Katri Salminen

Emotional Responses to Friction-based, Vibrotactile, and Thermal Stimuli

ACADEMIC DISSERTATION
To be presented with the permission of the School of Information Sciences of the University of Tampere, for public discussion in the Linna auditorium Väinö Linna on April 28th, 2015, at noon.

School of Information Sciences
University of Tampere

Dissertations in Interactive Technology, Number 20
Tampere 2015

ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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Acta Electronica Universitatis Tamperensis 1543
ISBN 978-951-44-9795-7 (pdf)
ISSN 1456-954X
http://tampub.uta.fi

The originality of this thesis has been checked using the Turnitin OriginalityCheck service in accordance with the quality management system of the University of Tampere.

Dissertations in Interactive Technology, Number 20

School of Information Sciences
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FINLAND

ISBN 978-951-44-9727-8
ISSN 1795-9489

Juvenes Print – Suomen Yliopistopaino Oy
Tampere 2015

Abstract

The present aim was to experimentally investigate how different types of haptic stimulations are associated with the human emotion system. Prototype technologies were built to create computer driven friction-based, vibrotactile, and thermal sensations. Haptic technologies (i.e., friction-based, vibrotactile, and thermal), stimulus parameters (e.g., amplitude and continuity), and modality (i.e., haptic only or haptic auditory) were varied in the studies. Responses were measured using emotion-related rating scales (i.e., valence, approachability, arousal, and dominance), behavioral measurements, and changes in skin conductance response (i.e., SCR) reflecting the level of physiological arousal.

The results showed that different haptic stimulations activated the human emotion system differently, as evidenced by subjective ratings and behavioral and physiological changes. The vibrotactile stimuli were connected to the level of arousal and dominance so that, for instance, stimuli with high amplitudes were rated as more arousing and dominant than stimuli with low amplitudes. However, on the scales of pleasantness and approachability vibrotactile stimuli were in general rated as neutral despite the parametrical variation. Friction-based and thermal stimuli effected the ratings on all of the four scales. Continuous stimuli and high intensity stimuli were rated as less pleasant, less approachable, more arousing, and more dominant than discontinuous and low intensity stimuli. Thus, friction-based and thermal stimuli resulted in a wider variation in respect of the emotion-related ratings than vibrotactile stimuli.

Variation of the modality affected the ratings of vibrotactile stimuli in somewhat different manner. The ratings of arousal and dominance were affected so that the vibrotactile-auditory stimuli were always rated as more arousing and dominant than auditory only stimuli. Interestingly, when the modality was varied also the ratings of pleasantness were affected. When the vibrotactile stimulus was congruent with the auditory signal, the stimulus was rated as less pleasant than when the stimulus was auditory only.

The results of SCR and behavioral measurements supported the findings of the subjective ratings. SCR was higher in magnitude when the stimulus was rated as arousing than when it was rated as calm. The stimuli rated as arousing were also differentiated faster and more accurately than the stimuli rated as calming.

In summary, the current thesis demonstrated that different computer driven haptic stimulations activated the human emotion system differently, as evidenced by subjective ratings and behavioral and physiological responses. Particularly in respect of the ratings along the four emotion related dimensions, it can be concluded that friction and thermal stimulations were better at evoking changes in the ratings of pleasantness and approachability than vibrotactile stimuli. Vibrotactile stimuli were associated with a higher level of arousal and a feeling of being controlled by the stimulation. As there is growing interest in using stimulation of the sense of touch in human-technology interaction, it is likely that the results of the current thesis can be utilized in designing haptics-based affective computing.

Acknowledgements

I would like to thank several people for contribution and support during the writing process of the current thesis. First, I would like to express my gratitude to Professor Veikko Surakka, who has guided my throughout my research career and this thesis. He has always had time to discuss and help when needed. This thesis would not have been completed without him.

The experiments in the thesis were mostly done in collaboration with other researchers. I would especially like to thank Jussi Rantala, Jani Lylykangas, and Professor Roope Raisamo for their help and support. Not only these people were helping to implement and publish the research, but we have also had inspiring discussions during the years.

Tampere Unit for Computer-Human Interaction (TAUCHI) has offered a fantastic research environment to develop as a postgraduate student. Both people and premises are top level. Especially, it has been a great joy to work in highly enthustiatic and skillful Research Group for Emotions, Sociality, and Computing (ESC). I would like to thank all the members of the group for intellectual support.

For the financial support for the thesis I would like to thank Tampere Doctoral Programme in Information Science and Engineering (TISE) and the Finnish Funding Agency for Innovation (TEKES).

Finally, I would like to thank my family, especially my parents who have always been there for me. I would also like to thank my spouse Arto for love and caring, and my friends, Tiina, Eeva, and Eeva for support and fun. You rock!

Tampere, January 26th, 2015

Katri Salminen

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List of Publications

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

I. Salminen, K., Surakka, V., Lylykangas, J., Raisamo, J., Saarinen, R., Raisamo, R., Rantala, J., & Evreinov, G. (2008). Emotional and behavioral responses to haptic stimulation. *In Proceedings of the 26th International Conference on Human Factors in Computing Systems (CHI '08, Florence, Italy),* 1555-1562, New York, NY, USA: ACM. doi:10.1145/1357054.1357298 89

II. Salminen, K., Surakka, V., Raisamo, J., Lylykangas, J., Pystynen, J., Raisamo, R., Mäkelä, K., & Ahmaniemi, T.T. (2011). Emotional responses to thermal stimuli. *In Proceedings of the 13th international conference on multimodal interfaces (ICMI '11, Alicante, Spain),* 193-196. New York, NY, USA: ACM. doi:10.1145/2070481.2070513 99

III. Salminen, K., Surakka, V., Raisamo, J., Lylykangas, J., Raisamo, R., Mäkelä, K., & Ahmaniemi, T.T. (2013). Cold or hot? How thermal stimuli are related to human emotional system?. *In Proceedings of Haptic and Audio Interaction Design (HAID '13, Daejeon, Republic of Korea),* 20-29. Springer-Verlag, Lecture Notes in Computer Science, Volume 7989. doi:10.1007/978-3-642-41068-0_3 105

IV. Salminen, K., Surakka, V., Lylykangas, J., Rantala, J., Laitinen, P., & Raisamo, R. (2011). Evaluations of piezo actuated haptic stimulations. *In Proceedings of the 4th international conference on Affective Computing and Intelligent Interaction - Volume Part I (ACII'11, Memphis, Tennessee, USA),* 296-305. Sidney D'Mello, Arthur Graesser, Björn Schuller, and Jean-Claude Martin (Eds.), Vol. Part I. Springer-Verlag, Berlin, Heidelberg. 117

V. Salminen, K., Rantala, J., Laitinen, P., Surakka, V., Lylykangas, J., & Raisamo, R. (2009). Emotional responses to haptic stimuli in laboratory versus travelling by bus contexts. *In Proceedings of the 3rd international conference on Affective Computing and Intelligent Interaction (ACII'09, Amsterdam, Netherlands),* 1-7. IEEE Computer Society, Washington, DC, USA. doi:10.1109/ACII.2009.5349597 129

VI. Salminen, K., Surakka, V., Lylykangas, J., Rantala, J., Ahmaniemi, T.T., Raisamo, R., Trendafilov, D., & Kildal, J. (2012). Tactile modulation of emotional speech samples. *Advances in Human-Computer Interaction.* Article ID 741304, 13 pages. Hindawi Publishing Corp. New York, NY, USA. doi:10.1155/2012/741304 139

Author's Contribution to the Publications

The publications included in the thesis were produced in collaboration with other researchers. The present author had the main responsibility for designing the empirical studies together with the supervisor and co-authors. The technical implementation was mostly executed by the co-authors. Collecting and analyzing the data was conducted by the present author. The present author was also the main author of all the publications in the current thesis.

1 Introduction

In our daily lives, we use our sense of touch for various purposes. Touch is frequently used to gain information about objects' weight, softness, elasticity, temperature, and texture. It gives us feedback about body movements and works as a warning signal through the sensations of pain. Touch also plays a significant role in interpersonal relationships. Touch is known to have a profound role in close, intimate contact as well as in the emotional and social development of an individual. It is silent and thus a private means of communication. People use the sense of touch when they aim at, for instance, communicating affection or gaining someone's attention. By touching, one can evoke strong hedonistic experiences in another person. Thus, we often use the sense of touch with our loved ones. The pleasant experiences evoked by, for example, a hug are mediated via warmth of the body and pleasant tactile sensations. Even though touching takes mostly place in private settings, it also has a significant role in more formal social contacts. For instance, handshakes and hugs can be shared in public situations.

Currently, mobile devices and computers have started to replace real life face-to-face communication, even with loved ones, especially when the distance between the parties is significant. Audio and pictures or videos are often attached to remote communications. However, the most intimate of the senses, touch, is rarely used in remote communication. One reason behind this may be found in technical development. In the field of human-technology interaction (HTI), studying haptics (i.e., technology that interfaces with the user through the sense of touch) has only gained popular interest during the last two decades. Devices that can be accurately programmed to produce controlled haptic stimulation have started to emerge to markets only recently. Due to the technological progress, the number of scientific papers studying haptics has increased enormously. A database search of the ACM Digital Library shows that, while in 2001 there were only 39 published papers related to haptics, in 2014 the number of published papers was 168. The most commonly used method for haptic feedback has been vibrotactile stimulation. Vibrotactile actuators are often implemented in, for example, mobile phones and touch screen devices to provide feedback to the user. Also, other kinds of haptic stimuli can be created with modern technology (e.g., skin stretch, force feedback, and temperature). However, these technologies are used less frequently in both scientific studies and commercial applications even though, for instance, temperature could easily be seen as mediating pleasant warmth to the user during remote communication.

Even though the technological progress has been rapid, we still have quite limited information concerning what kinds of haptic stimulations could evoke emotion-related experiences in the users and, thus, would be suitable to be implemented in technological devices. An area called affective haptics has taken its first steps during the years in which the studies included in the current dissertation have been conducted. The term was originally introduced by Tsetserukou, Neviarouskaya, Prendinger, Kawakami, and Tachi (2009). At this point, two of the papers in the current dissertation were already published. Affective haptics intrigues the scientific community and technology industry to study and design devices and systems that can affect human emotions by stimulating the sense of touch.

The present aim was to experimentally investigate how different types of haptic stimulations are associated with human emotions. Haptic technologies (i.e., friction-based, vibrotactile, and thermal), stimulus parameters (e.g., amplitude and continuity), modality (i.e., haptic only or haptic auditory), and experimental conditions (i.e., laboratory and outdoors) were varied to find out their potential differences and similarities in respect of the human emotion system. Responses were measured using emotion-related rating scales, behavioral measurements, and changes in skin conductance response reflecting the level of physiological arousal.

2 The Sense of Touch

Touch is considered to be one of the five traditional senses. It is a proximal sense which means that by touch we feel mostly objects near to us or actually in contact with us (Cholewiak & Collins, 1991). The sense of touch combines a variety of different sensations aroused by the stimuli contacting the skin (e.g., thermal, skin stretch, and mechanical pressure). Therefore, it has been argued that instead of referring to the sense of touch, it would be more appropriate to refer to the senses of touch (Heller & Schiff, 1991). Touch actually comprises different sensory sensations which can be categorized by their neural inputs and information-sensing receptors (Klatzky & Lederman, 2002).

Before moving forward, it should be highlighted that the sense of touch is an extremely complex modality. For instance, generalizations about the functioning of the sense can be challenging as it is possible to improve the haptic performance and sensitivity (e.g., Dinse, Kalisch, Ragert, Pleger, Schwenkreis, & Tegenthoff, 2005; Dinse, Kleibel, Kalisch, Ragert, Wilimzig, & Tegenthoff, 2006) and as touch-related sensations radically decrease during the aging process (Woodward, 1993; Stevens & Choo, 1996; Montagu, 1986). In addition, movement can greatly affect experiences acquired via the sense of touch. Already in 1962, Gibson (1962) noted that "Being passively touched tends to focus the observer's attention on his or her subjective bodily sensations, whereas contact resulting from active exploration tends to guide the observer's attention to properties of the external environment." Due to the complexity of the modality the following chapter can provide only an overview of the functioning of touch. As in the thesis, only friction, vibrotactile stimulation, and thermal stimulation have been used so the next section focuses on describing physiology related to these kinds of stimuli, thus, excluding, for instance, kinesthetic sensations.

2.1 SOMATOSENSORY SYSTEM

The somatosensory system is the term used to describe the primary modality subservient to the bodily sensations (McGlone & Reilly, 2010). It is an active modality, which helps humans to seek information from the world by exploratory movements (Klatzky & Lederman, 2002). The somatosensory system is comprised of receptors sensitive to pressure, pain, body movements, and temperature. The receptors cover the skin and epithelia, skeletal muscles, bones and joints, internal organs, and the cardiovascular system. At a more general level, the somatosensory system includes cutaneous sensitivity, kinesthesis, and haptics (Heller & Schiff, 1991). The term cutaneous is defined as related to or affecting the skin and kinesthesis refers to the sensation of movement. In 1950, Revesz stated that the term haptics includes both cutaneous and kinesthetic input (Revesz, 1950). According to Gibson (1966), through haptics we actively manipulate objects around us with cutaneous and kinesthetic input to obtain information. In more recent work, Lederman and Klatzky (2009a; 2009b) continue a similar line of definition by noting that "haptics is commonly viewed as a perceptual system, mediated by two afferent subsystems, cutaneous and kinesthetic, that most typically involves active manual exploration."

Most of the research concerning the sense of touch has focused on the human hand (i.e., palm and fingers) area. The current work is not an exception as all the stimuli used in the experiments have stimulated the glabrous skin of the human hand. Therefore, the remainder of the chapter mostly focuses on describing the functioning of the sense of touch in the glabrous skin areas. However, as noted, for example, by Cholewiak and Collins (1991) and McGlone and Reilly (2010), the anatomy of the skin as well as sensations of touch can be different in non-glabrous sites of the human body. The largest difference between glabrous and non-glabrous skin is the existence of hair follicle receptors which can only be found in non-glabrous body sites. They sense the position of body hair and therefore are able to mediate some tactile sensations before the stimulus touches the skin. There is evidence that these receptors can sense, for example, minute forces that cannot be perceived by the glabrous skin (Okazaki, Sato, Fukushima, Furukawa, & Kajimoto, 2011). Non-glabrous body sites are also covered with slowly conducting unmyelinated c-fiber afferents innervating human skin often referred to as C-tactile (CT) afferents. They respond to low force, slowly moving mechanical stimuli. This so called CT-system has been linked, for example, to the functioning of the tickle sensation (Vallbo, Olausson, Wessberg, & Norrsell, 1993; Vallbo, Olausson, & Wessberg, 1999; McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007) and the affective functions of touch (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). In contrast, there are non-glabrous body sites that lack receptors found all over in glabrous skin. For example, there are no Pacinian corpuscles in the skin of the cheek (Cholewiak & Collins, 1991).

Anatomy and the Main Receptor Classes of the Glabrous Skin

The skin is the largest and most ancient sensing organ of humans (Montagu, 1986). It is a multilayered sheet nearly 2 m^2 in area and 4 kg in weight in an average adult (Cholewiak & Collins, 1991). The functions of skin vary from protecting us from harmful ultraviolet radiation and dehydration to regulating body temperature (e.g., Heller & Schiff, 1991; Montagu, 1986). Skin consists of three major layers, namely the hypodermis, the epidermis, and the dermis. The hypodermis is not considered as part of the medical definition of skin, but it contains connective tissue and subcutaneous fat as well as a population of one mechanoreceptor end organs (Pacinian corpuscles) (Klatzky & Lederman, 2002). The epidermis (i.e., outer layer) consists of, for example, dead cell bodies that have migrated outwards as the skin renews itself (Cholewiak & Collins ,1991). The dermis (i.e., inner layer) consists of a layer of nutritive and connective tissues (Cholewiak & Collins, 1991). Within skin layers are located the physiological mechanisms (i.e., receptors) enabling humans to feel objects.

The receptors located in the skin can be classified into four main classes: thermoreceptors, mechanoreceptors, chemoreceptors, and nocireceptors. Thermoreceptors are responsible for sensing temperature (i.e., feelings of cold and warmth). Mechanoreceptors are sensitive to mechanical pressure or distortion and also to skin stretch. Chemoreceptors sense chemical stimuli (e.g., taste buds in the tongue). Nocireceptors are activated in the presence of potentially harmful stimuli which could cause tissue damage thus being responsible for the feelings of pain. They can respond to noxious thermal, mechanical or chemical stimuli (see, for example, Pasterkamp, 1999; Cholewiak & Collins, 1991; Lederman & Klatzky, 2009a; Lederman & Klatzky, 2009b).

Somatosensory Pathways and Somatosensory Brain

The somatosensory cortex is located at the postcentral cyrus, near brain structures that are responsible for human movements (i.e., primary motor cortex) (see Figure 1). It processes information acquired via skin receptors. The receptive fields in the skin and muscles project the information to the spinal cord via individual nerve fibers. There are both afferent (i.e., fibers projecting sensory information to the brain) and efferent (i.e., bringing motor information from the brain to, for example, joints) nerve fibers in the spinal cord (Cholewiak & Collins, 1991). The sensations responsible for conveying information related to mechanical, thermal, or noxious stimulation to the brain via the spinal cord are grouped into three pathways. All of them project to different areas in the brain (McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007) (see Figure 2). Finally, the information is divided into five perceptional groups: tactile perception (cutaneous, i.e., mechanical, thermal, and noxious stimulation), passive kinesthetic perception, passive haptic perception, active kinesthetic perception, and active haptic perception (e.g., Cholewiak & Collins, 1991; Klatzky & Lederman, 2002).

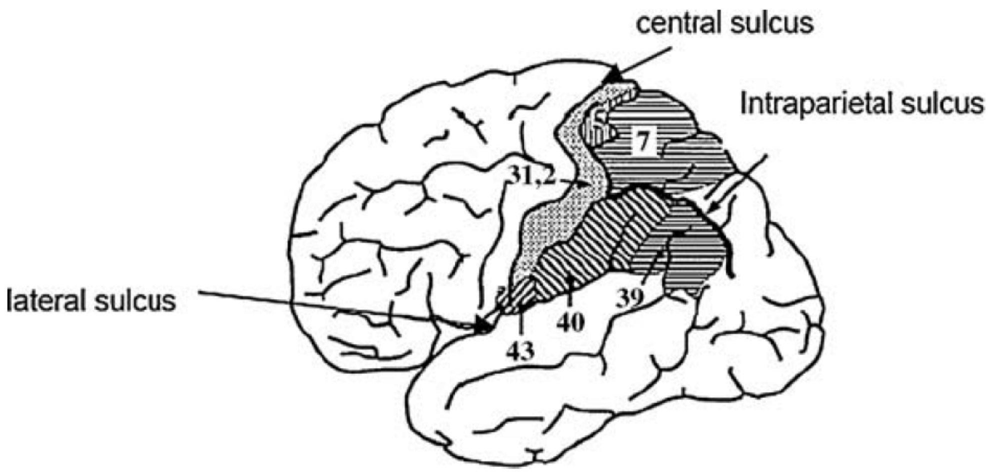

Figure 1. The location of the somatosensory cortex. Reprinted with permission from McGlone & Reilly, 2010, Figure 6, © Elsevier.

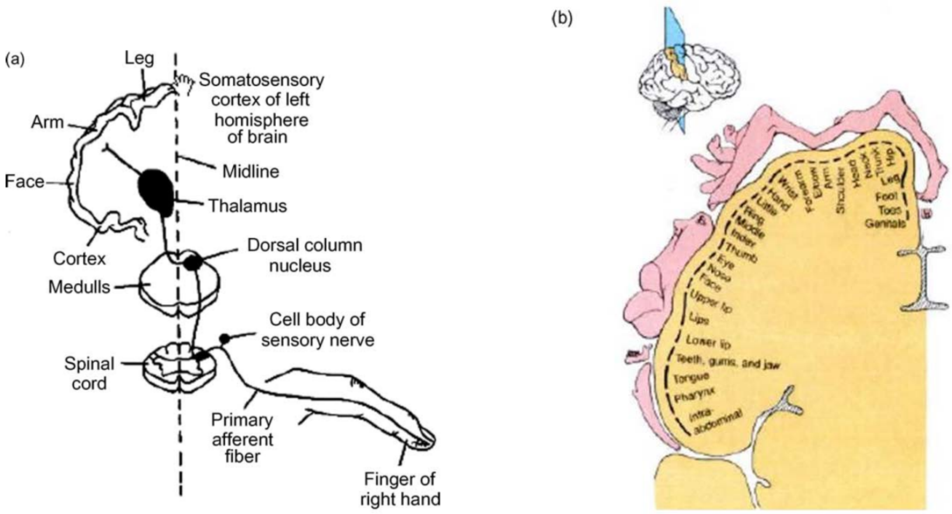

Figure 2. a) Somatosensory pathways from the finger via spinal cord to the brain. b) The somatosensory cortex and the tactile sensitivity of different body areas. Reprinted with permission from McGlone & Reilly, 2010, Figure 6, © Elsevier. Figure b was originally published in Jasper and Penfield, 1954, © Science, reprinted with permission.

Tactile information is actually processed in several areas of the brain, but most important among the areas processing tactile information are the primary somatosensory cortex (i.e., SI) and the secondary somatosensory cortex (i.e., SII) (e.g., Cholewiak & Collins, 1991). The SI receives information for somatic senses. The SII gets most of its input via the SI and associates input at a higher level, for example, in integrating somatic inputs (Klatzky & Lederman, 2002). The information acquired from the skin produces a representation of the body's surface at the somatosensory cortex (Cholewiak & Collins, 1991). It can be seen from Figure 2b that the size of the body area is not in direct relation to the amount of representation of the body area in the somatosensory cortex. The areas that are the most sensitive to tactile stimulation (e.g., tongue, genitals, and fingers) have the largest representation areas in the brain. In the somatosensory cortex, there are even cells highly sensitive to only a certain type of stimulation. For example, individual cells that process only stroking the surface of the forearm in a certain direction or to stimuli of a certain frequency have been found (Cholewiak & Collins, 1991). It also seems that the possibilities to train the functioning of the somatosensory system have a neural basis. This seems to be due to the plasticity of the size of the cortical receptive fields and the number of the cortical cells responding to the stimuli (Cholewiak & Collins, 1991). It has been argued that experience of a certain tactile stimulation can modify the functional organization of the somatosensory cortex and therefore also affect the tactile perception (Cholewiak & Collins, 1991; Dinse, Kleibel, Kalisch, Ragert, Wilimzig, & Tegenthoff, 2006).

The somatosensory cortex is also known to interact with brain structures responsible for processing information acquired via other modalities. Experiments focusing on multimodal and crossmodal information mediation have mostly concentrated on connections and interaction between tactile and visual modalities. Traditionally, it has been argued that the visual sense is dominant in most tasks related to utilization of both, touch and vision. However, recently it has been suggested that the modality most appropriate for the current task is dominant (Klatzky & Lederman, 2002). For instance, surface roughness is differentiated via the sense of touch better than via vision. There have also been studies regarding the interaction between tactile and auditory modalities. Already in his original work, Katz (1925) blocked the auditory cues to eliminate the possible effects of sound on the perception of tactile stimuli. Katz argued that vibrotactile sensations and audition are strongly related as auditory information can be mediated accurately via vibrotactile means alone. He based his arguments on the work of Gutzmann who noted in 1907 that by vibrotactile stimulation people are able to differentiate whole-tone differences in the range from A to E on a scale. But Katz never systematically studied the effects of auditory cues on tactile perception. Nevertheless, from the current neuroscientific point of view his initial theory is not surprising. Auditory and tactile modalities are closely related to each other. Information from tactile and auditory modalities is integrated in an early phase of the information processing chain and evokes responses partly in the same areas of the brain (e.g., Foxe, Morocz, Murray, Higgins, Javitt, & Schroeder, 2000; Foxe, Wylie, Martinez, Schroeder, Javitt, Guilfoyle, Ritter, & Murray, 2002). Several studies have shown that tactile stimulation can modulate responses related to auditory stimuli and vice versa (e.g., Ro, Hsu, Yasar, Elmore, & Beauchamp, 2009; Gilmeister & Eimer, 2007).

2.2 CUTANEOUS SYSTEM

Tactile, thermal, chemical, and to some degree noxious stimulations can be referred to as cutaneous sensations while kinesthetic sensations cannot. In the following two chapters, only the tactile and thermal subsystems are described in more detail because they are within the scope of the present thesis.

Tactile Subsystem

Tactile is often defined as being perceptible with touch, tangible, or affecting the sense of touch. Tactile sensations mediate information in regard to, for example, pressure, vibration, slip, and texture (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). They are conveyed via mechanoreceptors located in the epidermis and dermis. These so called mechanoreceptors are sensitive to mechanical pressure and distortion. The sensitivity of mechanoreceptors varies along body sites. The face, torso and fingers are most sensitive to mechanical stimulation (e.g., Lederman, 1991).

In human glabrous skin, there are four kinds of mechanoreceptors that are specialized to transduce mechanical forces in the skin into nerve impulses. The mechanoreceptors are Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini endings (e.g., Cholewiak & Collins, 1991; McGlone & Reilly, 2007). They can be classified based on their adaptation rate and the size of the receptive field. Fast adapting mechanoreceptors (Meissner's corpuscles and Pacinian corpuscles) respond to temporally or spatially moving mechanical stimulus on the skin. In other words, they adapt to mechanical stimulation quickly and the response dies off quickly, thus, meaning that they do not have a static response to the stimulus. Slowly adapting mechanoreceptors (Merkel's disks and Ruffini endings) on the other hand respond to constant mechanical stimuli. Therefore, they continue to fire throughout the duration of the stimulus. The receptive field of the mechanoreceptors can be either small (i.e., Meissner's corpuscles and Merkel's disks) or large (i.e., Pacinian corpuscles and Ruffini endings). The mechanoreceptors with small receptive fields are located in the surface of the dermal / epidermal boundary and the mechanoreceptors with large receptive fields are located deeper within the dermis (e.g., Cholewiak & Collins, 1991; McGlone & Reilly, 2007).

All of the four mechanoreceptors are specialized in detecting certain kinds of tactile stimuli (see Table 1). Meissner corpuscles detect edges. Meissner corpuscles are most sensitive to temporal changes in skin deformation in low frequency vibration (i.e., 5 to 40 Hz) and spatial deformation as well as stable precision grasp and manipulation. Pacinian corpuscles sense vibration and pressure. They are sensitive to temporal changes in skin deformation in high frequencies (i.e., 40 to 400 Hz) and specialized in fine texture perception as well as stable precision grasp and manipulation. Merkel's disks also detect edges. However, unlike Meissner corpuscles they detect sustained pressure at very low frequencies (i.e., below 5 Hz). They are also sensitive to spatial deformation and stable precision grasp and manipulation, although Merkel's disks are also responsible for coarse texture perception as well as pattern and form detection. Finally, Ruffini endings are associated with detection of skin stretch. In detail, they sense sustained downward pressure and lateral skin stretch while having low dynamic sensitivity. They are specialized in detecting object motion and force related to skin stretch, stable precision grasp and manipulation, and finger position (see, for example, Cholewiak & Collins, 1991; Lederman, 1991; Lederman & Klatzky, 2009a & 2009b; McGlone & Reilly, 2007).

	Adaptation rate	**Size of receptive field**	**Primary sensitivity**
Merkel	Slow	Small	Low-frequency
Meissner	Fast	Small	Temporal changes, spatial deformation
Ruffini	Slow	Large	Sustained downward pressure, lateral skin stretch
Pacinian	Fast	Large	Temporal changes in skin deformation

Table 1. Properties and primary sensitivities of mechanoreceptors.

The functioning of the mechanoreceptors is, however, not constant. A large amount of previous literature has concentrated on researching detection thresholds of mechanoreceptors. The detection thresholds are known to vary across body sites. For fingers the previous research suggests a detection threshold of about 0.14 Weber fractions to static pressure and 160 Hz for vibratory bursts (see Lederman, 1997, for a review). External factors may influence these detection rates so that, for instance, when external vibration level is 9.18g/s or higher, tactile stimuli becomes unnoticeable (Hoggan, Crossan, Brewster, & Kaaresoja, 2009).

Even rather simple distraction like walking can reduce the effectiveness of tactile stimulation up to 10% or more (Oakley & Park, 2008).

Finally, a further comment should be made about the mechanoreceptors. It has been argued that the measurement techniques most often used in previous research do not provide as clear cut knowledge about the functioning of the human tactile sense as might be wished. Traditionally, single-unit recordings are used (see, for instance, Lederman, 1991 for a review) in which an electrode picks up a response of a nerve fiber showing only how a unit responds to a tactile stimulus. However, they do not provide exact information about which mechanoreceptor produces the response. For instance, with more modern microneurography techniques, one can electrically stimulate nerve fibers and get participants to report tactile sensations related to the stimulation (e.g., Lederman & Klatzky, 2009).

Thermal Subsystem

In addition to the mechanoreceptors, there are thermal receptors all over the skin. The main function of the thermal receptors is body temperature regulation as well as avoiding unpleasant and harmful thermal stimulation (e.g., Stevens, 1991). Therefore, thermoreceptors provide information mainly related to the spatial summation of the temperature (i.e., stimulation of distinct thermoreceptors located in different areas of the skin), thus resulting in perception of the quantity of the temperature. The spatial summation of temperature has been tested frequently by, for example, providing heating or cooling stimulation to different body sites and asking participants to report when they can feel the stimulus, showing that when a stimulated area increases in size the perception threshold decreases (e.g., Hilz, Stemper, Schweibold, Neuner, Grahmann, & Kolodny, 1998). Temporal information and information related to the exact stimulus location are not mediated well via temperature alone (e.g., Stevens 1991). If someone feels heat in, for instance, their forearm area, it is rather difficult to localize exactly the area where the heat is felt and for how long. Interestingly, from a biological perspective, thermal sensations have been linked to the hedonistic aspects of the temperature: whether the temperature perceived is pleasant or unpleasant. This process enables thermoregulation of the body. For example, unpleasant experiences related to cold signal people to, for instance, stay in a hot shower for a relatively long period of time (Stellar, 1982).

Thermal sensations can be seen to be bipolar in a sense that there are both cold detecting receptors and warm detecting receptors in the human skin. The amount of cold receptors is higher than the amount of warm receptors so that their relationship is roughly 30:1. Cold receptors react to decreases in temperature in the range from 43°C to 5°C (Jones & Berris, 2002). Discharge is most vigorous at skin temperatures around 25°C. The conduction velocity of cold receptors is 10-20 m/sec (Darian-Smith, 1984). Thermal nocireceptors activate when skin temperature decreases to 15-18°C or below (Jones & Berris, 2002). However, it takes a while for cold pain experience to occur as the freezing of tissue takes time.

Warm receptors discharge to temperature increases up to 45°C (Stevens, 1991). Warm receptors have a conduction velocity of 1-2 m/sec (Darian-Smith, 1984). The threshold for pain experience is often said to be at 45°C (e.g., Heller & Schiff, 1991), even though external factors like duration of the stimulus can decrease the threshold (e.g., Pertovaara, Kauppila, & Hämäläinen, 1996). Reaction to painful warm stimuli is immediate as warm stimulus can cause instant damage to tissue. Therefore, exposure to too warm stimulus can trigger immediate withdrawal of the affected part of the body.

In addition, when the skin temperature is 30 to 36°C, there is a spontaneous firing of both warm and cold receptors (Jones & Berris, 2002). Therefore, the perception of the temperature in this range is neutral. However, outside the neutral zone continuous discharge is always limited to one class of thermoreceptors, cold or warm.

Finally, similarly to tactile sensations, thermal sensations are also affected by age, gender, body area, and the temperature itself (i.e., whether the stimulation is cold or warm). In a study by Harju (2002), the participants were divided into one of four groups by their gender and age (i.e., 20 to 30 or 55 to 65 years old). The results showed that, in general, the differences between the groups were complex. For example, the perceived intensity of the stimulus at knee areas was reported as higher by younger than older men. Also, elderly women reported higher intensities for the stimuli than elderly men. There were no significant differences between female and male participants in the younger participant group.

IN SUMMARY

Touch is a complex sense that can mediate a wide variety of different sensations. It provides information about only those objects near us. The somatosensory system is responsible for detecting haptic stimulation (i.e., cutaneous and kinesthetic input) from the environment. The functioning of the somatosensory system begins at skin level where receptors detect external stimuli related to, for example, mechanical vibration or temperature. The information from the skin is projected to the spinal cord and from there to the brain areas responsible of processing tactile and haptic information. The most important brain area for processing haptic stimulation is the somatosensory cortex. The somatosensory cortex interacts with the auditory cortex. From the point of view of the current thesis, tactile and thermal sensations are most important. Both subsystems have their own receptors as well as unique properties. For example, they work best at detecting different qualities of stimulation. Thermoreceptors work well in estimating the quantity of the stimulation, while mechanoreceptors can accurately detect the location of mechanical stimulation.

3 Haptic Technologies

Haptic technologies stimulate the sense of touch by applying, for example, force, vibration, movement, or temperature to the user. The devices used to produce haptic sensations can vary from rather complex systems (e.g., providing friction and movement together with thermal sensation) to simple mechanical vibrations (e.g., the vibration of a mobile phone). Haptic technology has high potential in scientific research of the sense of touch as it enables the accurate creation of computer-controlled stimulation (e.g., Hayward, Astley, Cruz-Hernandez, Grant, and Robles-De-La-Torre, 2004). Next, the technologies used in the current thesis are described in more detail.

3.1 VIBROTACTILE STIMULATION

Vibrotactile stimulation is the most commonly used method to stimulate the sense of touch (see Figure 3). It is commonly used in, for example, mobile phones to provide a vibration when the phone is ringing. It can be either localized (i.e., vibration stimulates only a small area of skin) or general so that the entire device is vibrating. Vibrotactile stimulation stimulates mechanoreceptors (mostly Pacinian corpuscles). Mechanical sound is often related to vibrotactile stimulation.

Vibrotactile stimulation is normally produced with vibrotactile transducers, which transfer electrical signals into vibrations produced by a motor (see, for example, http://www.atactech.com). For example, C2 actuators are driven by electrical current. When the motor driving is on, weight located inside the actuator moves downwards and when it is off, the weight moves upwards. The vibration is produced when the motor is driven on and off constantly. Another example of vibrotactile actuators are piezoelectric motors (e.g., http://www.aito-touch.com). They make use of convert edpiezoelectric effect. This means that piezoelectric motors produce acoustic or ultrasonic vibrations, thereby creating a linear or rotary motion.

Figure 3. A picture of a prototype capable of producing vibrotactile stimulation used in the current thesis. One vibrotactile actuator is embedded inside the device and two are on the surface of both sides.

3.2 FRICTION

Friction is a force resulting from the movement of two contacting objects. Friction has been produced by the user through a wide variety of methods (see Figure 4). Friction is often used in conjunction with, for example, force feedback (see, for instance, Oakley, McGee, Brewster, & Gray, 2000; Oakley, Adams, Brewster, & Gray, 2002) to present more realistic sensations of an environment or an object. In many studies, specifically created friction-based prototypes have also been used (e.g., Hayward & Cruz-Hernandez, 2000; Kildal, 2011; Meyer, Peshkin, & Colgate, 2013). These prototypes have been used mostly to study haptic sensitivity (e.g., capability to utilize textures while drawing). In addition, commercial applications in, for example, medical science can be found. For instance, a needle punctuation prototype by Gorman, Krummel, Webster, Smith, and Hutchens (2000) provided a sensation of surface friction on a skin layer with a force feedback device.

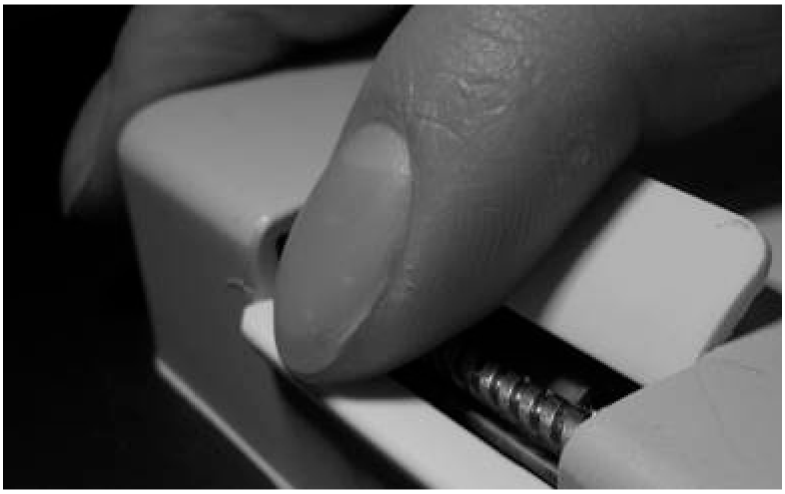

Figure 4. A picture of a friction-based prototype used in the current thesis.

3.3 THERMAL STIMULATION

Thermal stimulation is most often produced by utilizing Peltier effect-based prototypes (see Figure 5). Peltier effect refers to the creation of a temperature difference at the junctions of two dissimilar conductors in contact when a DC current passes through. Depending on the direction of the current, one side of the Peltier warms up and other side cools down (e.g., Jones & Ho, 2008). Therefore, with actuators that utilize the Peltier effect it is possible to produce both warm and cold stimuli which then activate either cold or warm receptors in the skin. Unlike vibrotactile stimulation and friction, thermal stimulation is silent.

Thermal stimulation is not often used in consumer products. However, the scientific community has during recent years become interested in studying how thermal stimulation could be utilized in the field of HTI despite some challenges related to the utilization of thermal feedback both in research and applications. Most of these challenges are related to the fact that thermal sense has good spatial summation but poor spatial acuity. For example, dense arrays of thermal actuators do not provide extra benefit to the user unlike dense arrays with vibrotactile actuators. Therefore, the amount of information that can be provided via thermal actuators is more restricted than the amount of information that can be provided via, for example, vibration or friction (Jones & Ho, 2008).

Figure 5. Peltier disk used in the current thesis.

IN SUMMARY

A wide variety of methods have been developed to artificially stimulate the human sense of touch. The most commonly used method is vibrotactile stimulation. However, other methods like force feedback, friction, skin stretch, and thermal stimulation have also been gaining attention from the scientific community. From the perspective of experimental research, many haptic technologies suffer from the fact that they also produce auditory signals. So, in order to investigate responses related purely to haptic stimuli, the auditory signals need to be blocked.

4 Utilizing the Sense of Touch in Human-technology Interaction

4.1 Research and Applications Considering Haptic-only Stimulation

The research related to haptics started to develop during the 1970s. The main focus of the studies in that era was the sensitivity of the sense of touch. Articles on, for instance, tactile pattern recognition (Loomis, 1981) and the tactile perception of surface roughness (Taylor & Lederman, 1975; Lederman, 1974) were published. One study on tactile acuity showed that the sense of touch can make as accurate spatial discriminations as the sense of vision (Loomis, 1980). Some studies noted the effect of skin temperature on the perception of stimulus roughness (Green, Lederman, & Stevens, 1979) as well as the role of the auditory component related to haptic stimuli by comparing haptic, haptic auditory and auditory only stimuli (Lederman, 1979).

In those days, mostly vibrotactile actuators were utilized to provide tactile sensations to the user (e.g., Lederman, Loomis, & Williams, 1982; Loomis, 1974). For instance, Loomis studied how easily letters could be recognized when presented to the back of the participant with a 20 x 20 matrix of vibrotactile actuators. He found out that, in general, participants were able to recognize letters with an overall accuracy rate of 34% (Loomis, 1974). This was one of the first studies on how easily people can recognize haptically mediated short messages.

Despite this early interest in the topic, for years haptics remained a key interest for only a small group of researchers, notably in the fields of computer science and HTI. Only during the last few decades has the amount of publications related to haptics grown enormously. Modern actuators enable the production of a wide variety of haptic sensations. The use of haptics in modern products varies from proving a vibration when a phone is ringing to force feedback imitating the resistance of a real steering wheel when playing a driving game. From a scientific point of view, haptics has proven to be relatively useful in human-computer interaction. Similarly, as in the early studies, haptics is today mostly used to mediate meaningful cognitive information to users. Next, some areas of research related to mediating cognitive information via haptics are introduced.

Until a few years ago modern technological applications (e.g., touch screens and remote controls) lacked the immediate haptic feedback familiar from, for instance, old radios and old remote controls (Rovers & Essen, 2006). Studies have, however, shown that adding a simple haptic feedback to touch screen devices both improves the measured performance (e.g., less typing errors and faster typing) as well as the experience of the user, so that the users evaluate devices with haptic feedback as being much more pleasant to use than the devices without haptic feedback (Koskinen, Kaaresoja, & Laitinen, 2008; Hoggan, Brewster, & Johnston, 2008; Kaaresoja, Brown, & Linjama, 2006). Also, the design of feedback has effects on the interaction with the device. A study by Lylykangas, Surakka, Salminen, Raisamo, Laitinen, Rönning, and Raisamo (2011) showed that varying the delay of feedback and the duration of feedback clearly affected the users' preference for feedback so that the participants preferred short feedback when the delay was short and long feedback when the delay was long. Thus, it is not surprising that haptic feedback in commercial applications like mobile phones has gained popularity during recent years.

Several studies have also shown that more complex and meaningful cognitive information can be presented to the users successfully via the sense of touch. As touch is an intimate modality, personal information could be mediated to the user privately via the sense of touch. An obvious use for haptics is targeting information collected to help special user groups. It is rather easy to understand why, for instance, the visually impaired can benefit from haptic representation of written text. In fact, several applications to help visually impaired people have been developed and tested. In a review article by Brewster, Wall, Brown, and Hoggan (2007), tactile displays created to help visually impaired users were described in detail. Most of the displays used to present Braille characters required an additional device (i.e., a portable pin array) to be attached to a computer (see, for example, Summers & Chanter, 2002). Technological progress has even enabled visually impaired users to use their mobile phones to present Braille without any additional hardware. In one study

(Rantala, Raisamo, Lylykangas, Surakka, Raisamo, Salminen, Pakkanen, & Hippula, 2009), the authors created a touch screen application capable of producing Braille characters for the users. Their results showed that the participants were able to recognize all the letters presented to them with an accuracy of over 90%.

The use of haptics is not limited to special user groups. One of the most well-known examples of mediating cognitive information to participants via haptics are so called tactons (Brewster & Brown, 2004; Brown, Brewster, & Purchase, 2005; Brewster & King 2005; Brown, Brewster, & Purchase, 2006). Tactons can be briefly described as haptic icons. In computer science, icons are traditionally defined as pictures on the screen that represent, for example, a certain file or a computer program. Tactons represent meaningful information to the user via the sense of touch. Studies have shown that by varying stimulus parameters (e.g., frequency, rhythm, and amplitude), participants are able to recognize a wide variety of tactons. For instance, in mobile phone contexts, tactons have been used to inform the user about whether the user is receiving an incoming call or a text message, and whether the message is urgent or not. The users have been able to recognize these messages with an accuracy of above 70% (Brown & Kaaresoja, 2006). Enriquez and MacLean (2008) went one step further. They let the participants decide the meaning of the haptic icons by themselves so that the participants were presented 20 varying vibrations and they had to decide which of them represented, for example, turning right or left. After two weeks of the learning, the participants were still able to recall the meanings of the icons with an average accuracy of 86%. Taken together, it seems that haptic icons are relatively easy to learn and later recall.

An interesting question is, however, whether tactile messages can present meaningful information to the users without any learning or teaching. In two previous studies (Lylykangas, Surakka, Rantala, Raisamo, Raisamo, & Tuulari, 2009; Lylykangas, Surakka, Rantala, & Raisamo, 2013), the participants were not taught the meaning of vibrotactile icons before presenting them. Despite this, the participants interpreted ascending vibrotactile frequencies as "increase speed", static vibrotactile frequencies as "keep speed constant" and descending vibrotactile frequencies as "decrease speed" with an accuracy of over 70%. These results show that it is possible to create tactile messages that users can interpret at least somewhat intuitively. Thus, to some degree at least, it is possible to use haptics to mediate information without explicit teaching.

Despite the emerging popularity of research on haptics in general, thermal displays are rarely studied. Only few studies have shown that meaningful information can be presented via thermal sense alone. In the previous studies, mostly the thermal properties of object surface materials (e.g., wood or steel) have been presented to the participants (Ho & Jones, 2006; Ho & Jones, 2007; Jones & Ho, 2008). The results have shown that different surface materials can be recognized relatively well based on only their thermal properties. Recently, some studies (e.g., Halvey, Wilson, Vazquez-Alvarez, Brewster, & Hughes, 2011; Wilson, Halvey, Brewster, & Hughes, 2011) have researched the potential for providing thermal stimulation in mobile contexts. The results are encouraging as they clearly show that people are able to discriminate small temperature changes (e.g., 2°C) while walking in the office or outdoors. However, in spite of this recent interest in utilizing thermal sense in the field of HTI, it is not yet known how detailed information can be mediated to the user via thermal sense. A significant step in this direction has been taken in two studies (Wilson, Brewster, Halvey, & Hughes, 2012; Wilson, Brewster, Halvey, & Hughes, 2013), which have studied how well people can understand thermal icons. For example, cool and strong stimulation implicates that person is working and the issue is important while warm and strong stimulation means that the message is personal yet important. The results were promising as the identification of individual parameters was as high as 94%. In addition, environmental conditions like humidity or outdoors temperature affected the ability to detect thermal stimulation. For example, an optimal environmental temperature range to sense thermal stimuli seems to be around 15 to 20°C (Halvey, Wilson, Brewster, & Hughes, 2012).

The studies described above provide only a small sampling of the vast amount of studies related to haptics. In addition, haptics has been used, for example, to provide navigational information to the users (e.g., van Erp 2000; Lylykangas, Surakka, Rantala, & Raisamo, 2009), to present numbers in touch screen environments (e.g., Pakkanen, Raisamo, Salminen, & Surakka, 2010; Pakkanen, Raisamo, & Surakka, 2012), to aid the elderly in interaction with mobile devices (e.g., Stößel & Blessing, 2010), to provide information to the pilot in the cockpit (Henricus, van Veen, & van Erp, 2000), and to indicate turn-taking processes while playing computerized games (Hoggan, Trendafilov, Ahmaniemi, & Raisamo, 2011). Thus, researchers in the HTI field with various interests seem to be intrigued by the idea of adding haptic feedback or alerts to the devices or user interfaces. The field considering haptic stimulation has yielded four conferences (namely, Haptics Symposium, EuroHaptics, AsiaHaptics, and World Haptics) and even has its own IEEE journal called *Transactions on Haptics*. Therefore, it is not an overstatement to say that, since the 1970s, haptics has become an important field in computer science and HTI.

4.2 Research and Applications Considering Multimodal Stimulation

The utilization of the sense of touch has also been studied in conjunction with other senses. In real user cases, it can be reasonable to provide information via several senses. For example, in a noisy environment auditory messages can easily go unnoticed. Similarly, in a trembling environment (e.g., on a train) vibrotactile messages may not be effective (Hoggan, Crossan, Brewster, & Kaaresoja, 2009). From scientific point of view, studying haptics in conjunction with other senses seems intriguing. Most commonly, haptic stimulation has been paired with visual stimuli, for example, pictures of faces. However, as there seems to be a strong integration and overlapping of auditory and tactile senses in the brain areas (e.g., Foxe, Wylie, Martinez, Schroeder, Javitt, Guilfoyle, Ritter, & Murray, 2002), it can be assumed that pairing haptics with auditory stimulation can provide more interesting scientific results. This can also be useful from the application point of view since most current haptic technologies produce a clearly hearable sound. The following chapter gives an overview of both the use of auditory and haptic stimuli in HTI and the functioning of haptic-auditory perception.

In HTI, auditory and haptic stimuli have often been used to mediate cognitive messages (e.g., errors or warnings). For example, in one previous study information related to, for example, errors (e.g., no battery power) and the type of message (e.g., SMS received) was presented to the participants using visual icons (Hoggan, Kaaresoja, Laitinen, & Brewster, 2008). Then, the participants were able to select a suitable auditory and haptic stimulus they considered to best correspond to the visual icons. The results suggested that the participants preferred either tactile or audio-tactile modality to provide the information. In addition, the results showed that the parameters chosen to best map the visual information were similar with all the modalities. For example, short rhythms were preferred to provide confirmations and fast tempo error messages independent of the modality used. In another study, a prototype named Shake2Talk (Brown & Williamson, 2007) converted hand gestures and audio (e.g., tapping the phone and the sound of tapping to a wine glass) to meaningful messages (e.g., "call when you can"). In a user evaluation test it was found that combinations of these audio-tactile messages were successfully used, for example, to send emotionally meaningful messages (e.g., purring heartbeats to mediate emotional affection). Thus, previous studies suggest that using haptics simultaneously with audio can help the user perform better as well as to enjoy the application more.

It is not surprising that the field of HTI can benefit from haptic-auditory interactions. From a neuroscientific point of view, it is widely recognized that auditory stimulus can modulate the perception of haptic stimulus and vice versa. The synchrony of the two modalities seems to be one important factor effecting this perception. A study by Jousmäki and Hari (1998) revealed an interesting phenomenon named parchment-skin illusion. This means that, when a sound is exactly synchronous with hand-rubbing, high frequency sound can make the skin feel paper-like and crispy when rubbing the hands together. Wilson, Reed, and Braida (2009) studied the perception of 500 ms long 250 Hz frequency auditory and haptic stimuli. The participants were able to detect both auditory and haptic stimulus components best when the stimuli were presented in synchrony. Gilmeister and Eimer (2007) made two studies on the synchronization of the two modalities. In their first experiment, the task was to rate the loudness of an auditory stimulus. The auditory stimuli were rated as significantly more intense (i.e., louder) in the presence of synchronous tactile stimulation than in the presence of asynchronous tactile stimulation. In their second experiment, the participants' task was to detect an auditory stimulus near the perceptional threshold. A tactile stimulus was always presented in the stimulus trial and the auditory stimulus in half of the trials. The results showed that synchronous tactile stimulus significantly improved the error-free detection rate of the auditory stimulus. Bresciani, Ernst, Drewing, Bouyer, Maury, and Kheddar (2005) tested whether auditory beeps can modulate the tactile perception of sequential taps. Either two or four tactile taps were presented to the participant in each sequence. The number of auditory taps was either less than, the same, or more than the amount of tactile taps. The amount of auditory taps modulated the perception of the amount of tactile taps, but only when the auditory and tactile stimuli were similar enough. Control beeps that differed in duration with tactile taps had no effect on the reported amount of taps. In their second experiment, it became evident that the stimulus synchrony was the most important parameter effecting the perception of tactile taps. Only, when the auditory beeps were presented simultaneously with tactile taps did they affect the perception of the number of the taps. When there was temporal asynchrony between the auditory beeps and the tactile taps, the amount of auditory beeps had no effect on the reported number of perceived tactile taps.

In addition to stimulus synchronization, it is recognized that the frequency of the audio-tactile stimulus can affect the perception. Ro, Hsu, Yasar, Elmore, and Beauchamp (2009) showed that auditory stimuli can help the detection of near-threshold tactile stimulus. In their three experiments, it was determined that simultaneous auditory stimulus improved the detection rate of the tactile stimulus, especially when located on the same side of the tactile stimulus and presented in same frequency. Yau, Olenczak, Dammann, and Bensmaia (2009) showed that auditory stimuli can affect the perception of tactile frequency. Their results showed that auditory stimulus can impair the detection of tactile stimulus only when the frequency of the auditory and tactile stimulus is the same. However, this effect was only evident for tasks where the participant had to discriminate between two tactile stimuli based on their frequency. The participants were still able to discriminate between the two tactile stimuli based on their respective intensities. In their second study (Yau, Weber, & Bensmaia, 2010), the roles of the modalities were switched. The results showed that the tactile component affected the discrimination of the auditory stimulus based on both its frequency and intensity. According to the authors, based on the differences between the results in the two studies, it can be argued that tactile and auditory stimuli are combined differently depending on the perceptual task and that, therefore, it seems that auditory and tactile signals in pitch and loudness are mediated via separate neural channels. A study by Wilson, Reed, and Braida (2010) also showed that perception of auditory loudness was heavily affected by tactile stimulation. The participants' task was to detect the level of auditory loudness when the frequency of the auditory stimulus and simultaneous tactile stimulus were varied. The matching of the auditory loudness was worse when the audio-tactile stimuli were close in frequency than when they were separated by an octave or more. This seems to reflect a strong frequency relationship between the auditory and somatosensory systems.

The effect of the stimulus synchrony and other parameters on the perception of the stimulation reflects a view called an assumption of unity (Welch & Warren, 1980). In short, this means that the brain considers multimodal information as coming from the same object or event only if it shares enough amodal properties. Therefore, the integration of the signals at brain level only happens when the stimuli are similar enough. Most important of these stimulus properties is temporal coincidence. Temporal lags in synchrony remaining under 20 ms, however, can go unnoticed (Vroomen & Keetels, 2010).

Speech can be seen as a special type of auditory stimulation having a unique task in inter-individual communication. It has been used to some degree together with haptic stimulation. Interestingly, the effect of temporal synchrony has also been found in speech perception. Sato, Cavé, Ménard, and Brasseur (2010) studied how manual exploration of speakers' faces effects the perception of syllables. The tactile information received from the face area was either congruent (i.e., synchronous) mouthing, incongruent (i.e., asynchronous) mouthing or no mouthing at all. The participants' task was to perform a forced-choice syllable decision task in which the syllables were either accompanied by additional noise or not. When the tactile information was synchronous with auditory syllables, the amount of correct responses was higher than when the tactile information was asynchronous or there was no tactile information. In addition, speech has been tested in conjunction with several prototypes. Chang, O'Modhrain, Jacob, Gunther, and Ishii (2002) converted the squeezing of pressure-sensing sensors to vibrations similar in, for example, timing to complement speech. Their results showed that the participants used tactile stimulation to emphasize important parts of spoken messages and indicate turn-taking. In general, the authors argue that their results showed that the participants were able to use tactile stimulation in conjunction with speech to transfer meaningful information.

Due to the special nature of thermal sensations (e.g., poor spatial acuity and the ability to discriminate mostly the quantity and direction of the stimulation), thermal displays for multimodal environments are not frequently tested or developed. According to Jones and Ho (2008), thermal displays are used in virtual environments to create a greater sense of realism or "presence" in the simulated environment. The testing of prototypes like Thermopad (Dionisio, Henrich, Jakob, Rettig, & Ziegler, 1997), Lovelet (Fujita & Nishimoto, 2004), and Homere (Lécuyer, Mobuchon, Mégard, Perret, Andriot, & Colinot, 2007) suggest that thermal cues can enrich the user's experience in multimodal virtual environments, for example, by imitating heat coming from a fireplace. Interestingly, one recent study has researched speech in conjunction with thermal stimuli. Suhonen, Väänänen-Vainio-Mattila, & Mäkelä (2012) investigated user experiences of vibrotactile stimulation, squeeze, or thermal stimulation delivered together with speech. Although the results, in general, showed that squeeze was preferred over vibrotactile or thermal stimulation, they also showed that, for instance, strong cold or warm thermal stimuli were easy to notice. However, it is still not conclusively known how essential or effective production of thermal sensations can be in multimodal environments.

In Summary

A mass of studies have concentrated on researching human responses to haptic and haptic-auditory stimuli. The previous studies have concentrated on mediating cognitive information to the user, studying tactile sensitivity, or mapping intermodal interactions in cognitive processing. It can be argued that various kinds of information can be successfully presented via the sense of touch. In general, the results seem to show that haptic only stimuli work well even in mediating rather complex information to the user. In addition, there is a strong interaction between haptic and auditory modalities, which can affect the cognitive processing of the information provided by either of the modalities. Previous studies suggest that adding haptic components to applications can have positive effects to the users' performance and experiences. When designing research or applications with both aural and haptic properties, these effects should be taken into consideration as they can affect user perception and behavior. Therefore, it is not surprising that research in this field is still emerging and so provides continuously meaningful and applicable results to the scientific community.

5 Human Emotions

5.1 What Are Emotions

The human emotions have intrigued scientists for decades. One of the early significant attempts to describe human emotions in a scientific manner was the book *The Expression of Emotions in Man and Animals* by Charles Darwin (1872). Darwin considered human emotions to be a fruitful line of research. To him, the main focus of interest in emotions was the evolutionary development of emotions. His work can be considered as one of the starting points for the scientific study of emotions.

During recent decades, both neuroscience and other fields of psychology have developed a significant interest in scientific research concerning emotions. In the field of neuroscience, the role of the limbic system and especially the amygdala has intrigued scientists as a source of processing emotions (LeDoux, 2000). For example, music-evoked emotions can activate those brain structures linked to the processing of emotions (Koelsch, 2014). Emotions are also often linked to responses visible in the human face and body. Several researchers think that facial expressions can convey emotional valence and even distinct emotions like fear or anger (Ekman, 1971). Bodily expressions (i.e., body postures and movements) have been closely linked to emotions and especially to the intensity of the experienced emotion (Wallbott, 1998). There seems to be quite a strong body of evidence suggesting that all kinds of emotions can activate the autonomic nervous system of humans (e.g., Anttonen & Surakka, 2005; Kreibig, 2010). In addition, several studies have collected qualitative reports and ratings concerning the subjective emotions experienced in relation to certain stimuli or even daily events (e.g., Bradley & Lang, 1994). Even debate about the naturalness of emotions (i.e., whether emotions can exist without our conscious perception of them) has been discussed

(Barrett, 2006). Thus, the field has expanded from philosophical discussions into an intriguing and fascinating field capable of explaining human behavior in detail.

Even though emotions have been widely studied for decades, the definition of the concept of "emotion" is at best ambiguous. In 1981, Kleinginna and Kleinginna collected 92 definitions of the word "emotion" from scientific journals and books. According to them, the explanations of emotions were divided into 11 categories including, for example, definitions of emotions concentrating on subjective experience, cognitive processes, and behavior. A more recent study by Izard (2010) showed that there is still no conclusive definition of the concept of emotion accepted in the scientific community. He collected a data set from 35 distinguished scientists specializing in emotions. His results showed that emotion cannot be defined as a unitary concept. However, there was considerable agreement about the structures and functions of emotions. According to the results, emotions consist of neural circuits, including personal experience or feeling, and have perceptual and cognitive aspects. The feelings or states related to emotions are used to organize human cognition and action. Consciously experienced emotion provides information about, for instance, cognitive evaluation related to the emotional state and the environment. Emotions can also help people to understand social and emotional signals as well as motivate approach/avoidance behavior.

Therefore, Izard (2010) suggests that, when writing scientific text on emotions, it is crucial to conceptualize the word "emotion" to the reader. Most of the research related to emotions has adopted either a discrete or dimensional model of emotions that helps to conceptualize the theoretical background in more detail. The current work is no exception, as the dimensional framework has been utilized in all the studies included in the thesis. These two approaches are clearly distinguishable, but can still be seen as complementing each other. In the following two sections, both of the approaches are described in more detail.

5.2 Discrete Model of Emotions

The discrete model of emotions is based on the idea that there is a set of emotions that are distinct states. Thus, for example, anger, joy, and fear are their own emotional categories with unique physiological, expressive (i.e., behavioral) and experiential properties. These emotional categories are named after adjectives in common language. Even though most theorists argue that the number of the most fundamental emotions is somewhere between six and nine, when collecting lists of emotional labels from laypersons the amount of distinct words describing emotions goes up to 383 (Fehr & Russell, 1984). Therefore, it is not surprising that a great deal of variation in defining what distinct emotions exist is found between researchers representing the discrete approach.

According to the discrete model of emotions, emotions can be somewhat prioritized. The most important emotions are often referred to as basic, primary, or fundamental emotions. Depending on the theorists, the amount of the basic emotions can vary from two (Mowrer, 1960) to eighteen (Frijda, 1986). In an article by Ortony and Turner (1990), 14 different theories of basic emotions were reviewed. According to them, even though the variation in defining the fundamental emotions may seem at first almost chaotic, there are also several agreements among different theorists. For example, most theorists include anger, happiness, sadness, and fear in their list of basic emotions. However, this does not fully eliminate the confusion rising from the different lists of fundamental emotions. Ortony and Turner (1990) point out that perhaps a satisfactory criterion for what makes basic emotions basic cannot be defined.

Despite the lack of clarity in terms of defining basic emotion, several theorists have taken a systematic approach to the issue. Paul Ekman is one of the most distinguished theorists in the field of discrete emotions. He has formulated a theory of six (or in some contexts seven) basic emotions. Like Darwin, he argues that these basic emotions are biological in nature, thus provided to us by evolution (Ekman, Davidson, & Friesen, 1990). These basic emotions are anger, fear, sadness, enjoyment, disgust, and surprise. In addition, he has twelve candidates for possible basic emotions. His theory assumes that basic emotions are universal, and therefore can be found in all existing cultures.

Ekman (1994; 1999) also answered the criticism of Ortony and Turner (1990) and Russell (1994) by developing a theory of 11 characteristics that can be used to define basic emotions. These characteristics involve distinctive universal signals (e.g., expressions), distinctive physiology, distinctive universals in antecedent events, presence in other primates, coherence among emotional responses, quick onset, brief duration, automatic appraisal, unbidden occurrence, distinctive thoughts, memories and images, and distinctive subjective experience. Further, Izard (1992) argues that basic emotions can be defined by the fact that they have biological and social functions essential for adaptive behavior and evolutional survival.

Theorists favoring the discrete model of emotions have collected evidence to support the theory of basic emotions. The human face can express several emotional cues like anger and surprise, and these facial behaviors seem to be consistent between different cultures (Ekman & Oster, 1979; Ekman, 1992a). Also, some physiological changes such as finger temperature decreasing less in anger than in fear have been observed in different cultures (Levenson, Ekman, Heider, & Friesen, 1992). Finally, there is some evidence that even animals may express some of these so called basic emotions, like fear (see Ekman, 1992b, for a review).

But when the previous body of evidence is reviewed systematically, how well can the theory of basic emotions be established scientifically? Mauss and Robinson (2009) have argued that there is little if any evidence supporting the discrete approach to emotions. They collected over 200 papers measuring emotional responses in terms of self-reports, autonomic nervous system responses, startle response magnitude, brain state, and behavior. Their review showed that, even though theorists argue that each discrete emotion has unique experiential, physiological, and behavioral correlates, the previous studies could not verify this assumption. Only observed facial behavior and observed whole body behavior were identified as able to show some emotional specificity in this extensive review of previous literature. The review thus seems to confront the common claim that discrete emotions would be categorically differently from one to another. This is in line with a notion by Posner, Russell, and Peterson (2005). They argue that basic emotions are a result of learning and therefore are not pre-determined by biological mechanisms at birth.

Taken together, it seems that the discrete model of emotions has several weaknesses. Even after decades of research, there is no definitive answer to the question of how many distinct emotions exist and what these emotions are. The theorists have not been able to explain how much these distinct emotions overlap. It can be assumed that distinct emotions like anger and fear share at least some common physiological, behavioral, and experiential properties. And last but not least, the recent review by Mauss and Robinson (2009) showed that there is little evidence supporting the discrete approach. The authors take a strong view, stating that discrete emotions are only salient combinations of often used emotional dimensions.

5.3 Dimensional Model of Emotions

The dimensional model of emotions does not view emotions as distinct states but rather as overlapping dimensions in human emotional space. This approach was first introduced by Wundt (1896), who felt that it is impossible to come up with an organized list of emotions as they blend too much. Instead, he suggested that three dimensions, namely Lust (pleasure or valence), Erregung (activation or arousal), and Spannung (strain or tension) would better capture the complex nature of human emotions. Wundt's dimensional view was further developed by Harold Schlosberg (1954) in his activation theory of emotions. He viewed emotions as the primary activation system of a human being consisting of pleasantness – unpleasantness, attention – rejection, and level of activation.

The first attempt to validate the dimensional model of emotions was made by Osgood (1952). His method of semantic differential used factor analysis to determine factors related to human emotions. According to him, several human emotions can be reduced to the three factors of valence, arousal, and dominance. Mehrabian continued this approach by finding similar dimensions underlying, for example, facial expressions of emotions (1970). Later, Mehrabian and Russell (1974) found further evidence to support the dimensional approach. Their so called PAD-modal (pleasantness, arousal, and dominance) was built from a set of 18 bipolar adjective pairs (e.g., unhappy – happy and sleepy – wide awake) rated along a 9-point scale (Mehrabian & Russell, 1980). A factor analysis showed that these 18 pairs could be reduced to the three previously discussed emotion-related dimensions.

Currently, Bradley and Lang (e.g., Bradley & Lang, 1994; Bradley & Lang, 2000) are the most famous advocates of the dimensional model of emotions. Their theory suggests the same three core dimensions introduced by Osgood (1952) and Mehrabian (1980). In the center of all the dimensions lies the neutral zone, which means that the obtained event is neither pleasant nor unpleasant. The dimension of valence varies from negative emotion to positive emotion (i.e., from unpleasant to pleasant), arousal varies from calm to exited or aroused (i.e., reflecting the state of emotional activation), and dominance varies from the feeling of being controlled to the feeling of being in control (i.e., reflecting the social dominance related to the emotion-evoking event).

The dimensions of valence and arousal are still seen as capturing most of the functioning of the human emotion system. Both physiological and experience-related data seems to support the view that these two factors account for the vast majority of observed variation in emotions (see, for example, Mauss & Robinson, 2009). There is evidence that these two dimensions are found at the brain level and that they both have unique neural networks (Colibazzi, Posner, Wang, Gorman, Gerber, Yu, & Peterson, 2010). The third dimension of dominance has also been usable in the field of emotion research. Dominance can track down the subject's feeling of control in the situation, therefore providing information on the interactive relationship between the perceiver and the object (Bradley & Lang, 1994).

Some theorists have also argued that a fourth dimension, namely approachability, exists and can be measured. Approachability is considered to reflect the motivational system underlying the core dimensions of valence and arousal. This dimension varies from avoidable to approachable. It is argued that, from an evolutionary perspective, emotions should prepare the individual to either approach a positive object or event (e.g., food or sexually interesting mating partner) or avoid a negative one (e.g., threat or pain). During recent years, several studies have taken this fourth dimension to be explicitly measured (e.g., Surakka, 1998; Anttonen & Surakka, 2005). In addition, measurements of the central nervous system (e.g., EEG and fMRI) have shown that brains may activate differently in respect to approach and withdrawal tendencies. For example, the frontal EEG asymmetry reflects the relative balance of avoidance and approach better than the dimension of valence (Davidson, 1995).

The review by Mauss and Robinson (2009) seems to strongly support the dimensional framework of emotions in contrast to discrete emotions. All the measurements commonly used in emotion research (e.g., self-reports and physiological activation) well reflect the functioning of the emotional dimensions. According to the authors, "the dimensions appear to capture the lion's share of variance of emotional responses." Even facial behavior traditionally thought to capture the specificity of discrete emotions actually only serves best to measure the dimension of valence.

However, the dimensional model of the emotions does not fully disclose the existence of discrete emotions. The so called circumplex model of affect suggests that the dimensions of valence and arousal form a circular pleasure-displeasure continuum and arousal continuum (Russell, 1980; Russell, Lewicka, & Niit, 1989; Posner, Russell, & Peterson, 2005). Affective experiences are the production of the combination of these two systems. The combination already exists at the neural level. The discrete emotional labels are assigned when the sensations produced by these systems are interpreted.

In the current thesis, the dimensional model of emotions was utilized as it seems to have advantages when compared to the discrete model of emotions in the relevant context. There is only little information available on how computer-mediated touch could relate to any emotions. The dimensional model allows the collecting of systematical yet unambiguous information on the relationship between touch and emotions that can be later used to specify discrete emotions if needed according to, for example, the circumplex model of affect.

5.4 Methods for Measuring Emotional Responses

Emotional responses consist of changes in different levels of human activity including neural, physiological, behavioral, and experiential changes. The processing of emotional information begins at the brain level. The changes in the central nervous system can be measured with electroencephalography (EEG) and other neuroimaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission topography (PET). The physiological changes are often measured as changes in autonomic nervous system (ANS) functioning. For instance, people sweat more during emotionally arousing stimulus presentation than during neutral stimulation (see, for example, Cacioppo, Berntson, Larsen, Poehlmann, & Ito, 2000; Mauss & Robinson, 2009). The behavioral responses are measurements of expressive behavior during the emotion-evoking event. For example, "active" emotions like anger and joy are related to high body movement activity and upward position while "passive" emotions like sadness result in low body movement activity and collapsed position with shoulders forward (Wallbot, 1998). Finally, the experiential changes are conscious conceptualizations arising from the processing of emotions (i.e., subjective experiences related to the emotions). For example, people can report a happy mental state after a stimulus presentation. All of the measurements of emotional responses have both advantages and disadvantages. Changes in human physiology and ANS particularly reflect bodily responses to all kinds of external events. For instance, heart rate can change as a response to physical activity as well as to an emotion-evoking event. Thus, in previous research, generally at least two of these levels have been measured. In the following section, the measurement methods employed in the current work are described in detail.

The subjective experiences of the participants were utilized in all of the six publications in the current thesis. By measuring emotion-related experiences, researchers can gain information on the part of the emotion-related processing that is conscious to the person. However, measuring subjective experiences related to emotions can be challenging. For instance, some people may be unable to conceptualize their emotional experiences in such a manner that would enable the self-reporting of them (Lane, Ahern, Schwartz, & Kaszniak, 1997). To solve these problems, several questionnaires and forms have been developed to aid people in labeling their experienced emotions (e.g., Bradley & Lang, 1994; Scherer, 2005). A promising and validated way to measure emotion-related experiences has been the use of ratings that are directly related to the dimensional theory of emotions. One way to collect these ratings is to use self-assessment manikin (SAM). In SAM participants are given pictures representing the variations in core dimensions of valence, arousal, and dominance (e.g., Bradley & Lang 1994; Bradley, Codispoti, Cuthbert, & Lang). For instance, for the ratings of pleasantness expressions of the manikin in five separate pictures vary from smiling to sad. The participant can place an "x" on any of these figures or between them so that there is a nine-point rating scale for each dimension. However, in many studies an adaptation of SAM has been used so that SAM has been directly converted to nine point bipolar numeric scales (e.g., Anttonen & Surakka, 2005).

After a stimulus presentation, a participant is given nine point rating scales reflecting the dimensions of valence (varying from pleasant to unpleasant), arousal (varying from calm to aroused), and dominance (varying from being in control to being controlled) (Bradley & Lang, 1994). In addition, the approach-avoidance tendency can be measured with a scale varying from avoidable to approachable (Anttonen & Surakka, 2005). The most valid way to measure emotional experiences is to ask for the ratings or opinions straight after the emotion-evoking event (Robinson & Clore, 2002). There is evidence that the longer the time-lag between the actual event and the self-report, the more biased the content of the report is, especially with female participants (Barrett, Robin, Pietromonaco, & Eyssell, 1998). Therefore, when designing experiments related to emotions, the measures of emotional experiences should be delivered to the participant immediately.

The behavioral response measurements utilized in the current thesis were reaction times and discrimination tasks. Reaction time measurements seem to reflect the level of stimulus arousal well. In general, stimuli rated as arousing are reacted to faster than calming stimulation (e.g., Bradley, Greenwald, Petry, & Lang, 1992). Interestingly, there is also evidence that for threat stimuli, the reaction times can actually be shorter (Buodo, Sarlo, & Palomba, 2002). Thus, the results seem to indicate that the attention can be shifted towards arousing or threatening stimuli quickly. Also, discrimination of the stimuli seems to be related to the stimulus arousal. Participants are quicker to detect or discriminate between a group of fear-related pictures like snakes (Öhman, Flykt, & Esteves, 2001), negative facial images (Eastwood, Smilek, & Merikle, 2001) and, in general pictures rated as high in the dimension of arousal (Leclerc & Kensinger, 2008).

Finally, physiological measurements in the current thesis included ANS responses. The functioning of ANS is largely involuntary and thus can be seen as somewhat involuntary or unconscious and therefore uncontrollable responses of the individual. ANS regulates, for example, digestion and attention (Berntson & Cacioppo, 2000) and relates to, for instance, stress level and motor behavior (Obrist, Webb, Sutterer, & Howard, 1970). Therefore, it is quite challenging to view ANS responses as straightforward responses to certain emotional states. However, a strong relationship between emotional dimensions and ANS responses (e.g., elevated level of sweating for arousing stimulation) can be found, which suggests that at least some ANS activity is closely related to the functioning of the human emotion system (e.g., Cacioppo, Berntson, Klein, & Poehlmann, 1997; Mauss & Robinson, 2009; Kreibig, 2010).

In the current thesis, electrodermal measurement (i.e., skin conductance response or SCR) was employed. SCR measures the functioning of the sweat glands, and reflects the activity of the sympathetic branch of the ANS (Lykken & Venables, 1971). Previous reviews suggest that SCR reflects well the activation of emotional arousal (see, for example, Cacioppo, Berntson, Larsen, Poehlmann, & Ito, 2000; Mauss & Robinson, 2009). It increases systematically when the rated arousal of the emotional stimulus increases (Lang, Greenwald, Bradley, & Hamm, 1993). This activation thus seems to be independent of the stimulus valence. Skin conductance can respond to both negative arousal (e.g., threatening event) and positive arousal (e.g., sexually appealing picture). Other frequently used measurements of ANS functioning (e.g., heart rate) also respond to emotionally arousing stimulation (e.g., Mauss & Robinson, 2009).

Interestingly, it has been shown that different measures of ANS activity can work independently or even in opposition to each other. This seems to suggest that at least one other dimension in addition to the dimension of arousal activates ANS response. Cacioppo, Berntson, Larsen, Poehlmann, and Ito (2000) argue that this dimension is valence because, to some degree, the response to negative stimuli tends to be larger than the response to positive stimuli. However, Lang, Bradley, and Cuthbert (1997) suggest that ANS activity reflects the activation of the approach and avoidance system. Therefore, when one aims to understand the data related to the ANS activity, one should also take other dimensions of emotions into consideration.

IN SUMMARY

Even though the concept of emotion is somewhat vague, by adapting a sound theoretical framework it is possible to study human emotions. Most of the modern research in the field of human emotions has adopted either a discrete or dimensional model as a background. The discrete model of emotions suggests that there is a set of several clearly distinguishable emotions that can be described as having unique responses and subjective experiences. The dimensional model suggests that distinct emotions do overlap and that the human emotion system can therefore be best described as a combination of dimensions. The discrete model has some disadvantages that the theorists in the field have not been able to solve. For example, the amount of the most important basic emotions is still to be determined. In addition, recent review data seems to suggest that most of the previous findings support the dimensional model over the discrete one. The emotion-related measurement can be divided in experiential responses, behavioral responses, and psychophysiological measurements. In the current thesis, subjective rating scales of pleasantness, approachability, arousal, and dominance were used to study experiential responses. For behavioral responses, reaction times and differentiation tasks were used. Finally, for psychophysiological measurements, SCR measuring the activation of sweat glands was utilized. This measurement technique should reflect an elevated level of physiological arousal. All measurement techniques have some weaknesses as well as advantages. For example, the change in heart rate can reflect emotional arousal but also high physical activity. Therefore, several measurement techniques are often used in combination.

6 Touch and Emotions

The sense of touch plays a large role in interpersonal relationships and emotions. For example, affection and love are communicated via the sense of touch. Lovers show their feelings to each other by cuddling in intimate settings. On public occasions, hand shaking and sometimes even hugs and kisses on the cheek are shared. The sense of touch starts to develop before birth, and studies on infant development suggest that physical and psychological health in childhood requires tactile stimulation (Montagu, 1986). As early as the 1950s, the research group of Harry F. Harlow (Harlow, 1958; Harlow, Dodsworth, & Harlow, 1965; Harlow & Harlow, 1966; Suomi, Collins, Harlow, & Ruppenthal, 1976) noted that deprivation of monkey babies from their caregiver caused severe and permanent damage to the social and emotional development of the monkeys. For example, monkeys that were raised by a surrogate mother made out of artificial materials turned out to be aggressive and unable to socialize with other monkeys as adults even though they were provided water and food on a regular basis. From his studies, Harlow reached the conclusion that tactile contact and warmth in early childhood are essential for normal socio-emotional development.

Quite a lot of previous work seems to have concentrated on studying tactile communication with nonhuman primates and rats. Etiological studies have shown that monkeys groom each other longer than is strictly necessary from hygienic point of view, suggesting that grooming has a role in the affective and social life of monkeys (Dunbar, 1991). In addition, in non-human primates touch is used to confirm status, sexual relations, and even attachment (see Hertenstein, Verkamp, Kerestes, & Holmes, 2006, for a review). For example, monkey mothers tend to show attachment to their children via touching. Tactile sense and warmth even play an important role in interactions between rats and their puppies (Hofer, 1994).

Therefore, it seems reasonable to argue that emotional touch has developed through evolutionary processes and that the affective functions of touch have biological roots. Graig (2002) suggests that the system for affective touch has developed through evolution to monitor the condition of body tissues and self. From a neural perspective, it is known that the discriminative functions of touch (e.g., spatial and temporal localization, and object recognition) can be separated from the emotional functions of touch (e.g., assessment of pleasantness) (McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). These two types of touch are processed in different brain areas (Francis, Rolls, Bowtell, McGlone, O'Doherty, Browning, & Smith, 1999). Pleasant touch is processed in the neural network including the insula, anterior cingulate cortex, frontal polar cortex, and orbitofrontal cortex (e.g., Rolls, O'Doherty, Kringelbach, Francis, Bowtell & McGlone, 2003; McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007; Kida & Shinohara, 2013). In the brain, there seem to be neurons responding to distinct experiences of, for instance, pain, temperature, itch, and sensual touch (Francis, Rolls, Bowtell, McGlone, O'Doherty, Browning, & Smith, 1999).

The processing of the affective qualities of touch starts from the afferents at the skin level (McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007; Löken, Minde, Wessberg, Perini, Nennesmo, & Olausson, 2011; Löken, Evert, & Wessberg, 2011). The affective functions of touch mediate two types of information, namely pain excluded from the scope of the current thesis and pleasantness of touch (McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). Interestingly, studies link pleasant touch to C-tactile (CT) afferents found all over human non-glabrous skin. The pleasantness ratings of, for example, brush stroking are highest at velocities most effective in activating CT afferents (Löken, Wessberg, McGlone, & Olausson, 2009). The fact that CT afferents are found only on non-glabrous skin does not exclude the capability to evoke pleasant tactile experiences by also manipulating glabrous skin sites like the palm by, for instance, tickling (e.g., Essick, McGlone, Dancer, Fabricant, Ragin, Phillips, & Guest, 2010; McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). According to previous research, it seems likely that A-beta afferents found in the palm and fingers can project towards CT afferents and, therefore, evoke pleasant touch experiences. This has been confirmed by fMRI studies showing activation of the orbitofrontal cortex related to complex emotion-related information processing when the palm area is stimulated (e.g., Francis, Rolls, Bowtell, McGlone, O'Doherty, Browning, & Smith, 1999).

Taken together, the affective functions of touch seem to have a strong evolutionary, neural, and biological basis. Therefore, the area seems to be a fruitful line for scientific research. The following sections review the role of touch in human emotional development, adult interaction, and emotional responses.

6.1 AFFECTIVE AND SOCIAL FUNCTIONS OF TOUCH DURING CHILDHOOD

Tactile contact during early childhood can affect social and emotional functioning. Several previous studies have concentrated on showing the effects of maternal touch on bonding between mother and infant (e.g., Bowlby, 1978; Main & Stadtman, 1981; Anisfeld, Casper, Nozyce, & Cunningham, 1990). Based on the results, researchers have argued that tactile contact between mother and infant is essential for bonding and that a secure attachment relationship between mother and infant requires tactile contact. For example, infants who received several additional hours of tactile contact during a 3-day period after birth showed faster development (e.g., scored higher in developmental tests at the age of 1 year old) than the comparison group. Also, their mothers seemed to verbally report more affection towards the baby (de Château & Wiberg, 1984). Even today, the experts consider skin-to-skin contact between a mother and infant beneficial for bonding, attachment and normal mental development (e.g., Ferber & Makhoul, 2004). For example, gentle and pleasant touch may play a role in the development of reward functions as well as the responsiveness of tactile emotional discrimination (Kida & Shinohara, 2013).

Touch can also evoke positive and negative emotions in children. One study showed that infants who received touch during eye contact with a researcher smiled more and cried less during the experiment (Peláez-Nogueras, Gewirtz, Field, Cigales, Malphurs, Clasky, & Sanchez, 1996). The relationship between touch and negative emotions are more clustered. Touch can both modulate and generate negative emotions. Gray, Watt, and Blass (2000) showed that skin-to-skin contact with the mother during doctoral operation decreased the amount of crying by up to 82%. Hertenstein and Campos (2001) provided negative tactile contact (i.e., mother tensing fingers around infants' abdomen while abruptly inhaling) to infants during object presentation. Two control groups received less disturbing tactile contact (i.e., relaxing grip around infants' abdomen) or no tactile contact at all. Infants who received negative tactile contact touched the object less and showed more negative emotions than infants in the two control groups.

Another interesting finding is that touch has a role in relieving stress and even aggression among infants and older children. According to Ainsworth, Blehar, Waters, and Wall (1978), touch from a caregiver can reduce infants' distress. Field (1999) has compared how touch can affect aggression expression in children. Children who are touched less show more aggressive behavior towards their peers than children who are touched (e.g., hugged and held) on more regular basis by their parents.

6.2 THE ROLE OF TACTILE COMMUNICATION IN SOCIALITY AND EMOTIONS LATER IN LIFE

The importance of tactile contact by no means decreases with age. Humans need to be touched during their adult years. Touching often takes place in private settings (Willis & Rinck, 1983). The tactile behaviors expressed in adulthood are greatly affected by culture. Also, personality traits seem to have an effect on the capability of, for example, communicating loving emotions via touch (Silverman, Pressman, & Bartel, 1973). People with high self-esteem seem to be better at communicating, for example, love emotions via touch than people with low self-esteem. On the other hand, people who are touch avoidant may require a greater amount of bodily contact from their romantic partners than people who are more accepting towards touching to confirm their relationship status (Johansson, 2013). Even when cultural and personal differences are put aside, touch has an important role in establishing and maintaining intimacy (see Hertenstein, Verkamp, Kerestes, & Holmes, 2006, for a review).

Research on actual touching behaviors and the meanings attached to them in real life social situations has been relatively rare. Jones and Yarbrough (1985) studied the meanings of touches reported by participants in their daily interaction. Their results showed distinct meanings of touch in communicating positive affect (i.e., support, appreciation, inclusion, sexual interest or intent, and affection), playful touches (i.e., playful affection and playful aggression), control touches (i.e., compliance, attention-getting, announcing a response), and ritualistic touches (i.e., greeting and departure). In addition, participants reported hybrid touches (e.g., a combination of greeting and affection), task-related touches (e.g., touches that occur when people exchange objects), and accidental (i.e., unintentional) touches. The authors reached three general conclusions from their observations. First, interpersonal touch is intrinsically and symbolically significant so that touch has an importance in its own right because it is needed by humans, but also seems to have symbolic content. Second, interpersonal touch codes include a wider range of meanings and degrees of ambiguity than previous research would suggest. Third, contextual factors are critical to the meanings of touch (i.e., social context affects the meaning attributed to certain touch).

Research in the field has also been conducted at more general level. Touch has a profound role in social structures of compliance, liking and status. The relationship between compliance and touch is straightforward: Touching encourages compliance in social situations. Studies show that, for example, when touched by a waitress, people tend to tip more (Crusco & Wetzel, 1984). People are also more willing to sign a petition (Willis & Hamm, 1980) or invest the time to fill in and rate questionnaires (Patterson, Powell, & Lenihan, 1986) when touched than when not. Touching can also affect the liking of another person. In general, initiating touch (e.g., handshake) makes people like the other person more (Fisher, Rytting, & Heslin, 1976). Some gender differences, however, can be found. Females tend to rate the person initiating touch as more likable than males (Whitcher & Fisher, 1979). The literature considering the relationship between status and touching is complex, but in general it seems that people higher in the social hierarchy are more often the ones initiating touch towards people whose status is lower (see Hertenstein, Verkamp, Kerestes, & Holmes, 2006, for a review). However, age, gender, and the relationship between the two people can affect the results. For example, men seem to initiate touch more often than women in most settings (Major, Schmidlin, & Williams, 1990). Interestingly, between married couples, women initiate touch more often during discussion than men, especially when the topic is chosen by the woman (Smith, Vogel, Madon, & Edwards, 2011).

From the point of view of this thesis, it is interesting that thermal sensations alone have also been linked to human social behavior. Williams and Bargh (2008) recruited 41 students who were assigned to one of two temperature priming conditions. The participants were briefly holding either a cup containing hot coffee or a cup containing ice cold coffee. After the priming, the participants read a story about "Person A" characterized as intelligent, skillful, industrious, determined, practical, and cautious. Then, the participants were asked to rate the target person with 10 bipolar scales. The results showed that priming affected the ratings so that when the participant was primed with a hot beverage, they tended to rate the person as warmer than the participants primed with a cold beverage. The rated personality traits of a target person outside the warm-cold dimension were not affected by the priming. In their second study, the participants held either a cold or hot therapeutic pad and evaluated its effectiveness. Then, they were asked to choose either a pro-social gift to treat a friend or a reward for themselves. The results showed that participants holding a hot pad had a higher tendency to choose the pro-social gift than the participants holding a cold pad. The authors concluded that physical temperature can affect one's impression of others as well as behavior towards others.

6.3 Tactile Sense and Emotional Responses

Research concentrating systematically on emotional responses to touch has focused on the relationship between touch and the quality of touch experiences (i.e., valence). Studying the hedonistic qualities of touch has a long tradition. Nguyen, Heslin, and Nguyen (1975) showed that playful and friendly touches are associated with squeezing and patting. Stroking, on the other hand, was mediating warmth and sexual desire. The body areas correlating with playful touches were located on the leg while sexual desire was located to the genitals. In general, gender has a strong effect on the experienced pleasantness of touch. Women tend to experience touch as pleasant if the tone of the touch is not sexual, while men seem to find sexual touches pleasant, playful, and warm (Nguyen, Heslin, & Nguyen, 1975). Men prefer to be touched by female strangers while women seem to enjoy touch only if the other person is, for example, a close friend (Heslin & Alper, 1983).

Hertenstein, Keltner, App, Bulleit, and Jaskolka (2006) studied the relationship between touch and emotions in the United States and Spain to compare possible cultural differences in touching behavior. The task of the participant was to communicate 12 distinct emotions to another participant by touching the forearm. The participants were separated by a barrier to block the possible effects of visual modality. The results showed that emotions of anger, fear, disgust, love, gratitude, and sympathy were recognized at accuracy rates ranging from 48% to 83%. A specific pattern of tactile behaviors was associated with each of the accurately recognized emotions. Sympathy was associated with stroking and patting, anger with hitting and squeezing, disgust with pushing, gratitude with shaking the hand, fear with trembling, and love with stroking. A further analysis (Hertenstein & Keltner, 2011) showed gender differences in the results. Anger was communicated successfully only when there was at least one male participant in a dyad, sympathy when there was at least one female participant, and happiness when both participants were female. The authors argue that one reason for the results may be gender stereotypes. Decoders may expect males to communicate different emotions than females. Also, encoders may adapt their tactile behavior according to the gender of the decoder (e.g., males deliberately touch other males differently than they touch females).

Studies implicate that material has a strong effect on the experienced pleasantness of touch. Guest, Essick, Dessirier, Blot, Lopetcharat, and McGlone (2009) compared touching of one's own skin and the skin of another person in two experiments. In the first experiment, the participants were asked to rate their perceived smoothness, softness, stickiness, and pleasantness of skin. The skin of another person was rated as more pleasant to touch than touching of ones' own skin. In the second experiment, participants rated touching the skin of another person. The skin was assessed with different skin emollients that changed the feeling of the skin. In general, the skin of another person without emollient was rated as more pleasant than the participant's own skin. The feeling of pleasantness in both experiments was associated with the perceived smoothness and softness of the skin, while stickiness made the rating of the skin unpleasant.

In general, soft and smooth materials tend to be rated as pleasant while stiff, rough, and coarse materials tend to be rated as unpleasant (e.g., Essick, James, & McGlone, 1999). Recently, Essick, McGlone, Dancer, Fabricant, Ragin, Phillips, and Guest (2010) conducted a comprehensive study on the valence of touch related to different materials (e.g., cotton and denim). In their results, previous observations about the effects of the material quality on the ratings were confirmed. In addition, they found gender differences in their study, indicating that males perceive materials in the calf area as more pleasant than women. Women, on the other hand, preferred stimulation to the forehead area more than males. Their study also seemed to confirm the theory that CT afferents play an important role in pleasant touch. Touching materials was rated as more pleasant in non-glabrous than glabrous body sites. However, their results also showed that CT afferents are not necessary in evoking pleasant or unpleasant experiences related to touch because non-glabrous body sites were also capable of conveying tactile stimulation observed as pleasant or unpleasant. In addition, an interesting observation was made concerning the intensity of the stimulation. Increased force of touch resulted in less pleasant ratings than lower touch force levels.

A study conducted by Löken, Evert, and Wessberg (2011) also adopted the CT theory framework. In this study, soft brushing was provided either first to the arm and then to the palm or first to the palm and then to the arm. The order of the stimulation affected the pleasantness ratings of the brushing of the skin. If the palm area was brushed prior to the arm, the pleasantness ratings were affected so that the rating was less pleasant when the stimulus was in the palm than in the arm. This result seems to support the idea that activating CT pathway may first influence the assessment of the pleasantness of touch.

Thermal sense is again studied to a lesser degree. Most of the studies have concentrated on thermal pain sensations (e.g., Brooks, Nurmikko, Bimson, Singh, & Roberts, 2002), a theme outside the scope of the current thesis. Most of the remaining studies have concentrated on the concept of so called thermal comfort (e.g., Chatonnet & Cabanat, 1965; Hensel, 1981). Thermal comfort refers to the human tendency to seek temperatures found pleasurable. For example, Stellar (1982) showed that if the human body temperature was increased, a long cold shower was found pleasant. Using the thermal comfort concept it has been shown that long exposure to hot temperatures can, for example, increase the amount of aggressive behavior (e.g., Anderson, 1989). In some studies, a general tendency to experience cold temperatures as unpleasant and warm temperatures as pleasant has been found. For example, whole-body cooling is experienced as unpleasant (Kanosue, Sadato, Okada, Yoda, Nakai, Yoshida, & Yonekura, 2002) while warm stimuli under 41°C are rated as slightly pleasant (Sung, Yoo, Yoon, Oh, Han, & Park, 2007). Interestingly, there is also physiological evidence linking thermal stimulation to emotions. Monkey brain cells responding to thermal stimuli also respond to non-thermal emotional stimuli (Hori, Kiyohara, Shibata, Oomura, Nishino, Aou, & Fujita, 1986). This could suggest that, at the brain level, there is some tendency to connect thermal and emotional stimulation even when presented separately.

An interesting notion derived from previous literature considers the role of touch in natural, multimodal contexts. It has been clearly established that touch alone can mediate hedonic information, and even evoke more detailed and discrete emotion-related responses (Hertenstein, Keltner, App, Bulleit, & Jaskolka, 2006). However, touch can also play a secondary role in emotion-related communication. When emotional information is mediated via other modalities (e.g., audio), the role of touch can mainly be seen as strengthening the emotional message mediated via the other modality used (Knapp, 1978).

IN SUMMARY

The sense of touch has a significant role in social and emotional processes. The need for touch in social interaction starts early in infancy as touch is needed for maternal bonding. Even in adulthood, the sense of touch is used frequently in social relationships. While some forms of touch (e.g., cuddling) mostly take place in private settings, ritualistic social interactions like greetings are also often associated with touch. The stimulation of the sense of touch can also evoke emotional responses without any communicative context. For instance, the pleasantness of tactile stimulation is affected by surface material so that smooth surfaces are rated as more pleasant than rough ones. Even though most of the studies in the field have concentrated on mapping tactile contact between individuals and tactile stimulation of skin, thermal stimulation can also affect to the human emotion system. In general, it seems that warm temperatures can positively affect pleasantness ratings and social behavior, while cold temperatures are rated as rather unpleasant and negatively affect social behavior.

7 Social and Affective Haptics

In scientific research studying the sense of touch can be challenging. Hertenstein, Verkamp, Kerestes, and Holmes (2006) point out three distinct methodological challenges. The first one is that touch often takes place in private, second is that due to the complexity of the modality touch is difficult to measure, and third is that the social restrictions humans hold for the sense of touch can be problematic in laboratory settings. Haptics provides a way to overcome many of these methodological challenges. For instance, haptics is rather easy to study in laboratory settings and can be preprogrammed to stimulate skin in a measurable and accurate manner.

Despite these advantages, in the field of computer science the study of emotions and haptics is largely a new and unmapped area. The ACM digital library finds an article with keywords “emotions” and “haptics” dating back to the year 2000. This study by Basdogan, Ho, Srinivasan, and Slater (2000) focused on haptically aided collaboration in virtual environments, but also studied to some degree the emotion-related experiences of participants in the study. The paper was among the first to concentrate on the relationship between haptics and human emotions. However, the methodological recommendations and terminology for the field has only started to emerge during the years in which the six studies included in the current thesis have been conducted.

In 2009, Tsetserukou, Neviarouskaya, Prendinger, Kawakami, and Tachi (2009) aimed to form initial terminology and methodology for studying haptics and emotional responses. They define affective haptics as the field of research “which focuses on the design of devices and systems that can elicit, enhance, or influence on emotional state of a human by means of sense of touch.” In addition, they suggest that physiological changes, physical stimulation, social touch, and emotional haptic design are the areas included into the definition of affective haptics. Thus, the field of affective haptics covers the areas described in previous chapter but also requires a technological device to stimulate the human tactile sense.

Only during the last decade has the evident connection between sociality, emotions, and touch received significant interest in the field of HTI. Previous research can be roughly divided into three distinct areas: haptic prototypes designed to evoke emotion-related responses in users, communicating emotions in remote settings, and emotional responses to haptic stimulation. The first two areas capture the lion's share of the existing publications. The following section describes the recent progress in these three areas in more detail.

7.1 PROTOTYPE TECHNOLOGIES

The idea of building a prototype capable of producing haptic stimulation to evoke emotions has become popular during the last decade. The testing of the prototypes has mostly not been tied to the tradition of measuring emotional responses and tested theoretical frameworks. However, most of the prototypes have been tested at least in small scale user studies. Overall, the results seem to suggest that different prototypes are capable of mediating touch sensations at least loosely connected to the human emotion system. Next, some interesting prototypes are described.

Perhaps most often prototypes have been designed to mediate the feeling of a hug to the user. These prototypes include, for example, The Hug, which is a special pillow which provides a vibrating "hug" to a faraway loved one (DiSalvo, Gemperle, Forlizzi, & Montgomery, 2003), Hug Over a Distance which turns the rubbing of a toy Koala into pressure in a wearable vest (Mueller, Vetere, Gibbs, Kjeldskov, Pedell, & Howard, 2005), HaptiHug (Tsetserkou, 2010) which turns a hug in Second Life into haptic stimulation, and HugMe (Cha, Eid, Rahal, & El Saddik, 2008; Eid, Cha, & El Saddik, 2008) which provides hugs in a teleconference environment. These prototype studies are motivated by the fact that hugging is an effective means to communicate affection. In general, the users have found these devices pleasant and useful.

Other kinds of prototypes have also been designed and built for interaction. LumiTouch was a photo frame for remote communication (Chang, Resner, Koerner, Wang, & Ishii, 2001). LumiTouch itself did not provide any haptic stimulation between two users. Instead, it allowed users to touch a photo frame to send flashing lights to each other. Some preliminary testing suggested that the participants found it rather easy to communicate with the flashing lights (Chang, 2008). TapTap was a blanket providing a comforting tap of vibration to the shoulder of a user (Bonanni, Vaucelle, Lieberman, & Zuckerman, 2006). It was designed to be used in touch therapy. It was able to produce sensations of tap, press, stroke, and contact to the user. The pilot study showed promising results to develop the prototype further. Hapticat mimicked the reactions and purring of a cat (e.g., Yohanan, Chan, Hopkins, Sun, & MacLean, 2005; Yohanan & MacLean, 2012). Hapticat was capable of evoking positive experiences in the user from which it was concluded that affective touch has a role in human-robot interaction. Interestingly, Hapticat had a warming element in its body. However, this warming element was not utilized in user studies.

In some studies, the potential of thermal stimulation to convey affective feelings via a specially designed prototype has been the focus. Lovelet conveys measured temperature data to a partner via Peltier devices (Fujita & Nishimoto, 2004). AffectPhone measured skin conductance and turned high arousal (i.e., high activation of the sweat glands) into warm stimulation to the communication partner and low arousal (i.e., low activation of the sweat glands) into cold stimulation (Iwasaki, Miyaki, & Rekimoto, 2010). Vaucelle, Bonanni, and Ishii (2009) designed the "cool me down" prototype. The idea was to provide cooling sensations to the user in therapy settings. In addition, a prototype named iFeelIM! was integrated in the Second Life environment (Tsetserukou, Neviarouskaya, & Terashima, 2013). One part of the prototype provided shivering vibrations as well as chilling sensations to the user.

Taken together, testing with the prototypes shows that users consider stimulation and communication rich and more fulfilling when it is accompanied by artificial tactual sensations. However, the prototypes themselves provide only a limited information on two issues: how the affective tactile sensations can be mediated to or between the users and what kind of emotional experiences and responses affective haptic stimulation can evoke in users. The latter part of the chapter is dedicated to the studies concentrating on human responses to haptic stimulation with and without communicative context.

7.2 COMMUNICATING EMOTIONS IN REMOTE SETTINGS

Most systematic studies on affective haptics have been conducted in remote settings. These studies are based on the assumption that mediated social touch can be perceived as real touch. Therefore, the methodology has often been similar to that used in the study by Hertenstein, Keltner, App, Bulleit, and Jaskolka (2006) described in a previous chapter. In general, in the following studies, the aim has been to study how well participants are able to communicate social or emotion-related content or to enrich emotion-related communication with haptic means. Thus, systematic studies of what kind of haptic stimulus parameters can evoke emotions or what kind of emotion-related responses (i.e., physiological, behavioral, or subjective) are related to the stimulation are included in the studies only infrequently.

Communicating emotions in instant messaging environments via haptic presentation of visual smileys has proved rather popular. Rovers and van Essen (2004a; 2004b) have conducted two studies where a set of six vibrotactile patterns symbolize different visual smileys (e.g., sad face and big smile). They suggest that the foot could be a suitable area for presenting these stimuli (Rovers & van Essen, 2005; Rovers & van Essen, 2006). In their tests, the users described the usage of haptic smileys as "more fun" and a "richer" form of communication. A similar approach was later adopted by Shin, Lee, Park, Kim, Oh, and Lee (2007). They also designed a set of so called haptic smileys for instant messaging environments to show that most of the stimuli were recognized well and that user responses were in general positive.

Other studies have taken steps towards mimicking non-mediated touch in remote settings and tested the assumption that mediated touch can be experienced similarly to real touch. Haans and IJsselsteijn (2009) made an interesting finding, which showed that mediated haptic messages can affect the social behavior of humans. In real life, a tap on the shoulder can increase helping behavior (i.e., willingness to comply with request). So, the researchers either provided a short tactile message to the arm of the participant or not, and studied the effects on helping behavior with a questionnaire. Even though their results were not statistically significant, the results indicated that the participants who received the mediated tactile message were more willing to help others than participants who were not touched during the experimental procedure. The authors concluded that their study was one of the first to show that artificial touch can have similar effects on the emotional and social behavior of people as real touch. Also, Bailenson and Yee (2008) were interested in whether mediated haptic touch mimics touch in real life settings. They compared the virtual touching of human and non-human objects and found that people used less force when touching virtual representations of humans than objects. In general, more force was used to touch male than female avatars. The authors concluded that the results show that people touch virtual objects in a similar manner to how they touch humans and objects in real life, further supporting the idea that mediated touch is used similarly to real touch.

Haans, de Nood, and IJsselsteijn (2007) studied whether gender differences identified in non-mediated touch are present in mediated situations as well. In their study, participants wore a haptic vest providing vibrotactile stimulation to different body locations. In addition, the participants were led to believe that they were being touched by female or male stranger. The participants were asked to report the pleasantness of the touch. The results showed that the gender of the stranger or the participant did not significantly affect the results even though same sex touch was in general viewed as more unpleasant than opposite sex touch. However, touch in body locations such as the stomach or wrist was perceived as more unpleasant than touching of the back. Based on this, the authors argue that, at least to some degree, mediated social touch is perceived similarly to real touch. Bailenson and Yee (2007) found gender effects in their study of how a mechanical hand shake could be mediated. Two participants interacted with a force feedback device. When they mimicked the other participant's handshake, male participants liked their interaction partner more than female partners did, indicating that, as in non-mediated touch, experiences related to haptically conveyed touch are also affected by the gender of the one being touched.

Some studies have tested whether it is possible to communicate detailed emotion-related information between users via haptic only cues. In previous experiments by Smith and MacLean (2007) and Bailenson, Yee, Brave, Merget, and Koslow (2007), the aim was to study how well participants could identify haptically presented emotions. In these studies, one participant's task was to create a haptic message with a force-feedback device, which in his opinion would communicate a certain emotion from a list of emotion-related words (e.g., happy or angry). The other participant's task was then to try to identify the emotion-related content of the message. The results of these two studies indicated that haptics can be used to communicate emotion-related information between two persons. In general, the participants were capable of recognizing messages at an above-chance level. The purpose of the experiment by Smith and MacLean (2007) was purely to test whether the participants were capable of recognizing haptically mediated emotion-related messages. Bailenson, Yee, Brave, Merget, and Koslow (2007) went a step further and tried to identify patterns that people used to mediate the emotion-related words in their study. In their analysis, some differences between emotions like slow movement when communicating sadness versus rapid movement when communicating anger were found.

Huisman and Darriba Frederiks (2013) and Huisman, Darriba Frederiks, Van Dijk, Hevlen, and Krose (2013) studied how people can mediate emotional touch using a tactile sleeve attached to forearm area. The participants communicated eight different emotions (e.g., anger and happiness) to each other by, for example, hitting or pressing the sleeve. The tactile sleeve turned the input into vibrations. However, the data obtained only partly confirmed the assumption that the participants could communicate emotions successfully. The authors also tried to find tactile and vibrotactile patterns that people used when aiming to communicate emotions. The results showed that it was rather difficult to find distinguishable tactile features for mediated emotions.

Finally, haptic stimulation has also been used to enrich the emotional cues of vocal and multimodal communication. For instance, Bickmore, Fernando, Ring, and Schulman (2010) added squeezing to a speaking animated human face. In short, the participant wore a glove which sent pressure to the hand area while interacting with the animated agent. When touch alone was used, the squeeze successfully mediated experiences related to both valence and arousal. However, when the face was shown to the participant, it dominated users' perception of valence. Arousal was more efficiently mediated via facial expressions and vocal cues, while touch had only little effect. This partly contradicts some previous studies showing that tactile cues in conjunction with speech can enrich the communicative experiences of the user. CheekTouch (Park, Lim, & Nam, 2010) provided additional tactile sensations imitating, for example, tickling to the cheek of the conversational partner when talking over a mobile phone. The technique was positively evaluated and according to the participants suitable for emotional communication. Later, a follow-up study was conducted to study how couples use CheekTouch (Park, Bae, & Nam, 2012). The results showed that CheekTouch was used, for example, to capture attention or to emphasize the users' emotional state while speaking. Touch and Talk (Wang & Quek, 2010) provided tactile sensations to the user via an armband. According to the results, touch was capable of reducing the negative mood of the user while listening to a story in the laboratory. Thus, most of the previous results indicate that tactile stimulation can successfully affect emotion-related experiences in conjunction with other modalities.

7.3 EMOTIONAL RESPONSES TO HAPTIC STIMULATION

Even though haptics has been successfully used to communicate and mediate emotion-related information, the actual haptic stimulus qualities (e.g., stimulus parameters) are difficult to isolate in such experimental settings. Therefore, it seems reasonable to argue that if one wants to study emotional responses to haptic stimulation and, thus, research stimulus qualities related to such responses, different kind of experimental setups should be utilized. In the next section, studies measuring emotion-related responses to haptic stimuli in non-communicative contexts are reviewed. It should be noted that the research taking this approach is still relatively limited. However, the existing results are promising and show that haptic stimulations can evoke emotion-related responses even when isolated from communicative contexts.

Raisamo, Raisamo, and Surakka (2009) evaluated the effect of temporal parameters for vibrotactile salutatory patterns. Saltation refers to an illusion where distinct tactile stimulations close in time and closely located along the skin are perceived as a continuous movement. The stimuli were presented to the participants' forearm with three vibrotactile actuators.

The burst duration and inter-burst interval were varied. The participants were asked to rate the valence and the continuity of the pattern. There were no statistically significant differences in the ratings of stimulus pleasantness even though the effect of the inter-burst interval approached significant results. The stimuli with long inter-burst intervals were rated as significantly less continuous than stimuli with short (i.e., less than 24 ms) inter-burst intervals. In addition, the participants were asked to rank the stimuli presented by their continuity and pleasantness. The ranking result for the continuity was consistent with the rating result. For the rankings of the pleasantness, the results showed that stimuli with 12 ms inter-burst intervals were ranked higher in pleasantness than stimuli with longer inter-burst intervals. In general, the results indicate an interaction between the experiences of pleasantness and continuity.

During the writing process of the introductory part of the current thesis, Seifi and MacLean (2013) studied how participants rated vibrotactile stimuli presented in the palm area. They adapted the dimensional theory of emotions, therefore asking participants to rate the stimuli with scales of pleasantness and arousal. In addition, the participants were asked to rate the stimuli with scales of weak/strong, smooth/rough, and rhythmic/non-rhythmic The vibrotactile stimuli were varied by frequency (i.e., 75 or 175 Hz), burst length, and rhythm (e.g., whether a single or several bursts were presented to the participant). One of the rhythmical changes was a long, continuous vibration. The stimuli rated as pleasant were in general rated as smooth and calm. The stimuli rated as unpleasant were, on the other hand, also rated as rough and alarming (i.e., arousing). The parameter most affecting to the ratings of pleasantness was the rhythm, while the ratings of arousal were affected by both rhythm and frequency. Long vibrations with few pauses were rated as smooth and pleasant, while several short bursts were rated as unpleasant and alarming. The long, continuous vibration was rated as strongest and smoothest.

Finally, Lemmens, Crompvoets, and van den Eerenbeemd (2004) and Lemmens, Crompvoets, Brokken, van den Eerenbeemd, and De Vries (2009) built a jacket with 64 actuators to enrich movie viewing. The jacket was able to stimulate the back and front sides of the human torso as well as the arms. For stimulus creation, the authors used a pattern editor capable of producing, for instance, energetic movements to indicate happiness or firing motors to shiver the spine area for fear. The participants watched movie clips with different emotional valence with and without additional tactile stimulation and were asked to rate each movie clip with the scales of valence and arousal as well as immersion (e.g., “I responded emotionally”). In addition, SCL was measured. The results showed that immersion-related ratings in particular were affected by tactile stimulation so that when the tactile stimulation was present, the scores on the scales were higher. The SCL was in general highest when there was an emotion-evoking clip with tactile stimulation.

Taken together, even though the area is still only little studied, the previous research shows clearly that even with explicit communicative context there is a connection between haptic stimulation and the human emotion system. The line of research is promising when aiming at systematically studying emotion-related responses to carefully controlled haptic stimulus parameter variation.

IN SUMMARY

Affective and social haptics is a new yet fruitful area of research. The first studies in the area concentrated on building a prototype and then evaluating the potential of the prototype for emotional communication and stimulation in rather informal manners. The prototypes built for emotion-related stimulation were evaluated positively. Later, the studies focusing on the potential of artificial touch to be perceived similarly to real touch or whether dyads can communicate emotions between others have emerged. The results showed that real and artificial touch are perceived rather similarly. In addition, the participants have been able to accurately haptically send and recognize even specific emotions like anger between each other. Thus, the previous studies suggest that mediated touch can be used for emotion-related remote communication successfully as it shares similar properties with real touch. Studying emotional responses to pre-programmed haptic stimulation without any communicative context is currently a rare approach. This line of research is able to connect haptic stimulation, emotional responses, and the tradition of emotion research together, thus providing information on, for example, generalizable and pre-programmable haptic stimulus parameters for consumer applications. The existing studies seem to suggest that haptic stimulation can evoke emotion-related responses even without explicit communicative context or complex devices. For example, stimulations rated as smooth have also been rated as pleasant.

8 Experiments

8.1 Publication I: Emotional and Behavioral Responses to Haptic Stimuli

The aim of Publication I was to study emotional and behavioral responses to haptic stimuli. For this purpose, a prototype of a friction-based horizontally rotating fingertip stimulator was built. The stimuli were created by varying rotation style so that the stimuli were varied by burst length (i.e., 20, 50, 100 ms), continuity (i.e., continuous and discontinuous), and direction (e.g., forward and backward), thus resulting in 12 different stimuli. All the stimuli were roughly 500 ms long. The stimuli were presented to the index finger of the dominant hand. To measure the emotional responses, the participants were asked to rate the stimuli presented one at a time using scales of pleasantness, approachability, arousal, and dominance. The behavioral responses were measured with differentiation tasks so that the 12 stimuli were presented to the participants sequentially. All the possible combinations of the 12 different stimuli were used, resulting in 132 pairs consisting of two different stimuli and 132 pairs consisting of two of the same stimuli. The task of the participant was to indicate with a response button as fast as possible whether the stimuli were the same or different. Both the error rates and reaction times were recorded.

The results showed that the rotation style was mainly responsible for the variations in the ratings. In general, continuous stimuli were rated as more arousing and dominant and as less pleasant and approachable than any of the discontinuous stimuli. However, burst length and direction did not affect the results. For the behavioral responses, the results showed that the participants were able to distinguish haptic stimuli with an accuracy of 87%. The lowest error rate was for the continuous stimulation. The reaction times were in general also fastest for the continuous stimulation. When the results of the behavioral responses and emotion-related ratings were compared, it was found that the continuous stimuli rated as arousing were in general distinguished more accurately and faster than the discontinuous stimuli rated as pleasant and calm.

8.2 PUBLICATION II: EMOTIONAL RESPONSES TO THERMAL STIMULI

The aim of Publication II was to study emotional responses to thermal stimuli. For this purpose, a Peltier element was programmed to present temperature variations to the palm area. Publication II was motivated by a scenario where a thermal actuator would be attached to, for example, the back of a mobile phone. If a user was holding the phone, that user could feel the stimulus heating up or cooling down. However, if the phone was, for example, on the table then the stimulus may have already reached target temperature when the participant first touched the phone. Therefore, the stimulus presentation style was controlled so that the stimulus was either pre-heated to the target temperature (i.e., pre-heated stimuli) or the participant was feeling the thermal stimulus heating or cooling to the target temperature (i.e., dynamic stimuli). The stimuli were varied by presentation style and temperature (i.e., 4 degree increase or decrease) in respect of the participants current hand temperature. A neutral stimulus (i.e., participants' own hand temperature) was presented to the participant in both blocks. The total amount of the stimuli was therefore 6. The stimuli were divided into two blocks based on presentation style. Emotional responses were measured with emotion-related subjective rating scales of pleasantness, approachability, arousal, and dominance, and as changes in skin conductance response (SCR). The participants were also asked to rate their experience of the stimulus temperature with a nine-point scale varying from cold to hot.

The results showed that warm stimuli were rated as more arousing and dominant than neutral or cold stimuli. However, the effects on the experienced pleasantness and approachability were small. In general, all the stimuli were rated as rather pleasant and approachable or neutral. The SCR was highest in magnitude for the pre-heated warm stimuli. In addition, there was an interaction with the rise time (i.e., speed) of the SCR. The response was slower to the pre-adjusted stimulus than to the dynamic stimulus when the stimulus was warm, but when the stimulus was cold, the response was faster to the pre-adjusted stimulus. The ratings of stimulus temperature showed that stimuli were rated adequately in respect of their temperature, thus suggesting that even small shifts in temperature were distinguishable. The results, therefore, suggested that pre-adjusted warm stimuli in particular can be seen as effective in activating the autonomic nervous system and the arousal and dominance dimensions of the affective rating space.

8.3 Publication III: Cold or hot? How Thermal Stimuli are Related to Human Emotional System

The aim of Publication III was go deeper into the relationship between thermal stimulation and emotions. In Publication III, the experimental setup was the same as in Publication II (i.e., the participants rated the stimuli with four emotion-related scales and the temperature scale while SCR was measured). However, as Publication II was designed to be pilotary, Publication III was conducted to gain more generalizable information about the relationship between the human emotion system and temperature.

In Publication III, the stimulus presentation algorithm was improved to gain more control over the presented temperatures. Six different target temperatures (i.e., 2, 4, and 6 degree increases and decreases in temperature) and two presentation styles (i.e., pre-adjusted and dynamic) were presented to 24 participants in two blocks. In addition, neutral thermal stimulation (i.e., hand temperature) was presented in both blocks. Thus, the total amount of stimuli was 14.

The subjective ratings of Publication III showed that both the variation in temperature and presentation style affected the ratings of pleasantness and approachability. In general, small shifts in temperature were rated as rather neutral or pleasant. However, a 6°C shift in temperature was rated as unpleasant and avoidable, especially when the stimulus was warm. The dynamic stimuli were rated as less pleasant and approachable than the pre-adjusted stimuli. The warm stimuli were rated as more arousing and dominant than the cold stimuli despite the presentation method so that when the intensity of the stimulus grew the rating always became more arousing and dominant. In general, dynamic stimuli were rated as more arousing and dominant than pre-adjusted stimuli. The results of the SCR showed that only a pre-adjusted 6°C increase in temperature raised the magnitude of ANS response. The rise time of SCL was not affected by the stimuli used in the experiment.

The results of the temperature ratings showed that participants were able to rate even 2°C degree shifts in temperature adequately in respect of the temperature. Interestingly, the presentation method also affected the results. The dynamic stimuli were in general rated in a more polarized manner than the pre-adjusted stimuli (e.g., 6°C degree increase was rated as hotter when the stimulus was dynamic than when it was pre-adjusted).

8.4 Publication IV: Evaluations of Piezo-actuated Haptic Stimulations

The aim of Publication IV was to study emotional responses to piezo-actuated vibrotactile stimuli with and without an auditory component related to the stimulus presented with a touch screen device. For this purpose, three experiments were conducted. In the experiments, the presentation modality (i.e., haptic only, haptic auditory, and auditory only) of the stimulus was varied. In haptic only conditions earplugs were used to mask the auditory component, in auditory only conditions the participants were not allowed to touch the device to mask the haptic component, and in haptic auditory conditions both modalities were presented to the participants. The task was to rank two sequentially presented stimuli in terms of pleasantness and arousal. Some 9 stimuli were created by varying the driving voltage and, therefore, the drive current of the piezo actuator. The controlling of the drive current resulted in measurable output parameters of stimulus amplitude, which was the value of the screen displacement, and rise time, which was the time to the peak of the stimulus from the rest state. The stimuli were varied by three stimulus amplitudes (i.e., 2, 10, and 30 μm) and rise times (i.e., 1, 3, and 10 ms). There were a total of 72 stimulus pairs in each experiment.

The results showed both similarities and differences between the three modalities. In general, haptic and haptic auditory stimuli were ranked in a similar fashion in terms of both pleasantness and arousal so that, for instance, stimuli with short rise times were ranked as arousing only when the amplitude was 30 μm. In contrast, in the cases where the rise time was short and the auditory component thus resulted in high frequency output, both the haptic auditory and the auditory only stimuli were ranked as unpleasant even though the rating of the stimulus with a haptic only component would have been pleasant. The results, thus, suggest that the role of the auditory component in the emotion-related ratings of haptic stimuli is strong. Therefore, to create pleasant haptic stimuli in situations where auditory stimulus is also provided, one has to be careful to design the auditory stimuli in a manner that does not reduce the experienced pleasantness of the stimulation.

8.5 Publication V: Emotional Responses to Haptic Stimuli in Laboratory versus Travelling by Bus Contexts

The aim of Publication V was to study whether the emotional ratings of haptic stimuli are affected by different experimental conditions. For this purpose, the participants were asked to rate 8 stimuli varied by burst number (i.e., 1 and 3), amplitude (i.e., 2 and 30 μm), and rise time (i.e., 1 and 10 ms) both in a laboratory and on a bus. As in Publication IV, a piezo-actuated touchscreen device was used to produce the stimuli by varying drive current. The participants' task was to rate the stimuli in both conditions with scales of pleasantness, approachability, arousal, and dominance.

For the experimental condition, the results showed that the profile of the emotion-related ratings of haptic stimuli was surprisingly similar both in laboratory and while travelling on the bus so that, for instance, stimuli with high amplitudes and several bursts were rated as more arousing and dominant than stimuli with low amplitudes and one burst in both conditions. Also, in general, in both experimental conditions several bursts were rated as less pleasant than fewer burs. From this, it was concluded that haptics can also be used efficiently to mediate emotion-related information and to evoke emotion-related responses in real life contexts outside the laboratory. However, there were also some significant differences between the experimental conditions. On a bus all the stimuli were rated as more pleasant but as less arousing and dominant than in the laboratory, suggesting that the stimulus ratings might be affected by external distraction.

8.6 PUBLICATION VI: TACTILE MODULATION OF EMOTIONAL SPEECH SAMPLES

The aim of Publication VI was to study whether concurrent tactile stimulation affects emotion-related ratings of speech when measured with scales of pleasantness, arousal, approachability, and dominance. Publication VI consisted of two experiments. In the first experiment, the task was to rate speech-only and speech-tactile stimuli. Two speech samples with positive tone and content and two with negative tone and content were presented to the participants with and without tactile stimulation so that the total amount of stimuli was 8. The tactile signal mimicked the parametrical changes of the speech sample (i.e., duration, rhythm, and amplitude). The results showed that speech tactile stimuli were rated as more arousing and dominant than speech only stimuli. However, the ratings of pleasantness and approachability were only affected by the content of the speech sample so that positive speech samples were rated as more pleasant and approachable than negative speech samples.

In the second experiment, the aim was to study whether the way the tactile signal was produced affected the ratings. Speech samples with positive, negative, and neutral contents were chosen for the study. The tactile signal either mimicked the parametrical changes of the speech sample in question or the parametrical changes of another speech sample. From a neutral speech sample a static vibration was created to mimic the lack of prosodic changes in speech. Therefore, the speech-tactile stimulus was either congruent with speech or incongruent. A total of 12 stimuli (i.e., 3 speech only, 3 speech tactile with congruent tactile stimulations, and 6 speech tactile with incongruent tactile stimulations) were presented to the participants. The task of the participants was to rate the stimuli with scales of pleasantness, approachability, arousal, and dominance.

The results of the second experiment showed that all the speech tactile stimuli were rated as more dominant and arousing than the speech only stimuli. When the tactile stimulus was accompanied by static vibration, the stimuli were rated as more arousing than speech tactile stimuli where the tactile stimulation was derived from positive or negative speech samples. Stimulus congruency affected the ratings of pleasantness so that congruent speech tactile stimuli were rated as less pleasant than the speech only stimuli when the emotional content of the speech was positive. Thus, variation of the stimulus parameters can affect the emotion-related ratings of speech, suggesting that in a multimodal context the parametrical variation of additional tactile stimuli should be carefully designed.

9 Discussion

The results of the current thesis showed both differences and similarities in the emotional responses to different types of haptic stimulation. For the ratings of pleasantness and approachability, the results showed that the stimulus types (i.e., friction, vibrotactile, or thermal) was connected to the responses in a different manner. In contrast, the ratings of arousal and dominance were surprisingly similar between the stimulus types. On the other hand, parametrical variations, experimental contexts, and modality affected the results. In the following chapter, the results of the ratings are presented so that first the ratings of pleasantness and approachability are discussed and then the ratings of arousal and dominance. After the ratings, the results of the behavioral measurements and psychophysiological measurements are discussed.

For the ratings of pleasantness and approachability, the results showed that, when the stimulation was friction based or thermal, the ratings were different than when the stimulation was vibrotactile. While variations in vibrotactile stimulation in general did not greatly affect the ratings in these two scales, the variation of friction based and thermal stimulation did. Therefore, based on the current results, it seems that vibrotactile stimulation is not as effective in producing pleasant or approachable experiences as other kinds of stimulations of the sense of touch. As noted in the introductory part of the thesis, different types of haptic stimuli activate different receptors located in the skin area. Although the activation of the receptors was not directly measured in the current studies, based on the results it seems reasonable to assume that different receptors are connected to the valence of a haptic stimulation in a different manner.

One reason why the vibrotactile stimuli were less effective in producing pleasant experiences might be found in the bodily location. In the current thesis, all the stimuli were presented to glabrous body sites (i.e., fingers or palms). These areas for stimulus presentation were chosen since in the field of HTI people mostly use their hands to manipulate objects instead of, for example, wearing a vest capable of providing haptic stimulation. However, from a theoretical point of view, providing mechanical haptic stimuli to non-glabrous body sites could affect the experience of valence more efficiently. CT afferents found in non-glabrous body sites seem to be well-connected to the subjectively experienced pleasantness of touch (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007; Löken, Minde, Wessberg, Perini, Nennesmo, & Olausson, 2011). The CT afferent theory does not claim that touch in glabrous body sites could not affect experienced pleasantness at all (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007; Essick, McGlone, Dancer, Fabricant, Ragin, Phillips, & Guest, 2010), but simply suggests that the ratings of valence can be different in terms of the magnitude if the stimuli are presented in non-glabrous body sites (e.g., Löken, Minde, Wessberg, Perini, Nennesmo, & Olausson, 2011).

Therefore, an interesting comparison could be made between the two body sites used in the current thesis (i.e., fingers in Publications I, VI, and V, and palm in Publications II, III, and VI). They are both glabrous skin sites. The fingers, however, have more mechanoreceptors and a larger representation in the cortex than the palm (e.g., Cholewiak and Collins, 1991). The fingers are responsible for the functioning of discriminative touch (e.g., sensations related to roughness or smoothness of the surface) (McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007). The palms can have similar functions but are less accurate for this purpose. If the stimulus type is excluded from this comparison, it seems that the palm area mediates experiences related to the pleasantness and approachability better than the fingers. If discriminative and emotional touches are processed via different neural pathways as suggested (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007), this result could indicate that the less sensitive the body site is to discriminative touch, the more sensitive it is to emotional touch. This indication could be studied in future by providing identical stimulations into different body sites with different discrimination sensitivity to get deeper insight to affective haptic perception.

Thermal stimuli were particularly effective in evoking differences in ratings of pleasantness and approachability, suggesting that the activation of thermoreceptors might be better connected to these experiences than the activation of mechanoreceptors. The results of Publications II and III showed that, in general, small shifts in temperature were experienced as pleasant and approachable or neutral. However, when the stimulus intensity (i.e., magnitude) was high, the stimuli were rated as unpleasant and avoidable, especially when the stimulus was warm. The effect of intensity on the ratings is not surprising since extreme cold and warm stimuli can be painful and cause tissue damage. Interestingly, the presentation style of the stimulus (i.e., dynamic or pre-adjusted) also had a clear effect on the ratings. The results showed that high intensity dynamic stimuli were rated as more unpleasant and avoidable than high intensity pre-adjusted stimuli. Perhaps when the participants feel the temperature changing, they may become cautious about the final limits of the heating and therefore experience the stimulus as unpleasant. This is supported by the result that, in general, pre-adjusted stimuli were rated as rather pleasant. The results thus suggest that even when thermal stimulus is provided to the participant under the thermal pain threshold of 45°C (e.g., Stevens, 1991), one must be cautious in the selection of the right temperature, especially in situations where the participants feels the stimulus heating. According to the results, if the temperature shift in respect to the hand temperature is over 4°C, the experience related to the stimulus is unpleasant. Thus, the differential of producing pleasant localized thermal stimuli is rather small.

Not only haptic stimulus type but also modality differently affected the ratings of valence. First of all, when vibrotactile stimulation was presented together with speech, there were variations in the ratings of pleasantness so that congruent speech-tactile stimuli were rated as more unpleasant than speech only stimuli. Thus, vibrotactile stimuli seems to tone down the ratings of valence. Second, in Publication IV, when the auditory component of the stimulus was high in frequency, haptic only stimuli were ranked as pleasant while auditory only and haptic auditory stimuli were ranked as unpleasant. Tones of high frequency were often identified as being related to unpleasant subjective experiences in previous studies (e.g., Bachrorowski & Owren, 1995). Thus, the results suggest that in cases where the auditory component is highly unpleasant, the haptic component cannot reduce this experience. Together, the results indicate that in multimodal settings both haptics and audio can affect the stimulus valence independently.

Finally, even though the haptic stimulus type captured most of the variation for the ratings of pleasantness and approachability, some similarities between the studies in the current thesis can also be found. The stimulus continuity was found to be related to these scales in two studies. In Publication I, continuous friction-based stimuli were rated as less pleasant and approachable than stimuli that were discontinuous. In Publication VI, continuous speech-tactile stimulation was rated as less approachable than discontinuous stimulation. Thus, it seems that continuity has an effect on the experienced stimulus pleasantness and approachability. However, in studies by Seifi and MacLean (2013) and

Raisamo, Raisamo, and Surakka (2009), continuous stimuli were rated contrary to the findings in the current thesis. This can be explained by the fact that in Publications I and VI there were no clear pauses in continuous vibrotactile stimulation as in studies by Seifi and MacLean (2013) and Raisamo, Raisamo, and Surakka (2009). Thus, perhaps not the continuity itself but rather the pauses and rhythm used in the stimulation had a significant role in evoking unpleasant or pleasant evaluations in previous studies. This assumption is supported by the findings in Publications V and VI suggesting that fewer bursts and static vibration are in general rated as more pleasant and approachable than stimuli with several bursts or varying rhythm, which seems to be in line with the results of Seifi and MacLean (2013).

The ratings of arousal and dominance were independent of the haptic technology and, thus, the haptic stimulus type. For instance, high intensity stimuli were always rated as more arousing and dominant than less intense stimuli regardless of the technology used. Therefore, the subjective experience related to arousal and dominance seems to be at least partly independent of the receptors activated in the skin. This seems to be an interesting finding as intuitively one might assume that the different functioning of the receptors would also be reflected in these two scales. One reason behind this might be found in human physiology. In the current thesis, it was not possible to provide vibrotactile or friction based stimuli that would be both pleasant and arousing. It seems logical to assume that there are biological reasons for this connection. When a tactile stimulus is perceived it is so near that if the stimulus is harmful, it has potential to cause immediate damage. If the tactile stimulus activates the arousal system, then to avoid potential damage, it may be logical to interpret the stimulus as a potential threat. This, on the other hand, would prepare the individual to avoid the stimulus as well as to experience it as unpleasant.

Interestingly, in contrast to mechanical (i.e., friction and vibrotactile) stimuli, the warm thermal stimuli with rather low intensity were rated pleasant or neutral as well as arousing and dominant. This can also be explained from a biological point of view. Unlike tactile receptors, thermoreceptors are specialized in estimating the magnitude of the stimulus (e.g., Stevens, 1991). Therefore, it might be possible that the information related to the magnitude of the thermal stimulus is mediated effectively to the central nervous system, and that the person touching the actuator understands that the stimulus is far from activating thermal nocireceptors and, therefore, from evoking pain sensations.

Irrespective of stimulus types, parametrical variation and modality affected the ratings of arousal and dominance. Continuous stimuli were rated as more arousing and dominant than discontinuous stimuli. The effect of continuous haptic stimulation to the higher ratings of arousal and dominance may be found in the fact that tactile stimulation is always in direct contact with skin and therefore requires extra attention for potentially harmful effects. The arousal system may easily respond to stimuli when the stimulus keeps on going and there is no additional information on when the stimulus is going to stop or how the stimulus is going to proceed (e.g., change the amplitude to potentially harmful level). The amount of bursts was also related to the level of arousal and dominance. In Publication V, several bursts with short breaks were associated with higher ratings on the two scales, while short bursts were in general rated as calming and less dominant. Based on these results, it seems that the continuous, rhythmic stimulation might render the subjective experience arousing and dominant.

In Publications II, III, and IV intense stimuli (i.e., high temperature or amplitude) were rated as more arousing and dominant than less intensive stimuli (i.e., low temperature or amplitude). Thus, the ratings of arousal and dominance can be argued to be related to the stimulus' "loudness". Similar results have been previously obtained with auditory stimulus (e.g., Scherer, Johnstone, & Klasmeyer, 2003). Therefore, the "loudness" of the stimulation seems to elevate the level of arousal and dominance with both audio and haptic channels, thus, possibly reflecting the somewhat similar processing of auditory and haptic stimulus parameters. The pattern where unpleasant stimuli are found highly arousing has also been found with visual stimuli (e.g., Bradley, Codispoti, Cuthbert, & Lang, 2001). Thus, this result seems to be independent of the modality used.

Finally, the results of Publication V showed that high frequency audio modulated the rating of the haptic stimulus as more arousing despite the haptic component. This result is supported by previous literature linking high frequency audio to high arousal (e.g., Bachrorowski & Owren, 1995). The results of Publication VI showed that all the speech tactile stimuli were rated as more arousing and dominant than speech only stimuli, thus also supporting the results obtained in previous studies (e.g., Chang, O'Modhrain, Jacob, Gunther, & Ishii, 2002). Interestingly, some parametrical variation related to these two dimensions was found. Stimuli with static vibration were rated as more arousing and dominant than stimuli mimicking the amplitude and rhythm of the speech sample. This seems to reflect the role of continuity along with multimodal stimulation. Thus, as for the ratings of valence, ratings of arousal and dominance can also be affected by both haptic and audio modalities at least partly independent from each other.

The behavioral responses (i.e., error rate and reaction time in differentiation task) showed in Publication I that continuous stimuli rated as arousing, dominant, avoidable, and unpleasant resulted in faster reactions than discontinuous stimuli rated as calm, non-dominant, approachable, and pleasant. The continuous stimuli were also discriminated more accurately. Previously, Buodo, Sarlo, and Palomba (2002) found the reaction times to be shorter for threat stimuli. Together, these findings could imply that highly arousing tactile stimuli are indeed perceived as somewhat threatening and, therefore, unpleasant. The temperature rating scale in Publications II and III suggested that the thermal stimuli could be differentiated successfully based on temperature when the temperature differential was as small as 2°C. This result implies that even a small thermal differential is sufficient for HTI purposes.

The psychophysiological responses measured with SCR seemed to reflect the levels of experienced arousal and dominance well. The stimuli rated as arousing and dominant evoked skin conductance response that were faster and higher in magnitude than previously suggested (e.g., Lang, Greenwald, Bradley, & Hamm, 1993). Interestingly, however, the results of Publication III showed that the stimulus rated as most arousing (i.e., warm dynamic increase of 6°C) did not elevate the SCR. Instead, only a warm pre-adjusted 6°C increase elevated the SCR. This result seems to indicate that the relationship between the experienced level of arousal and SCR is not always straightforward. Some physiological characteristic related to the stimulus presentation methods can be assumed to be behind this result. Most likely, the largest SCR activation rises occur when the nervous system prepares the participant to avoid the stimulus. A warm, pre-adjusted 6°C increase in temperature in respect to one's own hand temperature can feel quite sudden, and therefore a fast response is needed if, after cognitive evaluation, the temperature is perceived as potentially harmful. A similar ANS response is not needed if the presentation method is dynamic as the participant can actively monitor the shift in temperature all the time during the stimulus presentation.

The presentation method also affected the SCR in another manner. In Publication II, the results showed that when the stimulus is warm the change in temperature can activate SCR faster than a pre-adjusted stimulus. This can be explained by the previously mentioned activation of approach-avoidance tendency. However, when the stimulus was cold the response was faster to pre-adjusted stimulus than to dynamic stimulus. The reason behind this may be that the response to harmful cold stimulus takes longer to emerge, thus suggesting that the participants may not be as sensitive to the change of temperature to cold stimulus as to warm stimulus. Perhaps only if the participant feels the unchanged cold stimulus for several seconds does the ANS response have time to emerge. The interaction of the presentation methods was not statistically significant in Publication III. One reason behind this could lie in the smaller temperature differential. Thus, the ANS has time to adapt to the changes in temperature and therefore may not respond as rapidly to changes as in studies where the temperature differential is larger.

There are some general notions of caution that should be made in respect to all of the studies in the thesis. First, according to its aims this thesis was based mostly on laboratory studies to find out basic facts about haptics and emotions. Of course, environment is more complex outside laboratory and, thus, it is not possible to fully generalize the findings of this thesis from laboratory to out of the laboratory conditions. However, haptics may function somehow similarly both in and out of the laboratory as evidenced partly by, for instance, Publication V or Wilson, Brewster, Halvey, and Hughes (2013). Second, the findings of the different studies in the thesis revealed that the ratings of the stimuli varied mostely in a range of -2 to +2. A reason behind this may be that tactile stimulation in general evokes relatively mild emotion-related responses. However, it may also be the case that the range of responses found concerns only vibrotactile stimulation as the results of previous research using vibrotactile stimulation has been in line with the ones of this thesis (e.g., Rantala, Salminen, Raisamo, & Surakka, 2013; Raisamo, Raisamo, & Surakka, 2009).

Taken together, the results of the current thesis showed that different haptic stimuli have significantly different effects on the human emotion system when measured with subjective ratings, behavioral measurements, and psychophysiological responses. Probably the most important factor behind this was the haptic stimulus type activating different receptors in the skin. However, parametrical variation and modality of the stimuli also revealed that, with quite subtle changes, it is possible to evoke statistically significant differences in human reactions related to the activation of the emotion system. Finally, it should be noted that many of the studies in the field of affective haptics, including the studies in the current thesis, are motivated by the starting point that haptics could be used for designing HTI systems that could mediate or evoke emotion related information between people. It is likely that the findings of the thesis could be utilized in such designs. For instance, the elevated level of arousal can be seen from a theoretical point of view (e.g., Bradley and Lang, 1994; Bradley and Lang, 2000) as elevating the level of attentive behavior. Thus, emotionally arousing haptic stimuli can be used to efficiently catch the user’s attention.

10 Conclusions

In summary, in the current thesis I have shown that different haptic stimulations activate the human emotion system differently, as evidenced by subjective ratings and behavioral and physiological responses. The studies in the thesis were varied by haptic stimulus types (i.e., friction, vibrotactile, and thermal), parameters (e.g., amplitude and continuity, experimental conditions (i.e., laboratory or outdoors), and modality (i.e., haptic stimulations were presented either with or without auditory component or speech).

The results showed that the ratings of pleasantness and approachability were affected by haptic stimulus type so that all the stimulus types were connected to the responses in a different manner. When the stimulus was vibrotactile, in general the variations in the stimulus parameters did not greatly affect the ratings in these two scales, while for the variation of the parameters of friction based and thermal stimulation there were differences. This result seemed to suggest that the selection of a proper haptic technology is crucial when aiming to mediate pleasant or approachable information. On the other hand, the ratings of arousal and dominance were surprisingly similar between the stimulus types. Instead, parametrical variations, experimental contexts, and modality affected the results. For instance, high intensity stimuli were always rated as more arousing and dominant than less intense stimuli regardless of the technology used. The behavioral measurements showed that more arousing stimuli were differentiated faster and more accurately than less arousing stimuli. Finally, the SCR measurements were also closely related to stimulus arousal so that haptic stimuli rated as arousing also activated ANS.

From an application point of view, it can be noted that the studies in the current thesis were motivated by the starting point that haptics could be used for designing HTI systems capable of affecting and evoking human emotions. It is likely that the results of the current thesis can be utilized in designing haptics-based affective computing.

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