needs to be looked into in future studies. Third, only one type of haptic feedback signal (i.e., mixed sine wave) was evaluated. It would be interesting to compare different vibration textures (e.g., [35]) and see whether this affects the ratings of expressiveness that were mostly quite neutral. Although our main focus was not on the haptic feedback synthesis, the presented technical implementation proposes one solution to the problem of transferring users' gestures into haptic feedback [6]. Intensity and spatial features of input gestures were mapped to amplitude and actuator locations of haptic output.

The current study established two design implications for further research and development of hand-held haptic communication devices. First, squeezing interaction can be introduced when unobtrusive and quick gestures are preferred. An example of this is emphasizing spoken content during a phone call. Squeezing is suitable to situations where spatial presentation of the message is not vital. Second, stroking using a touch sensitive surface and multiple haptic actuators can be utilized when one can pay more attention to the interaction. Two-handed interaction and the use of multiple fingers bring additional precision and naturalness to the strokes.

From the perspective of haptic communication research in general, this study suggested a complementary approach to previous work that can be roughly divided into studies investigating either the successfulness of interpreting emotional information, e.g., [6], [7], or assessing design and feasibility of the different communication device forms, e.g., [11], [12], [13]. The current study was one of the first to

take into account both the input and output sides of haptic communication devices. The results can provide help in bridging the gap between real and mediated touch. In an ideal case, the interaction with a haptic communication device would resemble physical contact as if there were no artificial interfaces between the remote parties.

5 SUMMARY

In this paper, we have introduced and evaluated alternative interaction methods for hand-held haptic communication devices. The whole interaction of creating and perceiving haptic messages was assessed. In light of the insights gained through this study, we recommend designers to utilize squeezing to enable quick composition of haptic messages when engaged in other tasks. This is a particularly suitable method when one-handed interaction with the device is desired (e.g., enhancing spoken dialogue with haptic content). Touch sensitive areas and strokes, on the contrary, are preferable for creating more detailed haptic messages when two-handed interaction is possible. If accompanied with multiple haptic actuators, accurate gestures can be used to define spatial patterns. In our future work, squeezing and stroking as well as spatial feedback will be studied to gain more knowledge on how to introduce them into practical use. In addition, we will shift our focus toward two-user studies where participants communicate using haptics.

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Paper IV

Rantala, J., Salminen, K., Raisamo, R., & Surakka, V. (2013). Touch gestures in communicating emotional intention via vibrotactile stimulation. *International Journal of Human-Computer Studies, 71*(6), 679–690.

Touch gestures in communicating emotional intention via vibrotactile stimulation

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Abstract

Remote communication between people typically relies on audio and vision although current mobile devices are increasingly based on detecting different touch gestures such as swiping. These gestures could be adapted to interpersonal communication by using tactile technology capable of producing touch stimulation to a user's hand. It has been suggested that such mediated social touch would allow for new forms of emotional communication. The aim was to study whether vibrotactile stimulation that imitates human touch can convey intended emotions from one person to another. For this purpose, devices were used that converted touch gestures of squeeze and finger touch to vibrotactile stimulation. When one user squeezed his device or touched it with finger(s), another user felt corresponding vibrotactile stimulation on her device via four vibrating actuators. In an experiment, participant dyads comprising a sender and receiver were to communicate variations in the affective dimensions of valence and arousal using the devices. The sender's task was to create stimulation that would convey unpleasant, pleasant, relaxed, or aroused emotional intention to the receiver. Both the sender and receiver rated the stimulation using scales for valence and arousal so that the match between sender's intended emotions and receiver's interpretations could be measured. The results showed that squeeze was better at communicating unpleasant and aroused emotional intention, while finger touch was better at communicating pleasant and relaxed emotional intention. The results can be used in developing technology that enables people to communicate via touch by choosing touch gesture that matches the desired emotion.

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Keywords: Haptics; Mediated social touch; Tactile communication; Mobile devices; Emotions; Affective interaction

1. Introduction

Devices such as mobile phones have become pervasive in our daily lives. We tend to keep them within arm's reach throughout the day to stay connected with people. Traditionally remote communication has relied on audio/video calls and text messages. Lately, however, the role of touch has become more active in interaction with mobile devices. Due to a technological shift towards touch sensitive displays,

direct manipulation via different touch gestures has largely replaced physical keypads. The main purpose of gestures such as tapping and swiping has been to manipulate virtual buttons and other user interface elements. At the same time, these gestures remind us of the ways humans touch each other. For example, patting and stroking that are used in interpersonal touch interaction (Hertenstein et al., 2006, 2009) bear resemblance to tapping and swiping in terms of the type of physical contact. From this perspective, the possibility of introducing touch gestures as a remote communication modality seems intriguing. For example, one user could pat the screen of his mobile device to send a remote touch to another user.

Haans and IJsselsteijn (2006) defined mediated social touch as "the ability of one actor to touch another actor

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over a distance by means of tactile or kinesthetic feedback technology''. Tactile technology has been used in several studies as actuators such as vibration motors can be easily embedded in mobile and wearable devices (Bonanni et al., 2006; Chang et al., 2002; Hansson and Skog, 2001; Mueller et al., 2005; Park et al., 2011). It is possible to create different tactile sensations by varying the frequency, amplitude, duration, and rhythm of vibrotactile stimulation (Brewster and Brown, 2004). Although such stimulation is not capable of replicating forces of touch, tactile technology can imitate touch that moves on one's skin. This is possible by driving several spatially distributed actuators in a sequence (Park et al., 2011; Rantala et al., 2011a, 2011b; Wang et al., 2012). For example, Haans and IJsselsteijn (2009b) attached six vibrotactile actuators to one's upper arm to imitate a stroking touch. The goal was to evaluate whether a mediated touch would increase people's altruistic behavior and willingness to comply with a request similarly to real touch (i.e., Midas touch phenomenon). The results showed that touch-like qualities could be attributed to stimulation that imitated a stroking touch.

Research on imitating human touch has been largely motivated by the well-known relationship between touch and human emotions. Clynes (1977) observed that the use of touch and gestures varies depending on one's emotional state. McDaniel and Andersen (1998) reported that people who touched each other in public settings were most often lovers or friends who had emotional ties. Jones and Yarbrough (1985) studied meanings of interpersonal touch by instructing participants to report touches that took place in daily interaction. The results indicated that people in close relationships used touch, among other things, to communicate positive emotions. This included touches that expressed support, appreciation, inclusion, sexual interest or intent, and affection. Moreover, Hertenstein et al. (2009) showed that also persons who did not know each other beforehand could communicate intended emotions using only touch. One participant was presented with a list of distinct emotions and asked to communicate them to another blindfolded participant by touching him/her as deemed appropriate. The results showed that anger, fear, disgust, love, gratitude, sympathy, happiness, and sadness were recognized with above chance accuracies. For example, anger was most commonly communicated with shaking, pushing, and squeezing, while love was communicated with touches such as hugging, patting, and stroking.

As real touch has been shown to be capable of conveying intended emotions, it has been assumed that touch mediated by means of vibrotactile technology would have a similar capability. Researchers have presented different device prototypes and proposed that mediated social touch would enable new forms of personal or intimate interaction (Bonanni et al., 2006; Brave and Dahley, 1997; Mueller et al., 2005; Park et al., 2011; Rovers and van Essen, 2004). However, as Haans and IJsselsteijn (2006) noted, "very few studies are available that report on

empirical system validations beyond the level of anecdotal descriptions of user experiences''. For example, Bonanni et al. (2006) presented a wearable scarf designed for emotional touch therapy. Vibrotactile actuators attached to the scarf were used for imitating touch gestures of tap, press, stroke, and contact. Also, Park et al. (2011) proposed an affective interaction technique that was based on an array of vibrotactile actuators attached to the backside of a touch screen phone. The aim was to imitate touch gestures of pat, slap, pinch, stroke, kiss, and tickle. In a later study Park et al. (2012) evaluated the system in audio-tactile communication where pairs of users could use the prototypes as they saw fit during free-form phone calls. To the best of our knowledge, no systematic studies have investigated whether vibrotactile stimulation that imitates human touch can convey intended emotions between persons.

There are two general approaches to measuring communication of emotional intention. The differential theory of emotions suggests that human emotions can be seen as distinct categories (e.g., happiness, sadness, and anger) that have their specific motivational properties (Ekman, 1994; Izard, 1997). Bailenson et al. (2007) studied communication of distinct emotions using a joystick-like haptic device. One group of participants was given a list of seven emotions that were to be expressed by manipulating the device. Then, a second group of participants felt the recorded force stimulations and tried to recognize the intended emotions. The results showed that emotions were recognized with above chance accuracies. Smith and MacLean (2007) studied communication of distinct emotions using 1-degree-of-freedom haptic knobs. One participant was to communicate four intended emotions by moving his/her knob, while another participant attempted to recognize the emotions via a second knob. The participants were above chance when recognizing the emotions. While distinct emotions could be conveyed in both studies, it should be noted that the used devices are not applicable in mobile contexts due to their requirement of being attached to a table or other fixed structure.

Another approach is to work with the dimensional theory of emotions that maps emotions as combinations of two or more dimensions (Bradley and Lang, 1994; Russell, 1980; Russell et al., 1989). Bradley and Lang (1994) presented a three-dimensional affective space consisting of valence (from unpleasant to pleasant), arousal (from relaxed or calm to arousing), and dominance (from feeling of stimulus being in control to the feeling of user being in control). An established method to measure emotional reactions in relation to these dimensions is to use bipolar rating scales (Bradley and Lang, 1994; Schlosberg, 1954). Salminen et al. (2008) used the scales for measuring emotional experiences evoked by vibrotactile stimulation. A friction-based fingertip stimulator presented different predefined stimuli to a participant's index finger. After sensing a stimulus, the participant was to rate it using scales of valence, arousal, dominance, and approachability. The results showed statistically significant

differences in the ratings of different stimuli even though the experiment included no interpersonal communication context. Also, the stimuli were not deliberately designed to evoke particular emotions. To adapt this methodology to studying communication of emotional intention between users, it would seem feasible to ask one user to intentionally create a stimulus that represents a particular position in the dimensional affective space. Then, rating scales could be used to measure whether another user can interpret the intended emotion based on the felt stimulus.

In our previous study we introduced a hand-held device that used vibrotactile stimulation to imitate different touch gestures (Rantala et al., 2011b). A user could manipulate the device by squeezing it, by stroking its touch sensitive top part, or by moving it (i.e., tilting or shaking). The gathered sensor data was converted into vibrotactile stimulation in real time. The stimulation was presented on user's palm and fingers via four vibrotactile actuators located in the sides of the device. To imitate the three touch gestures, the stimulation was varied by intensity, duration, and actuator location. For example, moving one's finger along the device's top was represented by driving the actuators in a sequence to replicate the direction of finger movement. One participant at a time used the device in four example communication scenarios. The task was to communicate with an imaginary partner by creating vibrotactile stimulation suitable for the scenarios. The main finding was that the participants preferred squeezing and stroking to moving. One possible explanation for this was that when the participants squeezed the device or touched it with fingers, the device could be understood to be a metaphor of the communication partner. Moving the device, on the other hand, was more abstract.

Our current aim was to study whether vibrotactile stimulation that imitates squeeze and finger touch can convey intended emotions from one person to another. The devices introduced in our previous study were chosen for this purpose as they enabled converting touch gestures to vibrotactile stimulation (Rantala et al., 2011b). Participant dyads (i.e., sender and receiver) interacted in a laboratory setting using only the vibrotactile channel provided by the devices. When the sender squeezed one device or touched it with finger(s), the receiver felt corresponding vibrotactile stimulation on another device. The dimensions of valence and arousal were adopted for measuring communication of emotional intention. The sender's task was to use the two touch gestures for creating vibrotactile stimulation that would communicate the opposite ends of valence and arousal to the receiver. In practice, the sender attempted to communicate that he/she felt *unpleasant*, *pleasant*, *relaxed*, or *aroused*. The receiver felt the created stimulation without knowing that the sender was attempting to communicate specific information (i.e., one of the four intended emotions). Then, both the sender and receiver evaluated the stimulation using rating scales for valence and arousal. These ratings were used for comparing the match between senders' intended emotions and receivers' interpretations.

2. Methods

2.1. Participants

A total of 12 voluntary dyads (i.e., 24 participants) took part in the experiment (mean age 29.8, range 20–49 years). The dyads were either intimate couples or friends. On average, the participants had known each other for 4 years. All dyads were cross-gender (i.e., one male, one female) to avoid possible gender effects related to the interpretation of touch (Haans et al., 2007; Heslin et al., 1983). During the experiment participants were located in different laboratory rooms to ensure that the communication took place solely via the tactile modality. The participants signed consent forms and agreed on the use of video recordings for analysis. Each participant was compensated for the participation with a movie ticket.

2.2. Apparatus

A hand-held device (Fig. 1) with dimensions of $13.5 \times 5.5 \times 3.5$ cm (length × width × height) was given to both participants in a dyad. The device was designed to fit comfortably in hand so that a user could simultaneously provide touch input and sense vibrotactile output without having to change the grip from the device. For further details of the device, see Rantala et al. (2011b).

2.2.1. Input sensors and vibrotactile actuators

The touch gestures were detected by using two types of sensors: force sensing resistors and a capacitive touchpad. Four force sensing resistors (FSR) from Interlink electronics were mounted inside buttons located in the sides of the device (Fig. 1a). The FSRs were activated once a user squeezed the buttons. Each of the four FSRs reported separate values. The custom-built capacitive touchpad was located underneath the device's flat top surface (Fig. 1b). The touchpad consisted of 15 touch-sensitive regions that enabled touch interaction with one or more fingers at the same time. The sensors were sampled with a frequency of 100 Hz.

Vibrotactile feedback was created using four Minebea Linear Vibration Motor actuators (LVM8, Matsushita Electric Industrial Co., Japan) that were located inside the buttons (Fig. 1a). The buttons were separated from the

Fig. 1. Side view of the device with a white illustration of the button borders (a). Top view of the device with an illustration of the capacitive touchpad and its 15 touch-sensitive regions (b).

rest of the device body in an attempt to isolate vibration to the four specific locations. The actuators were driven using an audio signal of 160 Hz mixed sine wave that was previously found to be optimal in terms of hand sensitivity and minimal resonance sound (Rantala et al., 2011b).

In order to measure how accurately users could localize vibration from the different actuators, a separate localization study was conducted with 9 participants. These participants did not take part in the actual experiment. The participants were presented with 10 different stimulation patterns and asked to indicate which one they felt (see Rantala et al., 2011a for a more detailed description of the procedure). There were three types of stimulation patterns: positional patterns vibrated a single actuator, linear patterns vibrated two actuators at a time to present directions (i.e., left, right, forward, and backward), and circular patterns vibrated all four actuators in a sequence (i.e., clockwise and counter-clockwise). The results showed that positional, linear, and circular patterns were recognized correctly with mean accuracies of 72, 46, and 74% (when chance level was 10%).

2.2.2. Technical setup

The device was connected to an interface box via HDMI (Fig. 2). This connection transferred sensor data from the device, and audio output signals to the device. The interface box was connected to a PC via serial connection. Pure Data (PD) audio synthesizer software read data from the serial connection and generated audio output that was fed back to the interface box using an external Gigaport HD USB sound card and four 3.5 mm plugs. PD was also used for logging sensor data. A TCP/IP connection transferred data between the two laboratory rooms. Identical experimental setups were used in both rooms.

2.2.3. Transferring touch input to vibrotactile stimulation

Transferring the characteristics of touch gestures into vibrotactile stimulation was based on two principles. First, the intensity of touch input (i.e., pressure level of squeezing the buttons or amount of capacitive contact with the touchpad) was conveyed by varying the amplitude of the mixed sine wave. Second, the spatiality of touch input (i.e., squeezing only certain buttons or touching only part of the touchpad) was presented by driving actuators closest to the touch location.

Each of the four squeeze sensors in the buttons reported values between 0 and 150. This corresponded to force levels ranging approximately from 1.6 to 7 N. The threshold level of 1.6 N was set to ignore light squeezing needed to hold the device in hand. The values of the 15 touch-sensitive regions were used for calculating four combined values with the same range of 0–150. For example, combined value for the front left part of the touchpad was calculated by adding up values of six regions (Fig. 1b, grey regions). The resulting four input quarters (i.e., front left, front right, rear left, and rear right) were mapped to their corresponding actuators. In practice, squeezing the front left button or touching the front left part of the touchpad vibrated the front left actuator. Alternatively, touching the center of the touchpad as in Fig. 3b would activate all four actuators.

Linear mapping was used between the sensor input values and amplitude levels of the actuators. Thus, the more intense the touch input, the higher the resulting stimulation amplitude. The highest possible amplitude level was same for both touch gestures.

2.3. Procedure

First the laboratory and conditions were introduced to each dyad. Then, the participants were explained that the purpose of the study was to send and receive vibrotactile stimulation. The roles of sending and receiving stimulation were balanced between genders within the 12 dyads. The same roles were used throughout the experiment. The participants were then guided to separate laboratory rooms. The experiment was divided into familiarization, training, and test sessions. The sessions were followed by a
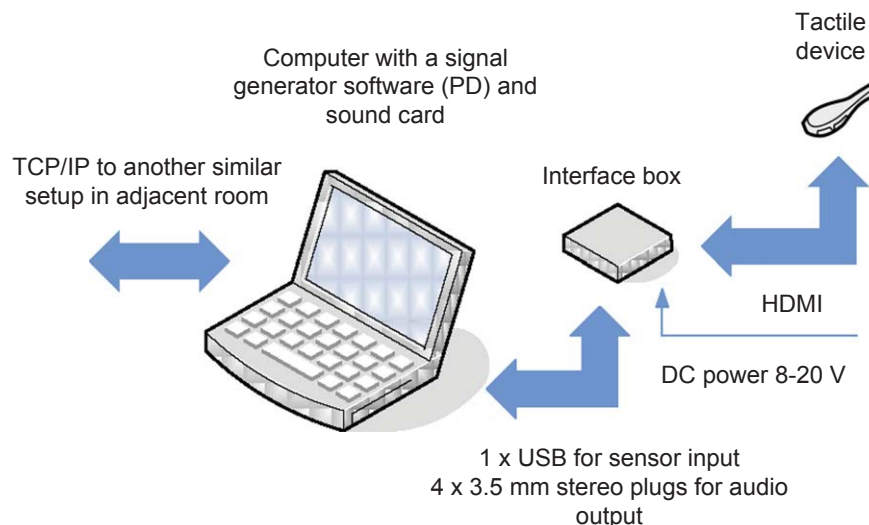

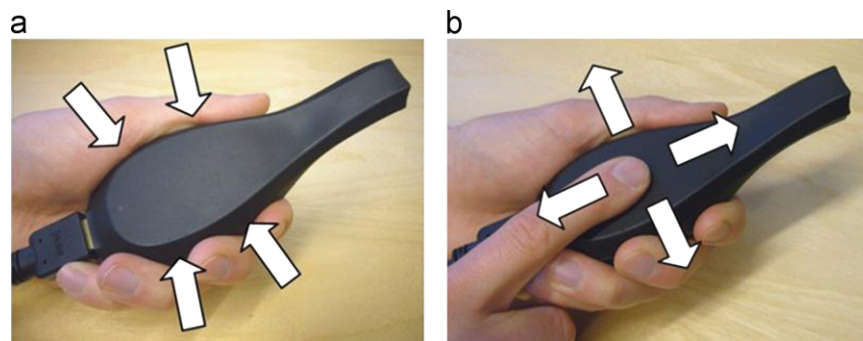Fig. 2. Experimental setup in one laboratory room.

Fig. 3. Touch gestures of squeeze (a) and finger touch (b).

post-experimental interview. Conducting the experiment took approximately 50 min per dyad.

2.3.1. Familiarization session

The purpose of the familiarization session was to let participants try how the device responded to touch. The participants were allowed to use approximately 2 min to familiarize themselves with the two touch gestures. The device was held in the hand that the participants would normally use for holding mobile devices (right hand for 20 out of 24 participants). The participants were advised to grip the device so that all the four buttons would be in contact with palm or fingers. They were instructed to use one hand in squeeze and both hands in finger touch (see Fig. 3). Vibrotactile stimulation was created instantaneously when a squeeze or finger touch was sensed. During the familiarization session the participants felt only stimulation created by their own interaction. Thus, they could neither sense the other participant's touches nor create any common tactile vocabulary. Noise-blocking headphones were used to ensure that audio created by the actuators was not perceived.

2.3.2. Training session

A training session with two trials was held to introduce the experimental procedure. In the beginning of the first trial the sender was given a slip of paper that stated the first touch gesture to be used. In the training phase the sender's task was to create vibrotactile stimulation without any particular emotional intention. The sender could sense stimulation on his/her own device while manipulating it. When the sender was ready to create stimulation, tactile channel was enabled also on the receiver's device. The sender then repeated the touch interaction once. At this point identical stimulation was felt on both devices with the exception that the sender was actively manipulating the device whereas the receiver was holding his/her device passively. The stimulation was followed by rating scales (as described in Section 2.3.4). The second training trial with the other touch gesture followed the same procedure.

2.3.3. Test session

The test session proceeded similarly to the training session with the exception that the sender was instructed to create stimulation that would communicate the opposite ends of

valence (i.e., *unpleasant* or *pleasant*) and arousal (i.e., *relaxed* or *aroused*) to the receiver. Only one dimension was varied at a time. For example, the sender's instruction was to "tell the other that you feel yourself relaxed". The receiver was not aware of the sender's task. The test session consisted of 2 × 4 trials (touch gesture × emotional intention) that were presented in a randomized order.

2.3.4. Subjective ratings

In the end of each trial both participants rated the felt stimulation using scales for valence and arousal. Although the sender's task was to vary the emotional intention only on one dimension (i.e., primary dimension), ratings were asked also for the other dimension (i.e., secondary dimension) so that the stimulation could be positioned to the two-dimensional affective space. Nine-point bipolar rating scales varying between −4 and +4 were used.

The sender's instructions for rating the arousal of created stimulation were as follows: "if you feel that the created message was relaxing, choose a number between −1 and −4 depending on how relaxing the message was" and "if you feel that the created message was arousing, choose a number between +1 and +4 depending on how arousing the message was". The same wording was used for valence by substituting "relaxing" and "arousing" with "unpleasant" and "pleasant", respectively.

The receiver's corresponding instructions for rating felt stimulation were as follows: "if you think that the sender felt relaxed, choose a number between −1 and −4 depending on how relaxed the sender felt" and "if you think that the sender felt aroused, choose a number between +1 and +4 depending on how aroused the sender felt". Again, similar wording was used for valence. The sender's task of communicating one of the four intended emotions was not disclosed to the receiver in order to elicit ratings that would not be guided by a predefined set of possible meanings. Thus, the receiver could also choose the midpoint of a scale (i.e., 0) in case the stimulation was perceived, for example, neither unpleasant nor pleasant.

2.3.5. Post-experimental questionnaire and interviews

Once the experimental tasks were finished, the sender was asked to choose which touch gesture he/she would have used for expressing each emotional intention if given

a choice. At the same time, the receiver was briefed on the sender's task of communicating the four intended emotions. Before revealing that the sender tried to convey each emotional intention with both touch gestures, the receiver had to judge which touch gestures he/she expected the sender used. Also, both the sender and receiver were asked whether they could imagine using such a touch communication system for sending SMS-like touch messages or enhancing phone conversations.

Finally, the participants were encouraged to comment on the experiment and prototype devices in a non-structured interview. For example, they were asked how they perceived the two touch gestures and how easy or difficult it was to communicate using the devices.

2.4. Data analysis

2.4.1. Subjective ratings

We were interested in measuring whether the participant role, emotional intention, or touch gesture affected participants' ratings of felt stimulation. For this purpose, the participants' primary ratings were analyzed using repeated measures mixed-model analysis of variance (ANOVA). If the sphericity assumption of the data was violated, Greenhouse–Geisser corrected degrees of freedom were used to validate the F statistic. Pairwise Bonferroni corrected t-tests were used for post-hoc pairwise comparisons.

Also, to get an overall success rate of communication, receivers' primary ratings were categorized as correct or incorrect based on the bipolarity of valence and arousal scales. For example, if the intended emotion to be communicated was *relaxed*, receivers' arousal ratings between -1 and -4 counted as correct. Neutral ratings (i.e., 0) were always counted as incorrect.

2.4.2. Parameters of vibrotactile stimulation

To understand whether the assigned emotional intention or used touch gesture had an effect on created vibrotactile stimulation, the mean intensity and spatiality of stimulation were analyzed. Repeated measures analysis of variance (ANOVA) was conducted for this purpose.

Mean intensity was the mean amplitude value of the four input quarters. Mean spatiality was measured using the number of peak actuator changes in stimulation. A peak actuator change was registered when one of the input quarters gained the highest input value for at least 150 ms. For example, moving one's finger in a circular manner between the touchpad quarters would result in several peak actuator changes and high spatiality value. Data of one participant dyad was excluded from the parameter analysis as an outlier because the mean duration of the created stimulation was 8.4 times longer as compared to the other dyads.

2.4.3. Observations and post-experimental interviews

Senders' touch interaction in each trial was coded from video using the following parameters: number of rehearsed touches, time used for choosing a touch, number of repeating sequences in a touch, used touch type, direction of touch, and intensity of touch.

Post-experimental interviews were first transcribed from video recordings. Individual interview comments were then grouped into categories using thematic coding. Section 3.5 is organized based on these categories. Comments that best represented the participants' general view or pointed out important challenges were included in the results section. The quotes were translated from Finnish to English. Analysis of the video recordings was conducted by one coder.

3. Results

3.1. Subjective ratings

3.1.1. Primary and secondary ratings in the affective space

To get an overall view of how the senders and receivers rated vibrotactile stimulation with different emotional intention, the primary and secondary ratings were positioned to the two-dimensional affective space (Russell, 1980). In Fig. 4, a short arrow between mean ratings
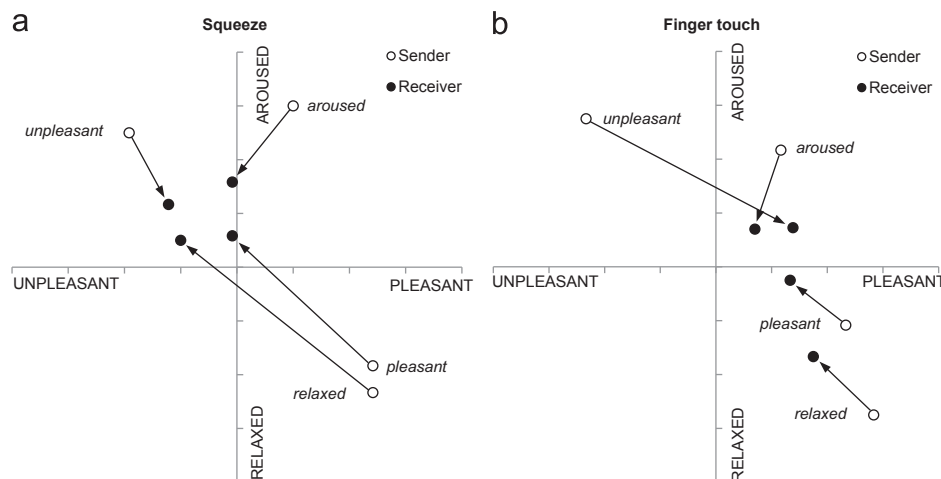

Fig. 4. Mean primary and secondary ratings for *unpleasant*, *pleasant*, *relaxed*, and *aroused* emotional intention positioned in the affective space by touch gestures of squeeze (a) and finger touch (b).

indicates that the match between senders' intended emotions and receivers' interpretations was good. In contrast, longer arrows indicate a poorer match.

The senders' mean ratings show that the senders based their ratings mainly on the instructed emotional intention. Stimulation with *unpleasant* intention fell in the unpleasant–arousing quadrant of the affective space regardless of the touch gesture (see Fig. 4a and b). Stimulation with *aroused* emotional intention, on the other hand, fell in the pleasant–arousing quadrant. Stimulations with *pleasant* and *relaxed* emotional intention were considered to be practically the same as both fell in the pleasant–relaxed quadrant.

On the contrary, the receivers' mean ratings show that the interpretations of vibrotactile stimulation varied depending on the used touch gesture. Squeeze was interpreted predominantly as unpleasant and arousing (see Fig. 4a), while finger touch was interpreted mainly as pleasant (see Fig. 4b). Comparing the match between senders and receivers shows that when squeeze was used only stimulation with *unpleasant* emotional intention was placed to the same affective quadrant by both dyad members. In terms of finger touch, stimulation with *aroused*, *relaxed*, and *unpleasant* emotional intention was placed to the same affective quadrants by both dyad members.

Overall, the receivers' mean ratings were located closer to the center of the affective space than the senders' mean ratings. Thus, the receivers interpreted the emotionality of vibrotactile stimulation to be somewhat weaker as compared to the senders.

3.1.2. Primary ratings of valence

For the primary ratings of valence (Fig. 5), a three-way $2 \times 2 \times 2$ (participant role × touch gesture × emotional intention) mixed-model ANOVA showed statistically significant main effects of touch gesture ($F_{1,22} = 6.6$, $p < 0.05$) and emotional intention ($F_{1,22} = 52.8$, $p < 0.001$). In addition, there were significant interactions between touch gesture and participant role ($F_{1,22} = 7.8$, $p < 0.05$) and

emotional intention and participant role ($F_{1,22} = 44.3$, $p < 0.001$).

Two one-way ANOVAs were conducted to analyze the interaction between emotional intention and participant role. The ANOVAs showed that the interaction was caused by the fact that emotional intention had a significant effect on senders' ratings ($F_{1,11} = 76.9$, $p < 0.001$), but not on receivers' ratings. Post-hoc pairwise comparison showed that the senders rated stimulation with *pleasant* emotional intention as significantly more pleasant than stimulation with *unpleasant* emotional intention ($MD = 4.8$, $p < 0.01$).

Also, two one-way ANOVAs were conducted to analyze the interaction between touch gesture and participant role. The ANOVAs showed that the interaction was due to the fact that touch gesture had a significant effect on receivers' ratings ($F_{1,11} = 8.3$, $p < 0.05$), but not on senders' ratings. Post-hoc pairwise comparisons showed that the receivers rated stimulation created with finger touch as significantly more pleasant than stimulation created with squeeze ($MD = 1.9$, $p < 0.05$).

The mean success rates of communicating valence varied between 17 and 75% when chance level was 50% (Fig. 5). The success rates indicate cases where the senders' and receivers' ratings were on the same side of the dimension.

3.1.3. Primary ratings of arousal

For the primary ratings of arousal (Fig. 6), a three-way $2 \times 2 \times 2$ (participant role × touch gesture × emotional intention) mixed-model ANOVA showed statistically significant main effects of touch gesture ($F_{1,22} = 24.1$, $p < 0.001$) and emotional intention ($F_{1,22} = 131.8$, $p < 0.001$). In addition, there was a significant interaction between participant role, touch gesture, and emotional intention ($F_{1,22} = 5.1$, $p < 0.05$).

To analyze the three-way interaction, two separate mixed-model ANOVAs were conducted. A two-way 2×2 (participant role × emotional intention) ANOVA showed a significant main effect of emotional intention ($F_{1,22} = 166.9$, $p < 0.001$) and significant interaction between participant role and emotional intention ($F_{1,22} = 29.8$, $p < 0.001$). Moreover, a two-way 2×2 (participant role × touch gesture) ANOVA showed a significant main effect of touch
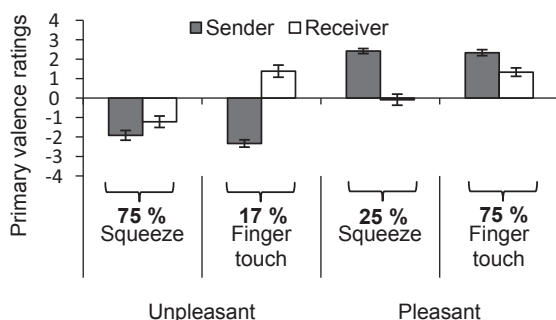

Fig. 5. Mean primary ratings of valence, S.E.M.s, and success rates of communication for stimulation with *unpleasant* and *pleasant* emotional intention.
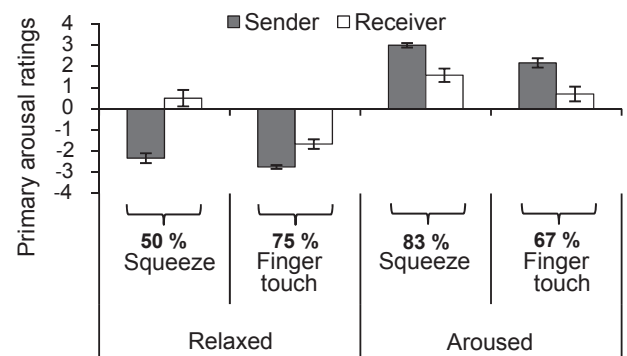

Fig. 6. Mean primary ratings of arousal, S.E.M.s, and success rates of communication for stimulation with *relaxed* and *aroused* emotional intention.

gesture ($F_{1,22} = 24.0$, $p < 0.001$) and significant interaction between participant role and touch gesture ($F_{1,22} = 13.0$, $p < 0.01$).

To analyze the two-way interaction between emotional intention and participant role, two one-way ANOVAs were conducted. The ANOVAs showed that the interaction was due to the fact that although emotional intention had a significant effect on both senders' ratings ($F_{1,11} = 332.8$, $p < 0.001$) and receivers' ratings ($F_{1,11} = 11.6$, $p < 0.01$), the effect was greater on senders' ratings. Post-hoc pairwise comparisons showed that stimulation with *aroused* emotional intention was rated as significantly more arousing than stimulation with *relaxed* emotional intention by senders ($MD = 5.5$, $p < 0.001$) and receivers ($MD = 2.0$, $p < 0.01$).

To analyze the two-way interaction between touch gesture and participant role, two one-way ANOVAs were conducted. The ANOVAs showed that the interaction was caused by the fact that touch gesture had a significant effect on receivers' ratings ($F_{1,22} = 24.8$, $p < 0.001$), but not on senders' ratings. Post-hoc pairwise comparison showed that the receivers rated stimulation created with squeeze as significantly more arousing than stimulation created with finger touch ($MD = 1.6$, $p < 0.001$).

The mean success rates of communicating arousal varied between 50 and 83% when chance level was 50% (Fig. 6).

3.2. Parameters of vibrotactile stimulation

3.2.1. Intensity

For the mean intensity (Fig. 7), a two-way 2×4 (touch gesture × emotional intention) ANOVA showed statistically significant main effects of emotional intention ($F_{3,30} = 5.9$, $p < 0.01$) and touch gesture ($F_{1,10} = 11.6$, $p < 0.01$). Furthermore, there was a significant interaction between the main effects ($F_{3,30} = 3.7$, $p < 0.05$).

To analyze the interaction between emotional intention and touch gesture, two one-way ANOVAs were conducted. The ANOVAs showed significant effects of emotional intention ($F_{1,21} = 25.1$, $p < 0.001$) and touch gesture ($F_{1,43} = 18.0$, $p < 0.001$). Post-hoc pairwise comparisons showed that stimulation with *unpleasant* emotional intention had significantly higher mean intensity than stimulation with *relaxed* ($MD = 26.8$, $p < 0.05$) and *pleasant* ($MD = 30.1$, $p \leq 0.001$) emotional intention. Also, stimulation created with squeeze had significantly higher mean
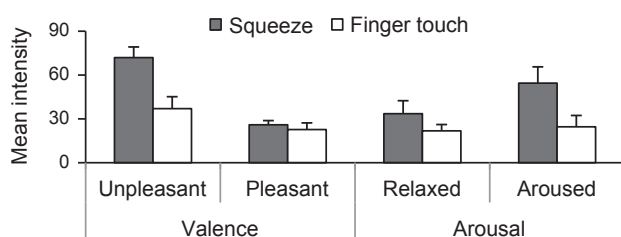

Fig. 7. Mean intensities and S.E.M.s by touch gesture and emotional intention.

intensity than stimulation created with finger touch ($MD = 20.0$, $p < 0.001$).

3.2.2. Spatiality

For the mean spatiality (Fig. 8), a two-way 2×4 (touch gesture × emotional intention) ANOVA showed a statistically significant main effect of touch gesture ($F_{1,10} = 13.4$, $p < 0.01$). There was also a significant interaction between the main effects ($F_{3,30} = 3.2$, $p < 0.05$).

To analyze the interaction between touch gesture and emotional intention, two separate one-way ANOVAs were conducted. The ANOVAs showed a significant effect of touch gesture ($F_{1,43} = 20.1$, $p < 0.001$). Post-hoc pairwise comparisons showed that stimulation created with finger touch had significantly more spatial variation than stimulation created with squeeze ($MD = 5.1$, $p < 0.001$).

3.3. Observations on touch gestures

The senders used four different ways to manipulate the device when creating stimulation with finger touch: index finger only (31% of finger touch gestures), index and middle fingers (31%), index, middle, and ring fingers (19%), or thumb (10%).

In addition, finger touch elicited different use strategies that can be categorized into separate touch gestures (Fig. 9). First, the participants moved one or more fingers on the device's top in a continuous manner (46% of finger touch gestures). These stroking or sweeping touches were used mainly when creating stimulation with *pleasant* and *relaxed* emotional intention. Second, patting or tapping was used for creating stimulation that consisted of multiple touches (40%). These touches were most often used when
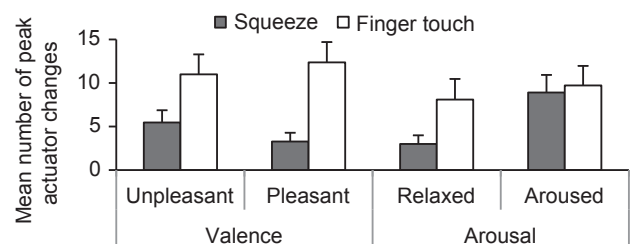

Fig. 8. Mean spatiality values and S.E.M.s by touch gesture and emotional intention.
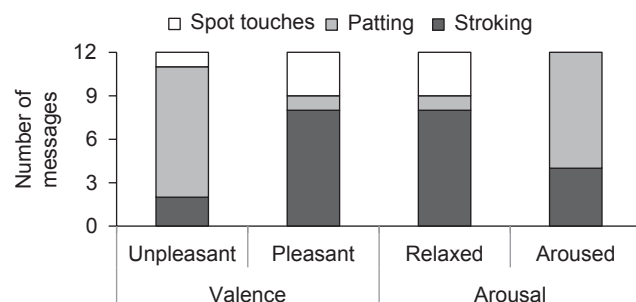

Fig. 9. Observed finger touch gestures by emotional intention.

creating stimulation with *aroused* and *unpleasant* emotional intention. Third, during spot touches the participants touched the device only once without moving finger(s) on the surface (14%).

Variations in squeeze interaction were more unnoticeable and subtle. In majority of squeeze gestures the participants squeezed all four buttons at the same time.

3.4. Preferred touch gestures

The results of touch gesture preferences showed that if given a choice, both the senders (Fig. 10) and receivers (Fig. 11) would have used finger touch mainly in communicating *pleasant* and *relaxed* emotional intention. Squeeze, on the contrary, would have been the dominant gesture in communicating *unpleasant* emotional intention. In terms of *aroused* emotional intention the preferences were more divided.

3.5. Post-experimental interviews

3.5.1. Touch gestures

Several participants commented that squeeze was easier to use than finger touch. One participant said that "squeezing had in a way less interaction [with the device] and because of that one did not need to think of the use (sender, male, 22)". Another participant felt that squeeze was less laborious to use. It was also commented that especially aroused intention was easier to communicate with squeeze.

On the other hand, some participants felt that finger touch was more precise than squeeze. One participant commented that "with finger touch you could adjust the
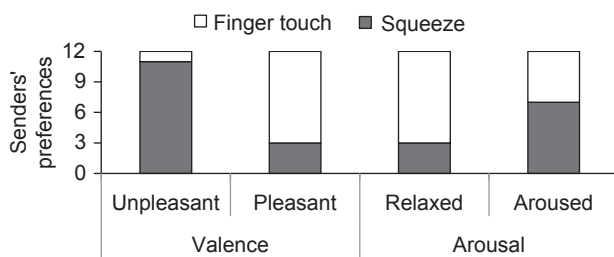

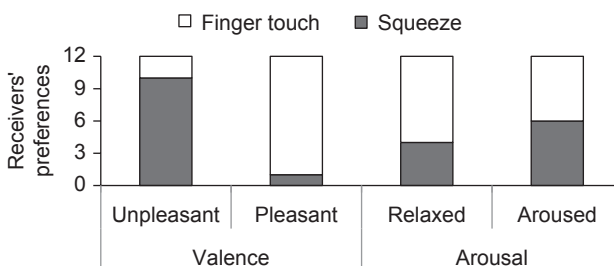Fig. 10. Touch gestures the senders would have preferred to use for communicating the emotional intention.

Fig. 11. Touch gestures the receivers would have preferred to use for communicating the emotional intention.

applied force better (sender, male, 23)". The vibration response of squeeze was noted to be more imprecise and vague. According to the comments, the impreciseness of squeeze might have depended on the applied force. One of the participants pointed out that gentle squeezing resulted in irregular vibration but with more force controlling became easier.

3.5.2. Communication partner

Several participants felt that the communication partner had an effect on how vibrotactile stimulation was used and perceived. One of the receivers commented that "if some stranger would have been sending the messages, I definitely would not have thought it as stroking and the messages would have been more neutral (receiver, female, 20)". Similarly, one of the receivers considered it strange to use stroking with a friend. According to one participant "the communication partner should be someone really familiar, a friend that I see at least once a week (receiver, female, 49)".

Contrary to other comments, friends in one dyad noted that they did not pay attention to the communication partner as much as they had presumed. Instead, the sender concentrated on the instructed emotional intention, while the receiver focused solely on the felt vibration. The dyad suspected that in a more naturalistic setting the partner would play a more significant role.

3.5.3. Possible use scenarios

Out of 24 participants, 15 said that they could imagine sending and receiving touch-only messages. According to the participants touch messages could be used in places where one cannot use other modalities for interacting with a communication device (e.g., work settings). Also, messages could be felt afterwards similarly to reading SMS messages. The comments indicated that touch messages alone would not be suited to abstract or complex communication. Instead, it was suggested that touch could be used for conveying simple information. One participant commented that "it could be used for communicating momentary feelings like with Twitter … if I got an enthusiastic touch message during the day, I would ask later at home what the message meant (receiver, male, 36)".

Furthermore, 15 out of 24 participants said that they could imagine sending and receiving touch information during a phone call. One participant suggested that touch could be used for adding presence and awareness to a phone conversation. She stated that "in face-to-face conversation you can nod to show that you are listening … if there was a way to express that you are listening [using touch during a call] (sender, female, 29)". Another participant was more skeptical of the need of a touch channel during conversation as she felt that the information could as well be communicated verbally.

4. Discussion

Our results showed that the match between senders' intended emotions and receivers' interpretations depended on the used touch gesture. In general, the senders thought that both touch gestures would perform equally well in communicating the intended emotions. The receivers, on the other hand, interpreted felt stimulation differently depending on the used touch gesture. The receivers' ratings indicated that squeeze was more suitable for communicating *unpleasant* and *aroused* emotional intention, while finger touch was more suitable for communicating *pleasant* and *relaxed* intention. This distinction between the gestures can also be seen when looking at the mean success rates of communication. Overall, the dyads communicated variations in valence and arousal successfully in 48 and 69% of trials, respectively (chance level 50%). It is noteworthy that the success rate of communicating valence was practically the same as chance level. However, when leaving out the gestures that provided a poorer match, the mean success rates for valence and arousal were 75 and 79%, respectively. Thus, the senders and receivers agreed on the emotionality of mediated touch in roughly three cases out of four when suitable touch gesture was used.

Analysis of the vibrotactile stimulation showed that the receivers' distinctive emotional interpretations of squeeze and finger touch could be due to differences in stimulation parameters. Stimulation created with squeeze had significantly higher mean intensity than that created with finger touch. Also, squeeze was interpreted mainly as unpleasant and arousing. This is in line with the work of Salminen et al. (2009) who showed that vibrotactile stimuli with high amplitude (i.e., intensity) were rated as more unpleasant and arousing than stimuli with lower amplitudes. It seems that this effect exists also when tactile stimulation is used to communicate emotional intention between two persons. Another main result of the stimulation parameter analysis was that stimulation created with finger touch had significantly more spatial variation than that created with squeeze. For example, when communicating *pleasant* intention, the mean intensities between touch gestures were comparable (see Fig. 7), but stimulation created with finger touch had more spatial variation (see Fig. 8). Consequently, the receivers interpreted stimulation created with finger touch as more pleasant and relaxed. It could be that the receivers perceived moving stimulation as more natural or tickling than constant stimulation with less spatial variation.

The differences in vibrotactile stimulation between squeeze and finger touch may be explained by looking at how touch gestures were converted to tactile representations. In our previous study we observed that applied pressure tends to distribute evenly when squeezing an object in one's hand (Rantala et al., 2011b). Similarly, in the current study the senders often squeezed several buttons at the same time and, thus, created vibrotactile stimulation with low mean spatiality. On the contrary, the two-handed interaction of finger touch provided more precise spatial control that enabled touch sequences activating only certain actuators (e.g., a stroke that moved along the device's top). This suggests that some spatial characteristics of squeeze and finger touch could be converted to vibrotactile stimulation despite the rather simple four-actuator output. Our approach of sensing real-time touch input differed from earlier studies that utilized predefined stimulation patterns for imitating interpersonal touch (Bonanni et al., 2006; Haans and IJsselsteijn, 2009b; Park et al., 2011). Moreover, as discussed above, squeeze and finger touch evoked different emotional interpretations in the participants who received mediated touch. Taken together, some evidence was found suggesting that physical touch gestures could convey different emotional intention in remote communication.

The results of preferred touch gestures showed that if given a choice, the dyads would have communicated intended emotions using particular touch gestures. In general, the preferences were in line with the success rates of communication. That is, the majority of senders and receivers would have chosen squeeze for communicating *unpleasant* emotional intention, while finger touch was preferred for conveying *pleasant* and *relaxed* emotional intention. In terms of *aroused* emotional intention the distinction was not equally clear. This was possibly reflected in the success rates of communication as *aroused* emotional intention was communicated at above chance rates with both gestures (see Fig. 6). The dyad members provided their preferences independently, and they were not aware of the success rates of communication. A possible explanation for the preferences might be that the participants opted for touch gestures they would have chosen to use in non-mediated (real) touch communication. Another possible explanation is that the participants perceived the difference in stimulation between the touch gestures and therefore associated particular stimulation parameters with different emotional intention. From the perspective of practical communication applications, the relationship between participant preferences and successfulness of communication is encouraging as it suggests that after a relatively short use people could select the more suitable touch gesture depending on their communication needs.

Certain similarities could be identified between our findings and prior research on communicating emotional intention via non-mediated touch. In a study by Hertenstein et al. (2009) cross-gender dyads used non-mediated squeeze most commonly for expressing anger and fear. If these two distinct emotions are mapped to the dimensional affective space (Russell, 1980), they fall in the unpleasant–aroused quadrant similarly to the receivers' interpretations of mediated squeeze in our study. In terms of finger touch, our video observations showed that the interaction could be divided into three touch gestures of stroke, pat, and spot touch. The ones used most frequently by the senders were stroke and pat. In non-mediated communication, these touch gestures were used

most commonly for expressing positive emotions of love, sympathy, and gratitude (Hertenstein et al., 2009). Since in our study mediated stroke and pat conveyed mainly positive valence, it would seem plausible that there could be similarities between the ways people use and perceive non-mediated and mediated touch. Some indication of this was also seen in our interview results. The participants commented that mediated touch would be appropriate mainly in close relationships as has been shown to be the case with real touch (McDaniel and Andersen, 1998). It is important, however, to note that we did not directly compare mediated and non-mediated touch in our study. Therefore, these similarities should be interpreted with caution.

There were some limitations in our study. First, similarly to previous empirical studies on mediated social touch (Bailenson et al., 2007; Smith and MacLean, 2007), our work investigated mainly communication of intended emotions rather than felt emotions. That is, the senders were asked to deliberately create stimulation with specific emotional intention. While it has been suggested that these "on demand" emotions might be the type that is used mostly during HCI (Bailenson et al., 2007), further work is needed to establish possible differences between our results and settings where participants have emotional experiences during communication (e.g., watch an emotional film). Likewise, encoding and decoding the meaning of vibrotactile stimulation required cognitive processing from the participants unlike real touch that is immediate and seldom planned. Wang and Quek (2010) proposed that the immediacy of mediated touch could be improved by including contextualizing information channels to communication (e.g., audio). Second, as Haans and IJsselsteijn (2009a) noted, vibrotactile stimulation is a crude substitute for physical touch. It is apparent that vibrotactile technology stimulating the user's skin cannot reproduce properties such as contact pressure, rubbing, or tugging. Alternative approaches include, for example, armbands for representing physical squeeze (Suhonen et al., 2012; Wang and Quek, 2010; Wang et al., 2012). On the other hand, our results can be seen as a hint of the powerfulness of touch as a communication medium. Certain similarities between the use of mediated and real touch were identified despite the rather simple sensing and actuation technology. Third, the prototype device had a unique form factor that was designed to afford various types of tactile interaction. While this form differed from devices such as phones, the same touch gestures could be adapted to other platforms. Researchers have presented phone prototypes with multiple vibrotactile actuators (Park et al., 2011; Yatani and Truong, 2009), while squeeze and finger touch could be sensed via force sensing resistors (Stewart et al., 2010) and touch screens. Fourth, we recruited only participants in close relationships as most physical touch communication takes place between acquaintances (McDaniel and Andersen, 1998). Even mediated touch communication between strangers can cause discomfort (Smith and MacLean, 2007) and, thus, no strangers were included. It is likely that the current results are not directly transferable to strangers. Lastly, analysis of interview data was conducted by one coder. In future studies the use of several coders is recommended so that inter-rater reliability could be established.

When looking at our findings from a wider perspective, certain implications can be identified for future development of touch communication applications. Squeezing as an interaction type could be applicable when thoughts of unpleasant and arousing information are desired. Conversely, spatial movement using one's fingers could evoke more pleasant and relaxed thoughts in the communication partner. We envision that such interaction could be useful, for example, in adding physical closeness to communication by sending a gentle stroke to one's companion. In addition, touch could be used to substitute other communication modalities in contexts where calling or texting is not appropriate (e.g., squeeze a device to send a touch message during a work meeting). In case such a touch communication channel would be introduced to practical use, privacy and ethical issues should be considered. As noted by Heikkinen et al. (2009), touch is a private way to communicate and users should have control over who can send touch messages to them. Also, while our current focus was on unimodal touch communication, in practice mediated touch would likely be used with other modalities. Addition of visual (Haans and IJsselsteijn, 2009a) and auditory (Wang et al., 2012) information has been shown to affect perception of tactile stimulation. Moreover, Park et al. (2012) observed that participants did not prefer to use mediated touch when the mood of discussion was negative in order to avoid making the other person angrier or more irritated.

In summary, our study showed that squeeze and finger touch evoked different emotional interpretations in the persons who received mediated touch. Using the dimensional frame of reference and rating scales seemed to be a feasible way to start measuring users' subjective interpretations of emotional touch communication. An alternative method to proceed would be to measure lower level reactions (e.g., pupil size variation or facial electromyography). Such measurements might prove useful in tracing immediate and involuntary emotional reactions to mediated touch. From the viewpoint of HCI research, our study proposed an interaction method that was motivated by physical touch interaction. The fact that users were able to mediate touch sensations using common physical gestures can be seen as an attempt to add spontaneity and naturalness to remote communication. In some sense, the device held in one's hand could be understood to be an embodiment of the communication partner. Lastly, our work relates to prior research in the field of haptics where researchers have mostly measured communication of emotional intention via non-mobile feedback devices (Bailenson et al., 2007; Smith and MacLean, 2007) or presented tactile communication prototypes along with pilot studies or informal evaluations (Bonanni et al., 2006; Hansson and Skog, 2001; Mueller et al., 2005; Park et al., 2011). Our aim was to combine these approaches and empirically measure the emotionality of touch mediated via tactile technology. Evidence was found indicating that touch has potential to convey emotional information between humans even in mediated form. It is our hope that the

present findings encourage researchers to further pursue the concept of mediated touch.

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Paper V

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Preferences for Touch Gestures in Audio-Tactile Communication

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ABSTRACT

People use different touch gestures in everyday life to interact with each other. However, remote communication typically supports only auditory and visual modalities. Gestures such as squeezing, stroking and patting could be used for supporting emotional communication between remote users. In this paper we study how different touch gestures are used as a part of audio communication. A user study was conducted where participant pairs were provided with hand-held devices that converted squeeze and finger touch gestures to vibrotactile stimulation. When one participant touched the device, another participant felt the touch simultaneously on a second device. The participants' task was to use the devices during conversations that varied in their emotional topics. The results of touch use analysis showed that the participants spent more time interacting via squeeze. Also, male participants rated squeeze as more suitable than finger touch. The emotional conversation topic did not have an effect on the use of touch gestures. In discussion the current findings are compared to prior research where only the tactile modality was used.

Keywords: Haptics, tactile stimulation, touch communication, audio communication, touch gestures, emotions.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

The introduction of devices such as mobile phones has allowed people to communicate remotely regardless of one's physical location. However, remote communication usually relies only on audio or vision even though touch plays an important part in social interaction between people. Compared to visual and auditory modalities, touch is more private by its nature. Consequently, it is mostly used between people who know each other. McDaniel and Andersen [8] reported that touch was used in public settings frequently by lovers and close friends who had emotional ties. The emotionality of touch has also been studied in more controlled settings. Hertenstein *et al.* [4] showed that interpersonal touch has a capability to communicate distinct emotions between people. In their study participant pairs were above chance in communicating intended emotions such as anger and fear to one another using only touch. Also, the participants used different touch gestures for different distinct emotions. For

example, anger was most commonly expressed with shaking, pushing and squeezing, while love was communicated with hugging, patting and stroking. Thus, the type of touch gesture partly defines how other people react to it and what type of emotional responses it possibly evokes.

Researchers in the fields of haptics and human-computer interaction (HCI) have developed a range of device prototypes for sensing user's touch input and presenting it to another user with haptic technology [2, 5, 6, 9, 10]. In this paper we focus on tactile and especially vibrotactile actuators that are usually small in size and therefore easy to embed to mobile devices. It should be noted, however, that vibrotactile technology can only approximate certain characteristics of interpersonal touch (e.g., location and intensity of touch). An alternative way would be to use kinesthetic feedback devices that can present forces of interaction (e.g., [12]).

One of the first tactile communication studies was conducted by Chang *et al.* [2] who converted finger pressure of one user to vibrotactile stimulation felt on another user's finger. The results showed that touch was used during conversation to signal emphasis, mimicry and turn-taking. Park *et al.* [9] developed CheekTouch that had a 3×3 grid of vibrotactile actuators attached to the backside of a mobile touchscreen device. By manipulating the touchscreen with fingers a user could send tactile patterns to another user who sensed them on the cheek. Different gestures such as tapping, pinching and patting were used depending on the conversation context. In an alternative approach, Hoggan *et al.* [5] sensed squeezing applied to the sides of a phone and converted it to vibrotactile stimulation felt by another user. In a longitudinal study three couples used squeezing during phone calls, for example, to emphasize speech and express affection. Lastly, Huisman *et al.* [6] developed a tactile sleeve for social touch that sensed gestures of poke, hit, press, squeeze, rub and stroke. In a following study Huisman and Darriba Frederiks [7] explored how users would touch the sleeve device for expressing different distinct emotions.

Despite the number of prior studies on mediated touch, relatively little is known of whether different gestures can indeed communicate affect or emotions when presented in vibrotactile form. Recently, Rantala *et al.* [11] studied tactile communication of intended emotions using squeeze and finger touch (e.g., patting and stroking) gestures. Hand-held prototype devices sensed user's touch input and converted it to vibrotactile stimulation in real time. In an experiment the task of one participant was to use squeeze and finger touch for communicating unpleasant, pleasant, relaxed and aroused emotional intention to another participant. The results showed that squeeze was more suitable for communicating unpleasant and aroused emotional intention, while finger touch was more suitable for communicating pleasant and relaxed intention. Based on the findings, it seems possible that touch gestures could communicate different emotional intention even in mediated form.

However, the study setting used by Rantala *et al.* [11] was limited to only tactile communication. It has been suggested that in real communication applications the tactile channel could be

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combined with speech [2, 5, 9]. To our knowledge, no studies have investigated the possible differences in the use of touch gestures between tactile and audio-tactile communication. This information could be used in designing touch interfaces that can adapt to different multimodal communication settings.

Our current aim was to study audio-tactile communication where participant pairs utilize squeeze and finger touch gestures during a conversation. In particular, we focused on possible differences in the use of gestures in conversations with varying emotional content. For this purpose, prototype devices were used that sensed the gestures and converted them to vibrotactile stimulation [10, 11]. In a user study the participants' task was to use the gestures the way they saw fit during conversations that varied in their given emotional topics. Subjective ratings, questionnaires, logged use statistics and post-experimental interviews were used for analysing the use of gestures.

2 METHODS

2.1 Objectives

We set two research questions for studying the use of squeeze and finger touch gestures during speech communication:

1. How much the two gestures are used and for what purposes?
2. Does the participant gender or emotional conversation topic affect how suitable the gestures are to use?

2.2 Participants

A total of 9 voluntary pairs (i.e., 18 participants) took part in the experiment (mean age 29, range 18-49 years). The pairs were either intimate couples or friends as real touch is used mostly between acquaintances [8]. All pairs were cross-gender to analyze possible differences between male and female participants. This was chosen also to avoid possible gender effects related to interpretation of same sex touch [3]. On average, the participants had known each other for 8 years. Informed consent forms were signed before starting.

2.3 Apparatus

Identical prototype devices were given to both participants. Squeeze was detected using four force sensing resistors (FSR) in the sides of the device (Figure 1a). Finger touch gestures were tracked with a 15-channel capacitive touchpad located underneath the device's flat top surface (Figure 1b). The input data of squeeze and finger touch were used for creating vibrotactile stimulation. The stimulation was presented to the user's hand via four actuators (LVM8, Matsushita Electric Industrial Co., Japan) that were placed inside moving buttons in the sides of the device.

Our aim was to make the touch gestures distinguishable by using different vibrotactile stimulation for squeeze and finger touch. Squeeze was presented with a pulsating sine wave that was designed to symbolize a heartbeat (Figure 1a). The rhythm of the pulsation was mapped to the pressure of squeeze so that the delay between pulsations decreased when more pressure was applied. Finger touch was presented using a mixed sine wave that imitated contact with a surface (Figure 1b). The amplitude of the mixed sine wave was proportional to the amount of capacitive contact between the touchpad and user's finger(s). The frequency of both vibrotactile signals was set to 160 Hz that was found to be suitable in a previous study [10]. In addition, the location of touch input was mapped to the four actuator locations. For example, squeezing the front left button or touching the front left part of the touchpad resulted in vibration from the front left actuator.
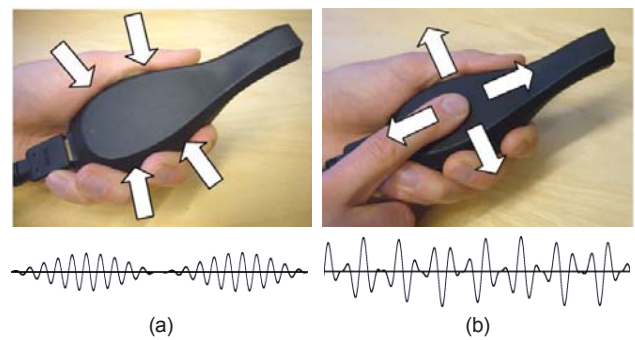

Figure 1: Touch gestures of squeeze (a) and finger touch (b) with their corresponding vibrotactile signals shown below.

The actuators were driven using audio signals from a PC running Pure Data (PD) audio synthesizer software. Feedback signals were fed to the devices using Gigaport HD USB sound cards. Two Sennheiser PC 166 USB headsets handled audio communication between participants. For more details of the used prototype device, please see previous work [10, 11].

2.4 Procedure

The participants were guided to separate laboratory rooms so that they could not see each other. They were instructed to hold the device in the hand they preferred (right hand for 9 out of 18 participants). The participants could then try how the device responded to squeeze and finger touch. At this point the participants did not yet feel mediated touches sent by their pair. Next the participants proceeded to a training task where they sent and received mediated touches and discussed what they could be used for. The participants felt vibration both from their own touch and from the touch of their pair. This was chosen similarly to some earlier studies [5, 11] so that the local feedback could help in knowing how one's own actions were felt remotely. Identical vibrotactile signals were used for both own and remote touch.

In the following three test tasks specific conversation topics were given to the participants. The topics were as follows: *"discuss an event that has made you happy"*, *"agree on a restaurant for a lunch or dinner"* and *"discuss an event that has made you sad or angry"*. The topics originating from a previous study [13] were chosen to stimulate conversations with different emotional themes (i.e., positive, neutral and negative), but the exact content of the conversations could still be chosen by the participants. This was chosen in order to have some control over the emotional content of conversation and still allow as natural conversations as possible. The participants were instructed to use squeeze and finger touch the way they saw fit but not to talk about the use during the conversations. The order of conversation topics was counterbalanced between the pairs, and the duration of one conversation was set to be between 5 and 10 minutes. Interaction data such as duration of touch gesture use per participant was logged for analysis using PD.

Each test task was followed by separate questionnaires that were given to both participants. The participants were instructed to rate how suitable the touch gestures were for a specific conversation topic. A bipolar scale ranging from –4 (not suitable) to +4 (suitable) was used. After this, both participants were asked to describe how and for what purposes they used the gestures. Also, they tried to interpret touches that were sent by their pair. The three test tasks were followed by a short free-form conversation without the devices to compare audio and audio-tactile communication. After this a second questionnaire was used

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for enquiring whether the participants would have liked to use the devices in the audio-only conversation if given a choice.

Finally, each participant pair was interviewed and asked the following questions: 1) how they perceived the use of squeeze and finger touch, 2) how well could they interpret the mediated touches sent by their pair, 3) how well could they differentiate between the vibrotactile stimulation of squeeze and finger touch, and 4) did the experiences of communicating with and without the devices differ?

2.5 Data Analysis

To analyze whether the participant gender, touch gesture or conversation topic affected the durations of touch usage, repeated-measures mixed-model analysis of variance (ANOVA) was conducted. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Pairwise Bonferroni corrected t-tests were used for post hoc tests. The average duration of one conversation was 7 minutes. However, because of variation in the durations between participant pairs, relative durations were used in the analysis. A relative duration of 100% would signify using touch throughout a conversation.

The rating data was analyzed to find out whether the participant gender or touch gesture had an effect on the experienced suitableness. Separate Friedman tests were conducted for the rating data of male and female participants. In case significant differences were observed between touch gestures, further Friedman tests were performed to analyze the effect of conversation topic on the ratings. Wilcoxon signed-rank tests were used for pairwise comparisons.

Post-experimental interviews were analyzed using bottom-up thematic coding. In practice, audio recordings of interviews were first transcribed, and then individual comments from the participant pairs were categorized based on their similarity. The reported interview results in Section 3.3 present the main findings from the interviews.

3 RESULTS

3.1 Durations of Touch Usage

For the durations of touch usage (Figure 2), a three-way $2 \times 2 \times 3$ (participant gender $\times$ touch gesture $\times$ conversation topic) mixed-model ANOVA showed a statistically significant main effect of touch gesture ($F_{1,16} = 8.4$, $p < 0.05$). Post-hoc pairwise comparisons showed that the participants used squeeze significantly more than finger touch during the conversations ($MD = 11.6$, $p < 0.05$). The main effect of the conversation topic, participant gender or the interactions of the main effects were not statistically significant.

On average, each participant spent 92 seconds for interacting via squeeze and 40 seconds for interacting via finger touch in one conversation.
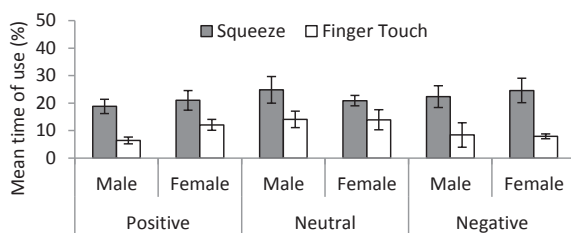
Figure 2: Means and SEMs for the durations of touch usage by touch gesture, conversation topic and participant gender.

3.2 Ratings of Suitableness

For the results of suitableness (Figure 3), a Friedman test showed a statistically significant effect of touch gesture on the male participants' ratings ($X^2 = 15.2$, $p < 0.01$). The results of pairwise comparisons showed that the male participants rated squeeze as significantly more suitable as compared to finger touch ($Z = 3.14$, $p < 0.01$). However, further Friedman tests showed no significant differences in the male participants' ratings of squeeze and finger touch for different conversation topics. The touch gesture did not have a significant effect on the female participants' ratings.
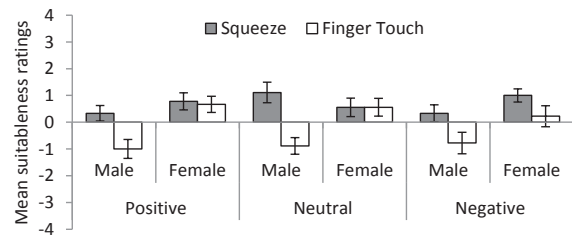
Figure 3: Means and SEMs for the ratings of suitableness by touch gesture, conversation topic and participant gender.

3.3 Meanings of Touch and User Acceptance

The questionnaire results indicated that the three most common uses for squeeze were agreement or disagreement (22 reported cases), emphasis of speech (8) and spontaneous touch (5). The respective uses for finger touch were agreement or disagreement (11), expression of comfort or affection (4) and spontaneous touch (4). According to the participants, spontaneous use of touch was mostly unconscious and automatic. For example, one participant noted that she had been using finger touch for drawing circles without realizing it.

The interview results indicated that two pairs preferred squeeze because it could be used with one hand and, thus, required less effort. Conversely, one pair preferred finger touch because the vibrotactile stimulation reminded them more of touching with a finger than squeezing with the whole hand. Five pairs indicated that they had at least occasional difficulties in interpreting the meaning of stimulation sent by their pair. Also, three pairs said that while the vibrotactile stimulation of squeeze and finger touch could be differentiated in the training phase, during the test tasks it was difficult to recognize the gestures when engaged in a conversation.

In eight out of nine pairs at least one participant would have liked to use the devices in the final audio-only conversation if given a choice. Three pairs commented that the use of touch added feeling of presence, closeness and warmth to the communication. On the other hand, four pairs felt that the devices took some attention away from the conversation because one had to concentrate also on the touch interaction.

4 DISCUSSION

Our results indicated that the participants used squeeze significantly more than finger touch during conversations. The ratings of suitableness showed that male participants preferred squeeze over finger touch, whereas female participants considered the gestures types to be equally suitable. The different emotional conversation topics had no effect on the durations of touch gesture use or ratings of suitableness. The participants' preference for using squeeze could be due to several reasons. Whereas squeezing the device required only one hand, in finger touch one hand was needed for holding the device and sensing vibrotactile stimulation

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and the other for touching the device's top surface. Also, the interview results indicated that the participants could not reliably distinguish which touch gesture their pair had used during conversation. This suggests that the vibrotactile stimulation design may not have been clear enough. On the other hand, the difficulties in differentiating the touch gestures could have resulted from the requirement of dividing one's attention between the auditory and haptic modalities. Several participant pairs felt that conversation using the devices required more concentration than audio-only conversation.

It is interesting to note that male participants rated the suitableness of finger touch more negatively than female participants. Previously, gender differences have been observed in real touch communication where male and female participants used different touch gestures when communicating intended emotions [4]. In addition, Bonanni *et al.* [1] studied affective touch using a scarf-like device. In their pilot study female participants preferred vibrating motors that provided gentle feedback, whereas men preferred solenoids that created more intense feedback. However, no empirical evaluation was reported where participant pairs would have interacted using the scarfs. Our findings suggested that gender differences can take place also in mediated touch communication. This lends partial support to the idea that mediated touch could have similar effects to real touch [3]. At the same time, it is important to note that we compared only two touch gestures using a single actuation technology (i.e., vibration). More research is needed to evaluate whether similar gender effects are observed with devices that use different gestures, feedback technologies and form factors. Also, we varied the emotionality of communication using predefined conversation topics. While the topics were designed to be emotional by their nature, we could not control the participants' felt emotions during the tasks. This could in part explain the lack of variance in gesture use between topics.

The results of post-experimental interviews showed that the participants did not always assign specific meanings to mediated touch but rather interacted with the devices in a spontaneous and unconscious manner. This could be related to differences in the cognitive processing between mediated and real touch. In general, mediated touch requires deciding the meaning of touch and coding it to vibrotactile stimulation, whereas real interpersonal touch is more immediate and automatic [11]. However, the current results indicated that mediated touch was, at least part of the time, used in a spontaneous manner. It is therefore possible that the required level of cognitive processing could decline as people get more used to the touch channel. Our future aim is to conduct longitudinal studies that could reveal whether the use of mediated touch changes over time. The other use cases reported in the current study (i.e., expressing agreement or disagreement, emphasizing words and showing affection) were mostly in line with previous work [5, 9, 10].

Two main design implications can be identified when looking at our findings from the perspective of tactile communication and mediated touch research. Firstly, in audio-tactile communication, squeeze was the preferred touch gesture type regardless of the participant gender and the emotional theme of conversation. Squeezing interaction could be added to consumer products by using touch sensitive areas in the sides of mobile devices (see [5] for an example). Secondly, it could be argued that the benefit of using multiple vibrotactile actuators for presenting touch gestures (e.g., [1, 7, 9, 10]) is greater when the communication takes place only via touch. Users can concentrate solely on the properties of touch and, thus, perceive possible differences in the emotionality of gestures as demonstrated earlier [11]. One possible use scenario for tactile-only communication would be sending touch messages similarly to SMS [5, 10] so that the messages could be opened at an appropriate time and, if necessary, be played back later.

5 ACKNOWLEDGEMENTS

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