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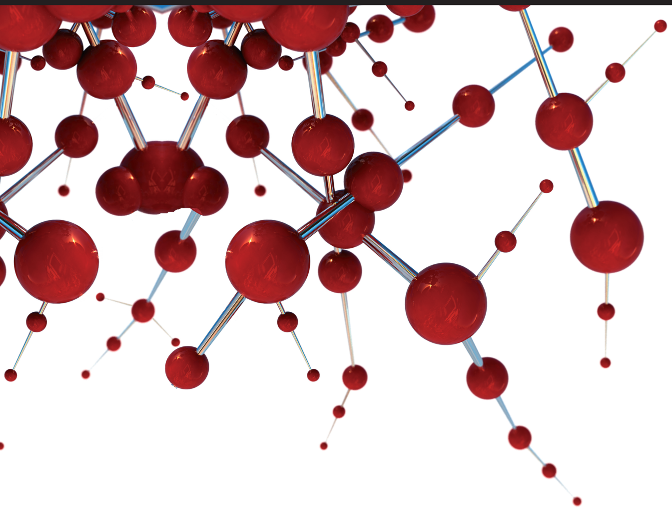

Jani Lylykangas

Regulating Human Behavior with Vibrotactile Stimulation

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ACADEMIC DISSERTATION
To be presented with the permission of the Faculty of Communication Sciences of the University of Tampere, for public discussion in the Pinni B5103 Campus Chapel on May 19th, 2017, at noon.

Faculty of Communication Sciences
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Dissertations in Interactive Technology, Number 25
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ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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Abstract

Using four carefully controlled laboratory experimentations, the aim of the present doctoral thesis was to contribute a profound understanding of how touch-based information can be designed to be easily understood (e.g., to change tempo in physical exercise) and result in fast and appropriate responses (e.g., to apply brakes while driving). As tactile stimulation is linked to the human emotional system, emotion-related ratings and user experiences of the stimulations were also analyzed. This was done to ensure that the stimulations could be delivered without the risk of being annoying or feeling uncomfortable.

Two experiments investigated the first impression -based interpretation of systematically varied vibrotactile speed regulation cues in order to, for example, change the tempo of physical exercise. The results showed that semantic associations between three types of vibrotactile speed regulation cues and their meanings were interpreted in a uniform fashion among the participants so that the ascending, constant, and descending vibration frequency profiles of the stimuli were mainly associated with speed acceleration, constant speed, and speed deceleration, respectively. Subjective ratings of pleasantness and the arousability of the stimuli coincided closely with the semantic content of the three speed regulation cues. For example, stimuli cueing to maintain speed as constant were rated as pleasant and non-arousing, whereas stimuli associated with cues suggesting a speed change (i.e., to accelerate or decelerate speed) were rated as more unpleasant and arousing. Thus, the results supported the view of the regulatory powers of emotions in guiding human behavior and decision making.

The other two experiments investigated the physical connectivity between vibrotactile stimulation and consequent bodily responses. Visual, vibrotactile, and combined visual-vibrotactile stimulations were used to present instructions on when to initiate a leg movement in two contexts of use: in physical training to perform knee lift exercise and during simulated driving to perform emergency braking. The results showed that vibrotactile instructions were feasible in initiating body movement as an alternative or supplement to visual instructions. For example, brake reaction times were significantly shorter in vibrotactile than visual warnings.

In conclusion, the results showed that relatively simple vibrotactile technology can be used to effectively communicate different types of instructions on how to regulate behavior. Further, the results showed that

vibrotactile cues can be experimentally designed so that they are intuitive in terms of being clearly intelligible without earlier experience and even without teaching them in any way. In addition, vibrotactile instructions turned out to be effective and preferred in compensating and augmenting visual instructions. Together, the results suggest that carefully designed and systematically tested vibrotactile stimulations can be functional in interactive applications able to deliver guidance on how to regulate behavior, for example, in physical exercise and driving. In general, the results showed that systematic research can result in easy-to-understand tactile human-technology interaction, one of the key aims of the haptics research community.

Acknowledgements

I would like to express my sincere gratitude to all those people who provided assistance and contribution throughout my thesis. First, I wish to thank my supervisor, Professor Veikko Surakka, who encouraged me to start this effort and gave his invaluable support and guidance always when needed. Without Veikko's catching enthusiasm and dedication, this thesis would not have been possible. I am also grateful for Professor Roope Raisamo for offering me the possibility to work in my first haptics research project in 2006, which later turned out to be the cornerstone of this thesis. Roope has the exceptional ability to create innovative research consortiums and lead them in a highly positive and inspiring atmosphere.

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The research was carried out at Tampere Unit for Computer-Human Interaction (TAUCHI), which has offered excellent facilities to work. I have been privileged being able to work in such a supportive and friendly community among absorbing topics through these years. I especially thank all the past and present members of the Research Group for Emotions, Sociality, and Computing (ESC) and Multimodal Interaction Group (MMIG), and I owe my special thanks to all my co-authors.

My parents and my sister have always encouraged and supported my educational interests unconditionally and without giving any pressure, of which I am deeply grateful. Getting the Commodore 64 in Christmas '84 started this journey through life with interactive technology that I am still fascinated by. Special, loving thanks go to Riina and, of course, our children Eeki and Iita. Watching them playing and adopting new things with an endless, open-minded curiosity has given me the grandstand view to realize how the evolution of interactive technology is forming a great part of the younger generations' lives.

Tampere, March 23, 2017

Jani Lylykangas

Contents

List of Publications

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

Author's Contribution to the Publications

The publications and experiments of this thesis were conducted in research projects involving close collaboration between academic, communal, and industrial partners. The initial ideas of the studies were proposed by Professor Veikko Surakka (Publication I and IV), Esa Tuulari (Publication II), and Arvo Laitinen (Publication III) and refined by the present author. The person responsible for implementing the field experiment in Publication III was Jani Heikkinen. Katri Salminen had the main responsibility of data collection and data analysis regarding Publication IV. The technological prototypes used in Publications III and IV were designed in collaboration with the present author, Kalle Myllymaa, and Ahmed Farooq. Final implementations were made by Kalle Myllymaa (Publication III) and Ahmed Farooq (Publication IV). The present author was the main author in each publication.

1 Introduction

The sense of touch serves several purposes for human behavior. It can, for example, provide information about the structure and form of objects; it offers information for the regulation of behavior (e.g., withdrawing fingers from hot surfaces); and it can mediate the emotional tone of another person's touch. Thus, the sense of touch is a profound means of interaction with objects, surroundings, and other people. In human-technology interaction (HTI), the potential of utilizing the sense of touch has recently been ascertained.

The term "haptic(s)" refers to technology-mediated touch sensations used in HTI. The use of the human sense of touch (i.e., haptic modality) as a communication channel is a promising alternative to visual and auditory modalities when users' ability to process sensory information is reduced due to aging, physical impairment, or distracting situation (Raisamo et al., 2009).

Currently, haptics is being used in many devices and contexts like mobile phones, video gaming, and driving. A familiar example is the vibration alarm of a mobile phone, which can be useful in socially delicate situations or when vision and hearing cannot be used. However, many applications lack the careful experimental research background about what functional haptics really is from the perspective of human perception and behavior. Knowledge of how vibrational stimulations are perceived at an emotional level is not particularly well known either. The present study addresses these questions by means of carefully controlled experimental research.

Interaction with devices has traditionally relied heavily on visual and auditory senses. This is the case despite the fact that the cognitive processing of visual or auditory information can be problematic in many situations due to limitations relating to human mental capacity (Oulasvirta, Tamminen, Roto, & Kuorelahti, 2005). Although the sense of touch is essentially involved in the everyday use of technology, it is only quite recently that research on developing haptic features in computers and mobile devices to actively support HTI has emerged. As technology is nowadays increasingly used on the move, there is an increased need for safe and effortless interaction in situations in which our vision and hearing are needed for other purposes like observation of the environment. Finding new ways to utilize the haptic modality offers a realistic potential for safer and more natural interaction with technology in various contexts, including physical exercise and driving, both of which were examined in the current doctoral thesis.

For example, visual and auditory information of a wearable heart rate monitor can be difficult to follow while jogging because vision and hearing need to be focused primarily on the environment. In this kind of situation, vibration signals felt in the body can inform the jogger about changes in the heart rate without interfering with the focus of visual and auditory attention. However, current devices use binary-type (i.e., on/off) vibration alarms, which are limited in the sense that they are incapable of conveying the actual meaning of the alarm. Therefore, there is a need to develop haptic stimulations so that visual or auditory information would not be required to confirm, for example, whether to slow down or speed up the exercise.

There is evidence that haptic stimulation can convey much richer information than simple alarms. Brewster and Brown (2004a, 2004b) introduced tactile icons as structured, abstract messages that can be used for presenting information via the sense of touch. They suggested that distinguishable and identifiable iconic information can be encoded by manipulating, for example, the frequency, amplitude, duration, rhythm, and spatial location of the haptic stimulation. One area in which haptics has real potential is its utilization to inform people about how to regulate their behavior during physical exercise. Rovers and van Essen (2006) introduced a gym equipment mediating iconic haptic guidance that provides information about overly low or high heartbeat by stimulating the exerciser's palms. The results showed that the icons were noticeable during the exercise, but the downside was that the interpretation required referring to visual information in order to understand and eventually learn the icons' meanings.

In general, there is evidence that haptic stimulation can complement and even substitute visual and auditory feedback in terms of alarming and mediating meaning-carrying information for behavioral regulation. It should be noted, however, that in earlier studies, participants have been provided with guidance or an opportunity to first learn the meanings of the stimulations. This type of individual priming is, of course, impossible when considering the everyday use of haptic icons in consumer devices. It is also known that people most typically want to learn how to use new devices and applications based on their intuition instead of reading manuals (e.g., Novick & Ward, 2006; Rettig, 1991). Intuitiveness is frequently referred to as an important factor in HTI (Naumann et al., 2007), but controlled experimental research in this area has been virtually non-existent. Thus, there is a clear demand for finding new ways to offer easily understandable haptic information and, as a consequence, pave the way for devices that could be introduced in an effortless "out-of-box-experience" fashion without extensive learning.

While learning to use a new device, our thoughts vary along the dimension of accessibility – some ideas come to mind much more easily than others (Kahneman, 2003). Kahneman (2003, 2011) introduced two generic modes of human cognitive functioning: 1) an intuitive mode in which judgments and decisions are made automatically and rapidly and 2) a controlled mode, which is deliberate and slower. When considering the intuitive way of responding to an arbitrary touch stimulus, it can be processed either on the basis of earlier experiences like associating ascending vibration frequency with accelerating speed, or the response can be innate based on biological evolution like pulling a limb away from an unexpected touch sensation.

The problem with the intuitive mode is that, although it is almost instantaneous, it often leads to a wrong interpretation, whereas the controlled mode, which is more likely to result in accurate interpretation, is often too slow. A concrete case of a time-critical HTI application is exemplified by the forward collision alarm of a car, which exemplifies the extreme importance of a response that needs to be fast and accurate at the same time. When considering touch-based information delivery, the system should support the most obvious and intuitive way of responding to it.

The aim of the present doctoral thesis was to enable a profound understanding, with carefully controlled laboratory experimentations, of how touch-based information could be designed for ease of understanding (e.g., to change tempo in physical exercise) and result in fast and appropriate responses (e.g., to apply brakes while driving). As tactile stimulation is linked to the human emotional system (e.g., Ackerley, Carlsson, Wester, Olausson, & Backlund Wasling, 2014; Koskinen, Kaaresoja, & Laitinen, 2008; Salminen et al., 2008), emotion-related ratings and user experiences of the stimulations were also analyzed. This was done to ensure that the stimulations could be delivered without the risk of being annoying or feeling uncomfortable.

2 The Sense of Touch

The human skin provides us with information about physical objects that are in direct contact with it as well as about ambient conditions such as wind, air temperature, and humidity around us. Thus, the sense of touch serves as a means to experience, explore, and interact with the environment. Its importance to competition and survival in the phylogeny of the entire animal world is undeniable (Kalat, 1998). Touch information has helped species survive by providing informing about when to avoid harmful conditions, such as coldness as well as burning sunshine, and enabling quick reactions to pull back from harmful objects.

In relation to humans, mechanisms to react to tactile stimulation are among the first to develop, as evidenced by the palmar grasp reflex of a fetus (Jakobovits, 2009). The essence of the sense of touch through the whole life cycle is demonstrated by the ability to respond to tactile stimulation in situations where humans are unresponsive to other external events like visual and auditory stimulations (Dolce & Sazbon, 2002). Touch is also centrally linked to social interaction and the human emotional system. Touch enables pleasant and relaxing experiences, such as a gentle massage, but it can also mediate negative connotations and cause unpleasant and highly arousing reactions. Even a relatively neutral stimulation like a poke on a shoulder will instantly grasp our attention if it happens unexpectedly. Thus, touch sensations can orient our attention, elicit emotional reactions, and change our behavior, for example, to withdraw or approach external stimuli.

The somatosensory nervous system, which provides sensations from the surface and inner parts of the body, consists of many sub-modalities.

Through these sub-modalities we are able to explore and distinguish the shape and weight of objects, feel pressure, vibrations, temperature, pain, and the position and movement of body parts (Kalat, 1998). A general term *haptics* often used in HTI covers somatosensory sub-modalities, as illustrated in Figure 1. Sub-modalities falling into the cutaneous perception category receive inputs from the skin surface. An example of a cutaneous technology utilized in HTI is a vibration alarm of a mobile phone. In contrast to the cutaneous modality triggered by external events, inputs for kinaesthesia and proprioception come mainly from inside the body as a result of movement, position, and force dynamics of muscles, tendons, and joints. An example of a kinaesthetic HTI application is a force feedback steering wheel that transmits dynamic steering torques to a gamer's hands.

The fundamental function of the human somatosensory nervous system is behavior control. Seamless interaction between somatosensory input and muscle control is continuous and enables complex and fine-grained bodily movements. Afferent pathways deliver nerve impulses from the sensory neurons of the peripheral nervous system (NS) towards the central NS where the touch information is processed. If the interpretation requires a bodily response, the efferent pathway from the central NS sends signals toward the motor neurons of the peripheral NS, which executes the desired motor responses. The following chapters introduce the physiology of this system, which forms the basis of touch sensations and consecutive body movements.

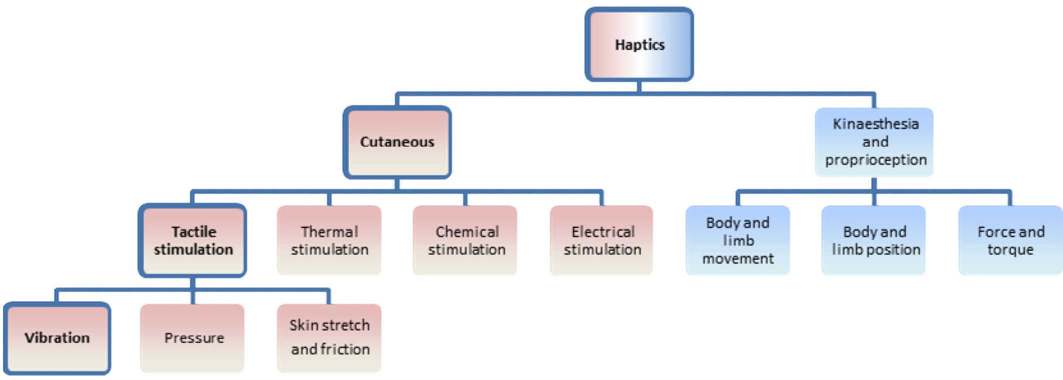


Figure 1. The main components of haptic sensation (excluding pain). The framed boxes illustrate the scope of this thesis. Adapted and redrawn from van Erp et al. (2010) and Goldstein (1999).

2.1 Mechanoreceptors and Neural Channels

The majority of the body's surface consists of hairy skin, a tissue containing hair follicles. The remaining surface is called glabrous skin, which is a tissue without naturally growing hair, such as the fingertips, palms, and soles of the feet (Freberg, 2010). Both glabrous and hairy skin are anatomically divided in three layers, *epidermis, dermis,* and *subcutaneous tissue (or hypodermis)*, with a gamut of sensory receptors, as shown in Figure 2. Each skin layer in both hairy and glabrous skin has a characteristic concentration of sensory receptors. Hair follicle receptors respond to the movements of body hairs, and free nerve endings provide information on temperature (i.e., thermoreceptors) and pain (i.e., nociceptors).

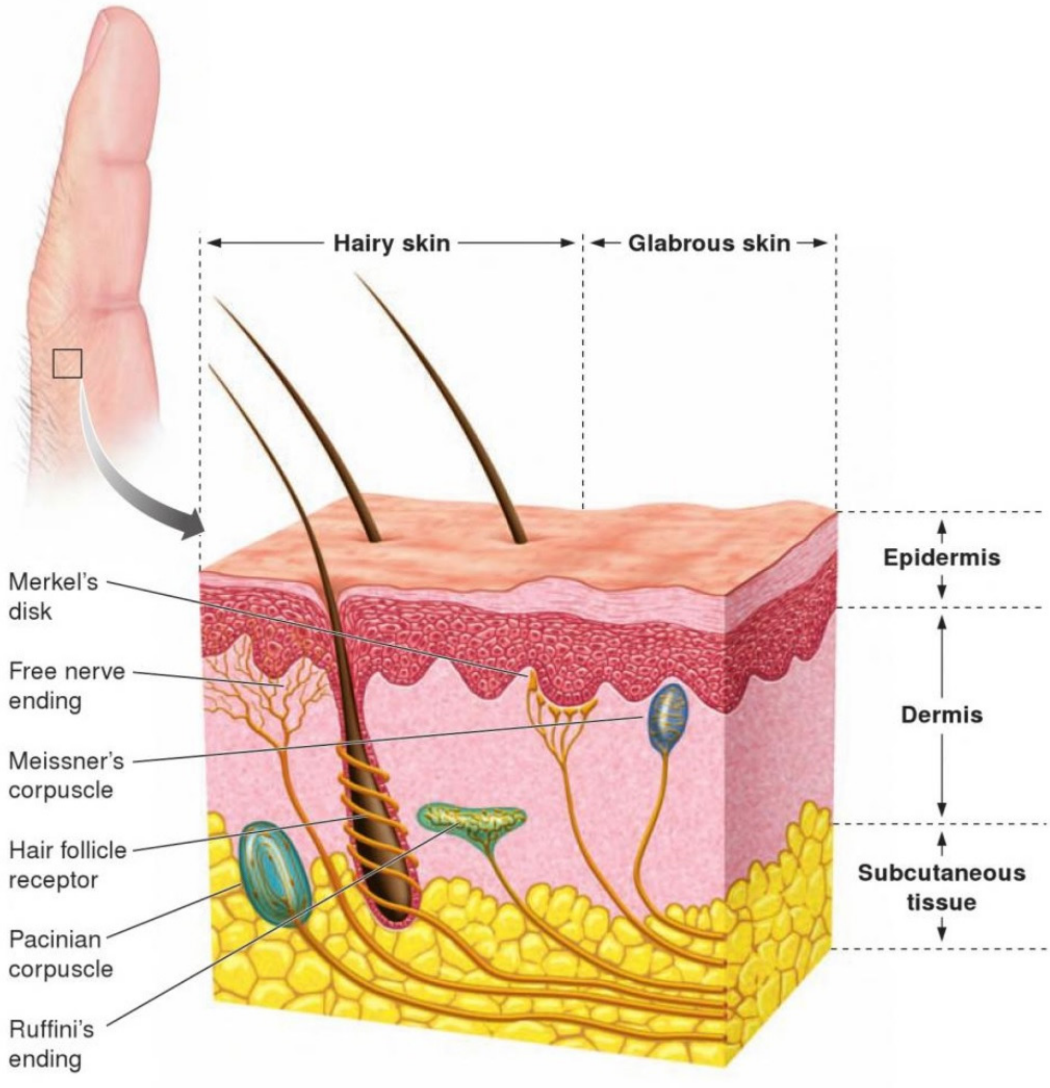


Figure 2. Cross-section of skin and the main cutaneous receptors. From Freberg, *Discovering Biological Psychology*, 2E. © 2010 South-Western, part of Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions

Glabrous skin is, by definition, more sensitive to tactile stimulation than hairy skin. It includes four main types of touch-sensitive receptors (i.e., mechanoreceptors), which are specialized to respond to different types of mechanical stimulations:

1) Merkel receptors located in the epidermis-dermis borderline have the simplest structure and are specialized to feel pressure, which makes them sensitive to edges, ridges, and corners (Johnson, 2001).
2) Ruffini endings located in the dermis are sensitive to skin stretch.
3) Meissner corpuscles lie in the dermal ridges and respond to slow-frequency vibrations.
4) Pacinian corpuscles are the deepest located mechanoreceptors in the hypodermis layer, but they can also be found in other places like the intestines and joints. Pacinian corpuscles are sensitive to vibrations around 10–500 Hz (Goldstein, 1999). The nerve ending of the Pacinian corpuscle is surrounded by several onion-like layers, which function as mechanical filters to protect the receptor from firing to the low-frequency stresses and strains of ordinary manual labor (Johnson, 2001).

The most sensitive parts of glabrous skin such as fingertips have up to 350 mechanoreceptors in one square millimeter area (Kalat, 1999). Except for Meissner corpuscles, mechanoreceptors can also be found in hairy skin, but with smaller density. Pacinian and Meissner corpuscles are classified as fast adapting (FA) receptors as they respond only to the initial and final contact of a prolonged stimulus on the skin. In contrast, Merkel disks and Ruffini endings are classified as slowly adapting (SA) receptors, which continue to respond during a constant mechanical stimulus (McGlone & Reilly, 2010). Table 1 summarizes the key features of the four mechanoreceptors.

Receptor	Skin type	Responds to	Receptive field	Adaptation rate (fiber)
Merkel disks	Glabrous and hairy skin	Pressure	Small	Slow (SA I)
Ruffini endings	Glabrous and hairy skin	Stretch	Large	Slow (SA II)
Meissner corpuscles	Glabrous skin	Stroke and flutter	Small	Fast (FA I)
Pacinian corpuscles	Glabrous and hairy skin	Vibration	Large	Fast (FA II)

Table 1. The general mechanoreceptor types and their main characteristics. Adapted from Kalat (1996) and Vallbo and Johansson (1984).

Mechanoreceptors differ from each other with respect to the size of a receptive field on the skin surface. Merkel disks and Meissner corpuscles have small receptive fields and, thus, better spatial resolution than Ruffini endings and Pacinian corpuscles, which have larger receptive fields. Each mechanoreceptor type is associated with a special receptive channel and type of fiber according to their adaptation rate, as shown in Table 1. The fibers deliver touch information towards the brain via medial lemniscal pathways in the spinal cord. Depending on the fiber type, different types of information, such as touch and temperature, take different routes and are projected onto different parts of the somatosensory cortex for further processing. The afferent pathway, from the mechanoreceptors in the skin to the brain's somatosensory cortex, is illustrated in Figure 3. The somatosensory cortex located in the posterior wall of the central sulcus receives input primarily from the contralateral side of the body (Kalat, 1996).

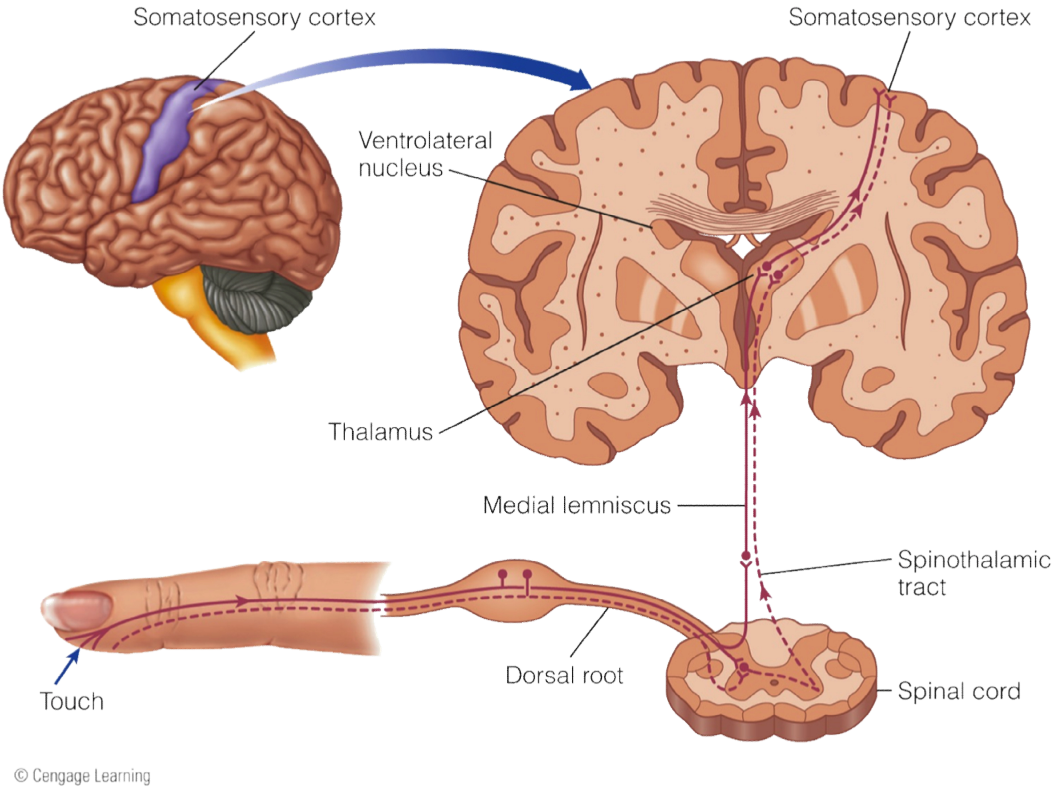


Figure 3. The afferent pathway from the skin to the brain. Nerve fibers from skin receptors enter the spinal cord through the dorsal root. Touch-based signals travel along the lemniscal pathway (solid line), whereas the spinothalamic pathway (dashed line) transmits signals related to pain and temperature. From Goldstein, *Sensation and Perception (with Virtual Lab Manual CD-ROM)*, 8E. © 2010 South-Western, a part of Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions

The present thesis focused on cutaneous sensations, which were created with mechanical manipulation of the skin by vibration stimulations (Figure 1). Thus, the stimulations mainly resulted in the activation of Pacinian corpuscles and FA II fiber.

Several physiological, individual, and external factors affect the ability to sense vibrations. A body of psychophysical research has focused on defining perception and discrimination thresholds in terms of spatial and temporal acuity in different body locations. In general, glabrous skin areas, including soles and the ventral side of the palms and fingers, are more sensitive than the hairy skin covering other body sites. Optimal sensitivity has been obtained at frequencies of 150–300 Hz for all body locations (Jones & Sarter, 2008). The overall sensitivity of an individual changes over the life span and depends on the context. The ability to sense vibration, for example, decreases with age (Wickremaratchi & Llewelyn, 2006; Verrillo 1979, 1980) and during physical movement (e.g., Post, Zompa, & Chapman, 1994). In addition, ambient vibrations of the environment can mask the perception of vibratory stimulation and impede its utility, for example, in mobile devices (Hoggan, Brewster, & Johnston, 2008). Karuei et al. (2011) found that masking the effects of body movement artifacts on vibration perception can be compensated by using sufficient stimulus intensity. Evidence of this has been shown in many studies in which a wide variety of body parts has been found applicable for stimulation during physical movement and exercise (van Erp, Saturday, & Jansen, 2006).

2.2 Perceptual Process

The perceptual process from touch stimulation to recognition in the brain includes multiple phases. Goldstein (1999) separated the process into six subsequent events. The starting point is a stimulus in the environment such as an insect on the hand, which is referred to as a *distal stimulus*. The next step is the transformation of the distal stimulus to a *proximal stimulus*, which is the stimulation of the tactile receptors of the hand. For example, the Merkel disc receptors, which are sensitive to pressure, respond mechanically to the light touch of an insect. This is followed by *transduction*, which is the transformation of the mechanical energy into electricity in the receptors. Then, *neural processing* takes place, during which electrical impulses travel through a network of neurons toward the brain. The neural processing time differs between the senses as it is typically faster for auditory than for visual stimuli (approximately 10 vs. 50 ms, respectively). For touch, however, the length of the neural pathway between the stimulus and the brain affects the processing time. For example, the neural processing time from a toe is about 35 ms, while from the nose, it takes only 5 ms (Vroomen & Keetels, 2010). When the electrical impulses reach the somatosensory cortex, the conscious *perception* (sometimes referred to as sensation) of being touched by something is created. *Recognition* is the subsequent function, which is our ability to place the perception in a category that gives it its meaning (Goldstein, 1999). This is enabled by comparing the perception to other similar tactile experiences stored in our memory. Together, these multiple functions – from a distal stimulus to its conscious recognition – form a perceptual cycle, which is a continuously changing, dynamic process without an actual end point.

Sometimes, the perception and recognition of a touch stimulus leads to action. Depending on the situation and earlier experiences, we may choose, for example, to approach or withdraw from the stimulus. In case of a potentially threatening thing such as spider, we may, for example, crush it, shake it off, or just freeze. The activation of muscles required for the chosen action is initiated in the primary motor cortex, which is located on the anterior wall of the central sulcus next to the somatosensory cortex. As is the case with the somatosensory cortex, each body part has a specific and contralateral representation in the primary motor cortex. In fact, the topographic structures of the primary motor and somatosensory cortexes have a very similar arrangement.

After the initiation of a body movement, muscle control is regulated by a complex mechanism, which is a mix of voluntary and involuntary (i.e., automatic) processes. Involuntary activation includes the spinal cord level activity loop between the proprioceptive feedback and the muscles. For example, while lifting a leg, the muscular system across the whole body activates and automatically adapts its functions to maintain body balance and to control movement. The importance of cutaneous and proprioceptive feedback with respect to muscle control is demonstrated by a deteriorated ability to regulate grip force with an anaesthetized hand (Johansson & Westling, 1984; Westling & Johansson, 1984).

In summary, the ability to feel our physical surroundings is a major prerequisite to interacting with the environment. Moreover, quick responses to, for example, engage with or withdraw from potentially harmful touch sensations have been vital for survival and development among various species. The sense of touch offers a diverse range of information from the external world via the skin as well as the internal state of our body, such as the position and movement of the limbs. Mechanical stimulation of the skin activates different mechanoreceptors, depending on the type of touch (e.g., vibration, pressure, and stretch). Touch information constantly, but often subconsciously, directs our attention and guides our behavior. Together, the interplay between the human somatosensory system and the motor functions enable the control of basic bodily movements.

3 Vibrotactile Stimulation in Human-Technology Interaction

3.1 HUMAN-TECHNOLOGY INTERACTION

The history of the interaction between humans and information technology devices as a discipline is relatively short. The origin of human-computer interaction (HCI) can be traced to the early 1980s when personal computers (PCs) began to emerge in ordinary (i.e., non-expert) people's homes and work places. Before that, computers were mainly operated by well-trained information technology professionals in large companies and institutions (MacKenzie, 2013).

The shift of computer users from professionals to the general population at the turn of 1970s and 1980s brought new challenges to developers to create products that were also usable for non-professional customers. This opened new markets for computers, software, and various accessories. The interaction between the human operator and the computer system became a substantial research topic. It boosted the inclusion of human factors in a multidisciplinary focus of academic research in HCI. At present, the field is a combination of many disciplines, including, for example, hardware and software engineering, psychology, usability, and user experience engineering.

The term *human-technology interaction* (HTI) is often used in parallel with the original term of HCI. This is probably because computers are now increasingly embedded in various consumer devices and other technologies besides the conventional PC. When using other technical appliances, such as the navigation system of a car, we operate a microcomputer that does not resemble our conventional image of a computer. Consequently, people experience that they are using one among a wide variety of technological devices rather than a computer in its popular meaning. In this doctoral study, vibrotactile interfaces were visible to the participants in forms of wearable straps (Publications I, II, and III) and a car foot pedal (Publication IV), but the actual computers used to control them were hidden in the background. Therefore, it seemed natural to use the term HTI in the current work to describe the chosen context, which can be regarded as being somewhat wider and more distinct from what traditional HCI is about.

Experimental research methods in HTI are derived largely from the tradition of experimental psychology. This research typically includes objectively measured behavior of a participant and his or her subjective experiences regarding interaction during an experimental task. Objective performance measures are related to factually obtained and quantifiable data such as the time used to perform a given task and the accuracy of the response. By contrast, subjective (i.e., self-reported) performance measures can be collected to gain insight about the participant's own thoughts regarding, for example, the difficulty of the interaction. Subjective ratings can also be used to obtain information such as preferences and feelings that cannot easily be measured with objective methods.

Typical examples of objective metrics in HTI research include performance and behavioral measurements, which can be directly observed and quantified with special instruments. These types of metrics can include measurements such as task success rate and stimulus detection accuracy. Reaction time (RT), commonly defined as the interval from the onset of a stimulus presentation to a participant's response (Pachella, 1974), is another typical example of an objectively measured behavioral data. Other properties of bodily responses, such as the speed and intensity of physical movement, can be objectively quantified, for example, by using wearable sensors measuring the dynamics of body movement (e.g., Lindeman, Yanagida, Hosaka, & Abe, 2006; Zeng & Zhao, 2011).

Subjective metrics have a long history in psychology, and these methods have also been adopted in HTI research. A typical subjective metric in usability evaluations is to ask participants to rate how easy or difficult each task was. The rating is typically asked according to a 5, 7, or 9-point scale. A *Likert scale* type question is formed by a statement, which can be either negative (e.g., "This task was difficult to complete") or positive (e.g., "This task was easy to complete). A common example of a 5-point response scale reflecting the level of agreement is 1 = Strongly disagree, 2 = Disagree, 3 = Neither agree nor disagree, 4 = Agree, 5 = Strongly agree. Another technique is to use the *semantic differential* method (Osgood, Suci, & Tannenbaum, 1957), which consists of pairs of bipolar (i.e., opposite) adjectives such as difficult/easy at the negative and positive ends of the scale. (Tullis & Albert, 2008.)

Interaction with technology is also centrally associated with human emotions. Emotions have a fundamental effect on why some products stand out from the masses, while some are left unused. A generally agreed definition of an emotion response contains three main components: physiological reactions, behavioral expression (or behavioral tendency), and subjective experience (Gross, 2010). A widely acknowledged model referred to as the *dimensional theory of emotions* conceptualizes emotions as a continuum (Schlosberg, 1954; Wundt, 1896) instead of separate categories such as fear, anger, disgust, sadness, enjoyment, and surprise (e.g., Ekman, 1992). In addition to psychological research, the dimensional model of emotions has been utilized in HTI to track users' feelings, for example, while interacting with a computer system. It is widely acknowledged that the spectrum of conscious emotional experiences can be mapped using two dimensions: valence (i.e., pleasantness) and arousal (Brave & Nass, 2009). The method reflects these dimensions on bipolar rating scales. The bipolar adjective pairs for the valence and arousal scales are unpleasant/pleasant and relaxed/aroused, respectively (e.g., Bradley & Lang, 1994; Mehrabian & Russel, 1974).

User experience evaluations are another way of analyzing people's feelings and experiences in HTI. ISO 9241-210 (2010) defines user experience as a "*person's perceptions and responses that result from the use or anticipated use of a product, system or service.*" The AttrakDiff questionnaire (Hassenzahl, Burmester, & Koller, 2003; Hassenzahl, 2003) is likely the most established and widely used user experience evaluation method for interactive products. The questionnaire consists of 28 seven-point bipolar scales with end-points that are also opposite adjectives (e.g. confusing/clear, good/bad). In a way, it has a strong resemblance with the measures of the emotion-related bipolar rating scales. The AttrakDiff scales are divided into four main categories. The *pragmatic quality* (PQ) scales are close to the traditional definition of usability (i.e., assessments on how useful and easy the system is to use). Hedonic quality reflects a product's potential to support pleasure in use and ownership, that is, the fulfillment of psychological needs (Bevan, Liu, Barnes, Hassenzahl, & Wei, 2016). It is divided into two sub-categories: stimulation and identification. *Hedonic qualities of stimulation* (HQS) scales reflect the possibility of gaining new knowledge and self-development with the product. *Hedonic qualities of identification* (HQI) scales can be explained as social self-expression through physical objects and possessions. Finally, *attractiveness* (ATT) scales describe the global value of the product based on the perception of quality.

Other typical subjective metrics used in HTI research can include post-experimental rankings and interviews. If an experimental design has two or more alternative independent variables (e.g., visual, tactile, and visual-tactile interaction modalities), people can then be asked to rank the alternatives in terms of preference, importance, and so forth. Additionally, open-ended questions can be included to allow the participants to express reasons and explanations relating to their ratings and rankings in greater detail (Tullis & Albert, 2008).

3.2 VIBROTACTILE INTERACTION

Interaction between technology and the human operator is typically based on visual, auditory, and haptic modalities. For example, when pressing a typical hardware button of a computer keyboard, vision is used for selecting the object and for guiding the finger. The haptic modality (both tactile and kineasthetic) is involved when a finger touches the button and moves it downward. The pressing of the button may also result in auditory feedback, providing confirmation of a completed press. In contrast to the passive and purely mechanical haptic feedback described above, digitized haptic feedback is less frequently utilized than digitized visual and auditory feedback modalities in HTI-applications. One comprehensive example of a digitized multimodal application is a mobile phone's touchscreen keyboard in which vibration presented together with the visual animation and auditory tone indicates a successful button press and, thus, mimics the functionality of a hardware keyboard. It has been found that vibrotactile feedback improves the speed, accuracy, and subjective experience of touchscreen typing (e.g., Fukumoto & Sugimura, 2001; Hoggan et al., 2008).

In addition, tactile stimulation has been found useful when vision and hearing are overloaded or cannot be used due to a sensory deficit. Earlier research has shown that people with visual or aural impairment can especially benefit from vibrotactile sensory substitution in many ways. In fact, the earliest vibrotactile applications were developed for deaf and hard of hearing people to render speech into touch sensations (Gault, 1925, 1927). The use of digitized vibrotactile stimulation for interaction purposes among sighted and hearing users emerged much later along with the invasion of computing devices. Among the first application areas in the consumer market were the vibration alarms of pager devices, which were followed by mobile phones. In addition to the sensory substitution systems, vibrotactile interaction displays have been developed for numerous purposes, including spatial orientation and guidance, notifications and alerts, and feedback on the successfulness of control actions in HTI (Jones & Sarter, 2008). Currently, vibrotactile features have become omnipresent, for example, in touchscreen operated communication devices in providing augmented touch sensation from virtual buttons.

There is evidence that the tactile interaction modality has some advantages in comparison to its visual and auditory counterparts. In general, using vibrotactile stimulation for alerts or communication has demonstrated advantages over visual stimulations in presenting the same information (Jones & Sarter, 2008). As an example, people typically respond faster to vibrotactile than to visual stimulation, which has been found useful, for example, in designing time-critical warnings (e.g., de Rosario et al., 2010; Scott & Gray, 2008). There is also evidence that in comparison to auditory stimuli, response times to tactile stimuli are less affected by distraction (Mohebbi, Gray, & Tan, 2009) and the cognitive load of the observer (Hanson, Whitaker, & Heron, 2009).

Actuator Technologies

There are several methods of delivering digitized, technology-mediated tactile stimuli to the human skin. The majority of tactile user interfaces utilize vibration stimulations mainly due to the affordability and technical simplicity of vibrotactile actuators. Vibrotactile technologies and, especially, their controlling possibilities have been in development since the early days of the technological revolution. Two main types of vibrotactile actuators, which were also used in the current thesis, are introduced in the following paragraphs.

The eccentric rotating mass (ERM) motor is probably the earliest technology used to generate vibrational stimulation for information delivery. The vibration is generated by a DC motor, which rotates an unbalanced weight with respect to its shaft center point. ERMs are inexpensive due to their simple structure and high production volumes. The downsides include a slight operation delay caused by a time lag between the onset signal and the actuation of the motor (Choi & Kuchenbecker, 2013). In addition, the poor spatial resolution of the vibration and mechanical sound limit their use to some extent. Despite the flaws, ERMs are widely used in consumer devices such as mobile phones and video game controls. Two main variants of actuators are referred to as the rod and pancake according to the shape of their mechanical structures. The rod-shaped actuator has a long shaft for the eccentric mass, which typically rotates uncovered. The pancake actuator has a shorter shaft, which allows a full enclosure and protection of the rotating parts. Both types of ERMs were used in Publication III of this thesis.

Linear resonant actuators (LRAs) have an operation principle that resembles a conventional moving coil audio loudspeaker, and therefore, they are also referred to as voice coil actuators. Vibration is provided by the linear up and down movement of a coil, which moves a contact plate placed directly against the skin or an object. LRAs can create vibration with shorter delay than ERM-based actuators. In addition, LRA technology allows more accurate and versatile controlling of the stimulus parameters, including the duration, frequency, amplitude, and wave form (Choi & Kuchenbecker, 2013). In this thesis, LRAs were used in Publications I, II, and IV.

In addition to ERMs and LRAs, which were applied in the present thesis, there are also other actuator solutions, which are, so far, less frequently used in consumer products. Piezoelectric actuators provide linear movement by a plate that squeezes on one side and stretches on the opposite side when electricity is applied to it. As a result of consecutive back-and-forth bends, the piezo electric plate creates vibrations. In comparison to the ERM and LRA–based technologies, piezo actuators operate at a faster pace and enable more precise control of the stimulus parameters. In addition, piezos provide more localized stimulation than ERM motors. The negative aspects of piezo-based actuators are mainly related to low stimulus intensity, which somewhat limits their applicability. For example, piezo feedback has successfully been used in keypads (e.g., Lylykangas et al., 2011) and mobile phone touchscreen interaction (e.g., Poupyrev, Maruyama, & Rekimoto, 2002); however, the vibration alarm, which shakes the whole device, is beyond its capacity.

Displays

Tactile display is an artefact that presents digitized information via mechanical stimulation of the skin by means of various tactile actuators. Displays based on vibration actuators are currently more commonly used and studied compared to those based on other tactile sensations like pressure, skin stretch, or friction (Choi & Kuchenbecker, 2013), whose use has been mainly restricted to experimental prototypes and special applications such as physical rehabilitation aids (e.g., Jirattigalachote, Shull, & Cutkosky, 2011).

Perhaps one of the earliest vibrotactile displays dates back to the mid-1920s when Robert Gault published his first investigations on sensory substitution systems designed for aurally impaired people. The device transformed spoken speech into vibrations that were sensed by the palm of a hand (Gault, 1925). This was followed by a device called the teletactor, which transformed the auditory frequencies of speech into vibrations of five separate actuators in contact with a recipient's fingertips (Gault, 1927). Gault's pioneering research initiated the acquisition of knowledge about the data-processing capacities of the vibrotactile channel (Parisi, 2015).

Since the early days, different types of vibrotactile displays have been developed for sensory substitution and augmentation in various application areas. The displays can provide stimulation passively and actively. *Passive touch* occurs without the user's active manipulation or change in behavior (e.g., sensing a vibrating mobile phone alarm in the pocket). By contrast, *active touch* takes place when the touch sensation is produced in response to the user's movements (e.g., sensing vibrational feedback as a result of pressing a touch screen). Psychologically, passive and active touch are different phenomena; to apply a stimulus to an observer is not the same as an observer obtaining a stimulus (Choi & Kuchenbecker, 2013; Gibson, 1962). A self-produced tactile stimulus can be perceived, for example, as less ticklish than the same stimulus generated externally (Blakemore, Wolpert, & Frith, 1998).

Choi and Kuchenbecker (2013) classified displays into two main categories: *monolithic displays* vibrate the whole object to deliver a widespread vibrotactile cue, whereas *localized displays* vibrate one or more small zones on the skin. Most typically, monolithic displays are embedded inside a rigid structure, and localized displays are attached to the body with wearable straps and belts. The majority of current displays fall into the monolithic category. These include, for example, mobile phones and video game controllers. Currently, localized displays such as navigation belts with an array of tactile actuators (e.g., van Erp, 2007) are under extensive study but are less frequently used in commercial products. The number of applications needed to embed vibrotactile actuators and create vibrotactile displays is virtually infinite (Choi & Kuchenbecker, 2013). The most fundamental domains of currently used vibrotactile displays are introduced in the following paragraphs.

The majority of the state-of-the-art mobile devices generate vibrations using ERM actuators to provide vibration alarms and touchscreen feedback. Newer but less widely available use cases are touch-augmented videos such as commercials and movie trailers. Immersion Corporation has introduced a library of various pre-designed vibration effects for mobile application content providers. In addition, some mobile games utilize vibrational feedback.

In addition to the mobile domain, video gaming consoles are currently the main platforms utilizing vibrotactile technology. The first vibrotactile gaming device in the mass market was Nintendo 64 Rumble Pak introduced in 1997. It was a separately sold extension kit to the original gaming controller. This was soon followed by Sony's DualShock game control pad, which had two built-in actuators. Since then, vibrating gaming controllers have set themselves up in the gaming market. Vibrations are mostly used to enhance the experience of presence of the game play by sensory augmentation, which means that vibrotactile stimulation typically occurs in synchrony with the visually and aurally presented content and simulates events like explosions, collisions, and trembling.

An early example of a vibrotactile PC accessory was the Logitech iFeel mouse introduced in 2000. It was a conventional mouse equipped with an

ERM motor, which vibrated when a cursor hit window borders or functional spots such as buttons or links on a desktop. The utilization of vibrotactile stimulation in desktop and laptop computers has not emerged to the same extent as the gaming domain. A recent exception is Apple's Force Touch trackpad, which provides different touch sensations to fingertips depending on the force applied to the touch surface.

3.3 Meaningful Vibrotactile Information

There is evidence that vibrotactile stimulation can be encoded so that it has a certain meaning to its perceiver, even without the help of vision and hearing. The meaning-carrying content of the vibrations can vary from simple alarms and effects to more complex vibrational patterns, which are capable of delivering diverse and abstract information with high reliability when the stimuli are optimized for the context of use (Choi & Kuchenbecker, 2013).

A vibrotactile warning alarm is an example of a relatively simple piece of information. For example, in the automotive context, vibrotactile warning signals have been applied via the steering wheel (e.g., Chun et al., 2012), seat (e.g., Higuchi & Raksincharoensak, 2010), belt (e.g., Scott & Gray, 2008), and gas pedal (de Rosario et al., 2010), and they have been found beneficial in helping to avoid forward collisions. In many studies, vibrotactile warnings have resulted in shorter brake reaction times compared to visual warnings and no warning baseline conditions. However, beyond the simple alerting function, dynamic vibrotactile warnings varying, for example, in intensity and location, can convey more meaningful information to drivers and, thus, further speed up their responses to avoid collision (Meng & Spence, 2015; Meng, Gray, Ho, Ahtamad, & Spence, 2015).

Vibration has also been used in various other contexts to mediate relatively complex information. For instance, work in the field of sensory substitution has mainly concentrated on assisting the blind to "see" and the deaf to "hear" by using their sense of touch (Tan & Pentland, 2001). Vibrational patterns can deliver information on, for example, visual images (e.g., Bach-y-Rita, Collins, Saunders, & Scadden, 1969) and acoustic signals of speech (e.g., Gault, 1925, 1927; Keidel, 1973). In addition, recognition of more abstract pieces of information, such as alphabets (e.g., Linvill & Bliss, 1966; Rantala et al., 2009; Tan, Durlach, & Reed, 1997), have been investigated. For example, Rantala et al. (2009) used spatial location and rhythm-based coding to communicate Braille characters via a vibrating touchscreen of a mobile device. Their results showed that blind readers were able to identify individual characters with 91–97% accuracy after a short period of training.

Brewster and Brown (2004a, 2004b) introduced the concept of tactile icons, which are structured, abstract messages that can communicate information non-visually and non-aurally to complement or substitute the graphical or auditory feedback of the user interface. Similar to visual icons, tactile icons are symbols that can represent concepts in a more compact form compared to, for example, a textual description of a concept. The authors suggest that distinguishable and identifiable information can be encoded by manipulating, for example, the frequency, amplitude, duration, rhythm, spatial location, and spatiotemporal pattern of the tactile icons. Enriquez and MacLean (2008) separated iconic information in two representation models. *Semantic icons* represent information through literal or direct symbols that can be intuitively associated with familiar concepts, events, or things (e.g., using the sound of paper being crumbled to provide information about a computer file being deleted). By contrast, *abstract icons* have no intrinsic or cultural meaning, and they typically require learning before they can be understood.

Brown, Brewster, and Purchase (2006) analyzed the identification of vibrotactile icons providing information about types of phone alert and their priority. The icons were applied to a fingertip by using LRA technology. Nine different icons were created using three rhythms and three amplitude modulations of the vibrotactile signal within each rhythm. Different rhythms were used to encode alerts for phone calls, text messages, and multimedia messages. Low-, medium-, and high-priority alerts were encoded with low, medium, and high vibration amplitude modulations, respectively. The results showed that the icons were identified correctly with an accuracy of 71% when the chance level accuracy was 11%. Equal identification rates were also obtained with standard mobile phones using ERM actuators by Brown and Kaaresoja (2006). In these studies, the alert type in terms of vibration rhythm was based on abstract coding, which is impossible to recognize without learning. However, encoding the priority dimension by stimulus amplitude (i.e., low amplitude for low-priority and high amplitude for high-priority alert) can be regarded as an attempt toward semantic coding being potentially understandable without teaching.

Enriquez and MacLean (2008) investigated the learnability and recall of abstract vibrotactile icons in two learning conditions. In one condition, the association between ten icons and their meanings were chosen individually by the participants. In the other condition, the associations were determined arbitrarily. The results showed that 80% (chance level 10%) of the icons were correctly identified immediately after the learning session, and two weeks later, they were identified correctly at 70% accuracy. The identification rates showed no significant differences between the participant-chosen and arbitrarily assigned associations. Even though the results showed a relatively high longitudinal recall accuracy of the icons, they also suggested that it was not possible to facilitate the identification rate of the abstractly coded icons by allowing the participants to make their individual associations between the stimuli and their meaning.

The potential of iconic vibrotactile information has also been studied in computer-assisted guidance for controlling bodily activity. Rovers and van Essen (2006) introduced a gym device with tactile features; the handles of a cross-trainer were equipped with a matrix of twelve vibrotactile actuators, which mediated iconic guidance information by stimulating the exerciser's palms. The icons were designed to provide information about overly low or overly extensive training according to the exerciser's heart rate. For example, an overly extensive workout was represented as a signal consisting of a strong beat at the center of the palm and a weaker after beat at the lower palm. The results showed that the icons were noticeable during the exercise, but their interpretation required first referring to visual information to understand and eventually learn their meanings.

A further example in providing vibrotactile stimulation to control behavior comes from studies in which spatially varied stimuli have been applied with a wearable display. These systems typically encode relatively simple pieces of information such as navigation direction with multiple actuators embedded in a waist belt (e.g., Tsukada & Yasumura, 2004). In addition, spatiotemporal patterns implemented with two or more actuators at different body locations have been used to provide information about how a body movement should be made (e.g., desired movement direction of limbs) during skills training and physical rehabilitation (e.g., Spelmezan, Jacobs, Hilgers, & Borchers, 2009; Bark et al., 2011). In Lee and Sienko (2010), the task was to replicate prerecorded trunk tilt movements, which consisted of an anterior trunk tilt followed by a static hold and posterior tilt back to the upright starting position. The instructions were either visual, tactile, or combined visual-tactile cues. Visual instructions were provided with a virtual avatar representing the prerecorded example movements of an instructor. Tactile instructions were delivered with two separate vibration actuators placed on the trunk midline on the navel and back, indicating the anterior and posterior tilts, respectively. An offset of the vibration communicated the achievement of the desired tilt angle. The results showed that the participants mimicked example tilts significantly more accurately and faster with combined visual-tactile and tactile instructions compared to visual-only instructions.

In a follow-up study (Lee, Chen, & Sienko, 2011), the speed of the example trunk tilt movement was altered, and this time, only tactile instructions were provided. The results showed that slow (approximately 1.12°/s) example movements were mimicked more accurately than medium (approximately 2.0°/s) and fast (approximately 4.0°/s) example movements. Together, the results of Lee and colleagues (Lee & Sienko, 2010; Lee, Chen, & Sienko, 2011) indicate the serious potential of using tactile instructions to mimic the physical movements of another person in eyes- and hands-free fashion. The results showed that the example tilts were mimicked more accurately and faster with combined visual-tactile and tactile instructions than with visual instructions. However, apart from studies investigating the abstract encoding of iconic information and varied stimulated body location, other design characteristics as well as more varied dimensions of vibrotactile information remain largely unstudied in the behavioral regulation context.

3.4 Stimulus-Response Compatibility and Intuition in Decision Making

Knowledge of basic human information processing mechanisms is essential in the effective design of vibrotactile messages. Fast reaction to a prompting stimulation is desirable, especially for alarms that require immediate action. For example, driving safety-related notifications such as collision warnings should be perceived quickly, prompting an instantaneous response from a driver. Aiming at a highly efficient alarm design is crucial because it can be a matter of a fraction of a second whether to encounter or avoid a traffic accident.

There is evidence that tactile stimulation and motor response can have high spatial compatibility (e.g., Aglioti & Tomaiuolo, 2000). This is exemplified by a quick automatic reaction to withdraw a limb from a sudden, unexpected touch sensation. Following this analogy, a spatially congruent association between a stimulus and consecutive reaction would suggest that stimulation should be presented to the body location that is primarily required for the response (De Rosario et al., 2010). Applying stimulation to a foot to instruct a person to perform a foot lift in physical exercise, for example, would thus seem a rational way to proceed.

The phenomenon referred to as stimulus-response (S-R) compatibility is an example that highlights the bond between cognitive psychology and human factors research in the field of HTI; the former produces the basic understanding and principles that the latter utilizes and validates through application design (Alluisi & Warm, 1989). A high-level S-R connection has been shown to facilitate the speed and accuracy of a performed task in comparison to those with lower-level S-R connections. For example, when a visual stimulus, such as light, is presented in the left or right visual field and the subject is required to press either the left or right key in response, the response time is faster and more accurate when the stimulus and response are on the same (congruent) side than when they are on opposite (incongruent) sides (Umiltá & Nicoletti, 1990). Similar facilitative effects of spatial congruence have also been obtained for touch stimuli. Aglioti and Tomiaiulo (2000) found that a stimulus applied to either the left or right hand received a faster response from the stimulated hand than from the non-stimulated hand. Considering a high-level S-R compatibility (Wang, Proctor, & Pick, 2003) between a vibrotactile stimulus and its expected consequence in applied contexts, such as driving (e.g., braking response followed by a warning signal), it is important to ensure that the chosen response is appropriate for that particular situation.

There are two basic principles in mediating body movement instructions with a single vibrotactile actuator. The methods are referred to as *push* and *pull* metaphors (Jansen, Oving, & van Veen, 2004). The terms repulsive and attractive stimulation are sometimes used to depict the push and pull metaphors, respectively (Lee & Sienko, 2011). In the push metaphor, the touch stimulation is applied to the opposite side of the desirable movement, and thus, the body is moved away from the stimulus. By contrast, the pull metaphor stimulation suggests that the body is moved toward the stimulus. Both metaphors have been used in instructing bodily movements, but so far, it is not clear which metaphor is more natural in terms of S-R compatibility in different situations.

In general, studies comparing the functionality of the two metaphors have yielded mixed results. Evidence supporting push stimulation was reported by Lee and Sienko (2011), who studied vibrotactile instructions during the motion replication of anterior and posterior trunk bend tasks. The movements were instructed by stimulating either the anterior or the posterior side of the trunk. The results showed that stimulation using a push metaphor (i.e., an instruction to bend the trunk away from the vibration) outperformed stimulation using a pull metaphor (i.e., an instruction to bend the trunk towards the vibration) in terms of motion accuracy, speed, and error rate. There is evidence to suggest that pull metaphor stimulation can also be functional in initiating body movement. For example, Lee, Martin, and Sienko (2012) showed that random, non-meaningful vibrotactile stimulation applied to certain locations of the torso induced a reflexive postural shift of about one degree oriented in the direction of the stimulation. However, imperative stimulations for which the participants have been instructed to respond according to the pull metaphor have also been found applicable, for example, in hand rotation tasks (Jansen et al., 2004) and trunk tilt training (Kinnaird et al., 2016). In some cases, the functionality of push and pull metaphors has turned out to be unclear and merely depend on individual preferences (Spelmezan et al., 2009).

Interestingly, the S-R compatibility phenomenon is closely related to the concept of intuition. Intuitive uses of technology have frequently been regarded as an important characteristic in HTI, but in the scientific literature, concepts relating to intuition have been commonly avoided because their definitions have been regarded as vague or non-scientific (Naumann et al., 2007). A widely acknowledged conceptualization by Kahneman (2003) makes a distinction between deliberate reasoning and effortless intuition. He described intuitive decision making as *thoughts and preferences that come to mind quickly, spontaneously, and effortlessly under appropriate circumstances*. In this sense, S-R compatibility and intuition are slightly different phenomena; while S-R compatibility is regarded merely as physical in nature (i.e., the rapidity and accuracy of a motor response to a stimulus), intuition emphasizes more cognitive processes (i.e., the rapidity and accuracy of the semantic interpretation of a stimulus), and it does not necessarily manifest itself in motor responses. Intuition can be, for example, just an immediate feeling that something is either right or wrong.

Intuitive decision making is fast, while deliberative reasoning recruits more cognitive resources, making it a slower process. These two basic forms of thinking are often referred to as system 1 and system 2, respectively (Stanovich & West, 2000). System 1 functions automatically with little or no effort and without the feeling of deliberate control of thinking. Some of its basic mechanisms are inborn (e.g., directing attention to a sudden stimulus) and some become automatic along with training (e.g., calculating 2 + 2). The operation is often emotionally charged and governed by habit and, therefore, difficult to control or modify. By contrast, system 2 operations are slower, serial, effortful, and more likely to be consciously monitored and deliberately controlled; they are also relatively flexible and are potentially rule governed. System 2 is activated when system 1 runs into difficulty and fails to provide a meaningful answer to a current problem (Kahneman, 2003).

The main deficit of system 1 is that, despite being fast, it often results in a wrong outcome. To exemplify this, Kahneman presented a simple problem:

> *If a baseball bat and a ball cost $1.10 in total and the bat costs $1 more than the ball, how much does the ball cost?*

The instant and intuitive answer by many people is 10 cents. However, after more profound reasoning (i.e., using system 2), it becomes clear that this intuitive answer is incorrect. If the ball cost 10 cents, the bat would be $1.10, resulting in a total of $1.20. Therefore, the ball costs 5 cents.

The distinction between systems 1 and 2 is not always as clear as the examples introduced above. The systems may also function in parallel in our daily routines. Sometimes, even an overlearned task like driving, normally taken care of by system 1, needs to allocate resources from system 2. This may occur, for example, when a familiar context of the task changes to the unfamiliar (e.g., a Finn driving in left-hand traffic for the first time). Despite this interplay of automatic and more laborious thinking, people are prone to rely primarily on system 1 when they need to make decisions and solve problems (Kahneman, 2003). When using interactive systems, people try, at least in the first instance, to build the logic behind the interface by trial and error on the basis of their intuition and experimentation (Novick & Ward, 2006).

In summary, as touch information is centrally associated with the regulation of human behavior, the use of digitized tactile information offers richer potential in supporting the rapid, natural, and effortless use of technology than has so far been realized. For now, intuitive associations of vibrotactile stimulation and the information they may represent for users are a largely unstudied field in HTI. Nevertheless, earlier research has shown that, in many cases, vibrotactile displays enhance task performance compared to the use of, for example, visual displays (Prewett, Elliott, Walvoord, & Coovert, 2012). This can be considered an indication in support of the potential of using vibration-based information in supporting the intuitive use of technology.

4 Introduction of the Publications

The high-level aim of this thesis was to study the use of vibrotactile motion instructions through four controlled laboratory experiments reported in Publications I, II, III, and IV. Publication III also included a follow-up user field study. Brief overviews of each publication now follow.

4.1 Publication I: Vibrotactile Information for Intuitive Speed Regulation

The aim of Publication I (N = 12) was to design and study potentially intuitive vibrotactile stimulations that users can easily interpret to inform them to either 1) speed up, 2) keep their performance as is, or 3) slow down their performance. Vibrotactile stimuli varied according to three vibration frequency profiles (ascending from 50 to 300 Hz, a constant of 175 Hz, and descending from 300 to 50 Hz), three durations (500, 1750, and 3000 ms), two waveforms (sine wave and saw-tooth), and two body locations (wrist and chest), resulting in 36 different stimulations. A wearable apparatus (see Figure 4) was used to present the stimuli to the participants, whose task was to evaluate the meaning of the stimuli, based on their intuition, using three response options: “accelerate your speed,” “keep your speed constant,” and “decelerate your speed.” The participants also rated the pleasantness and arousability of the different stimulations.

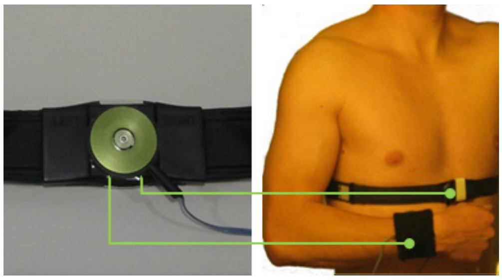


Figure 4. Vibrotactile actuator (left) and its attachment to the wrist and chest (right) - Publication I.

The results showed that as expected, the meaning of the stimuli was primarily deduced by analogy with the vibration frequency profile without any teaching. The best functioning stimuli represented “accelerate your speed,” “keep your speed constant,” and “decelerate your speed” information in accuracies of 88, 100, and 79%, respectively. These response rates were, thus, clearly above the 33.3% level of chance. Differences between the stimulus durations were non-significant. In general, sine wave stimulations performed better than saw-tooth wave stimulations. The response rates between the wrist and chest stimulations did not differ significantly. This indicates that the sensitivity of the skin areas under the wrist band and chest belt of a heart rate monitor would be sufficient in mediating vibrotactile messages. Ratings of pleasantness, however, showed that the stimulations were experienced as more pleasant in the wrist than chest location. Both ascending and descending stimulations were rated as more arousing than stimuli with constant frequency.

The results suggested that vibration frequency modulations could be utilized for informing, for example, exercisers about how they should regulate the speed of their performance in order to maintain a desirable level of activity throughout training.

4.2 Publication II: Intuitiveness of Vibrotactile Speed Regulation Cues

In Publication II (*N* = 24), a subset of the stimuli from Publication I was used to further test the intuitiveness of the haptic speed regulation cues. The same wearable apparatus was used as in Publication I. However, in contrast to the previous study, which only consisted of male participants, gender was balanced in this study to increase the generalizability of the results. In addition, response times were measured in this study. Two groups of 12 participants were treated differently so that one group was primed by first teaching the meaning of the stimulations, and the other group was not (i.e., unprimed group). Comparisons of the response rates between the primed and unprimed groups enabled an investigation of the intuitiveness of the haptic cues for behavioral regulation.

The results replicated the findings of Publication I by showing that the unprimed participants evaluated the stimulations by analogy with the vibration frequency profile. Interestingly, the performance of the unprimed and primed groups was almost identical in terms of statistical significance. The best performing stimulations communicated the three intended speed regulation cues at a rate of 71–83% in the unprimed group and at a rate of 88–100% in the primed group. Both groups performed identically at evaluating the "keep your speed constant" and "decelerate your speed" information. However, the primed group performed better at evaluating the "accelerate your speed" information. In this case, the highest response rates were 100% and 83% in the primed and unprimed groups, respectively.

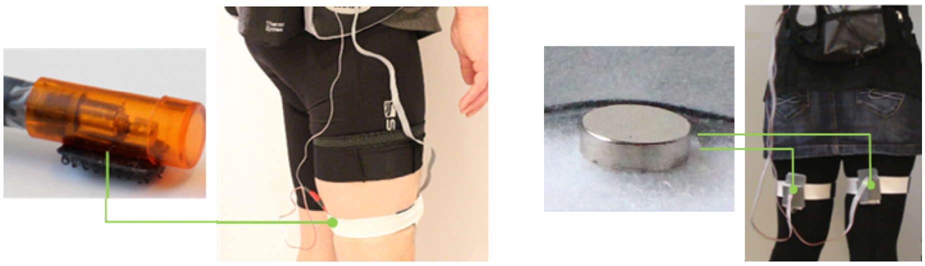
The results of Publication II supported the earlier findings of Publication I and added further evidence of the intuitiveness evidenced by the predominantly coherent performance of the primed and unprimed groups. Response time analyses revealed no differences in temporal performance between the groups. Both groups, however, responded significantly faster to wrist stimuli than to chest stimuli.

Subjective ratings showed that the male and female participants experienced the pleasantness of the stimuli differently. The female participants rated constant frequency stimuli as more pleasant than the other two frequency profiles, whereas the ratings by the male participants followed the earlier results of Publication I and did not differ significantly in this respect. In contrast to Publication I, the pleasantness ratings between the wrist and chest stimulations showed no differences. The arousability ratings mainly replicated the results obtained in the previous study and showed no significant differences between the genders.

4.3 Publication III: Vibrotactile Stimulation as an Instructor for Mimicry-Based Physical Exercise

Publication III consisted of two studies (i.e., a laboratory experiment and a field study) investigating the functionality of vibrotactile stimulation in mimicry-based behavioral regulation during physical exercise.

The use of the wearable exercise device was first investigated in the laboratory (*N* = 12). A specifically devised prototype system (Figure 5 a) was designed to stimulate the exerciser's leg in synchrony with the instructor's knee lift movements. These example movements were shown from a videotaped instructor whose movements were synchronized with vibrotactile stimulations. The stimuli communicated instructions regarding when to perform a knee lift movement of a single leg from an instructor to an exerciser. In the laboratory experiment, participants performed knee lifts with exercise guidance provided by three modality conditions (visual, tactile, and visual-tactile instructions). The effects of the different instruction modalities were measured objectively (i.e., reaction time and intensity of the leg movement), by using leg acceleration data, and subjectively (e.g., pleasantness and interest of the exercise).



(a) (b)

Figure 5. Vibrotactile actuator and its attachment to a leg in (a) laboratory experiment and (b) field study - Publication III.

The results of the laboratory experiment showed that vibrotactile knee lift instructions were recognized with 100% accuracy. Tactile instructions were found applicable both for complementing and substituting the conventionally used visual instructions provided by the videotaped movements of an instructor. Leg movement reaction times to tactile instructions were 158–183 ms slower than visual and visual-tactile instructions. This was explained by a robust detection threshold for recognizing the instructor's leg movement with the accelerometer. This caused about 200 ms delay in the onset of the tactile instruction. As a result, the visual instruction was visible earlier than the tactile instruction could be perceived. Subjective ratings revealed that the pleasantness, easiness, and interest in the exercise were clearly positive in each modality condition, indicating that the tactile instruction channel was accepted along with the conventionally used visual instructions in physical exercise. In fact, performing the exercise movements with tactile and visual-tactile instructions significantly increased interest in the exercise in comparison with the use of visual-only instructions.

The laboratory experiment was followed by a field study with a further developed version of the wireless exercise system (Figure 5b). The study was conducted in a real use context with a potential target group (N = 8) consisting of 73–92-year-old exercisers. The field study focused on users' experience of the device in a recreational exercise session for elderly participants. In contrast to the laboratory experiment, videotaped instructions were replaced by a real instructor, and the exercise system enabled the measurement and stimulation of both legs. The results of the field study showed that the user experience of the vibrotactile instruction was mainly positive. The tactile exercise system turned out to be easy to learn and pleasant to use. The results revealed that the exercise sessions with and without the device were experienced in a highly similar fashion, except that the device increased the motivation for doing the exercise. The instructors assumed that the system would be suitable mainly for slow-paced training due to the slight delay between the example movement and the consecutive vibrotactile stimulation.

In general, the results showed that tactile stimulation to the leg functioned successfully in mediating real-time instructions for leg movement exercises in both simulated and realistic group exercise contexts. The results further suggest that even a simple and inexpensive system could be used to increase the exercise possibilities of special groups that are currently at risk of being excluded from organized group exercise due to sensory or cognitive deficits, which impair their ability to follow visual and auditory instructions.

4.4 Publication IV: Responses to Visual, Tactile and Visual-Tactile Forward Collision Warnings while Gaze on and off the Road

The aim of Publication IV (*N* = 20) was to examine the functionality of visual and tactile warning stimulations in a simulated driving context. The task was to drive and respond to a warning signal by braking as fast as possible. The driver's visual orientation was altered by manipulating the driver's gaze direction between the road, left mirror, center mirror, and right mirror. The warnings were provided in three different modality conditions: the visual warning was a blinking light in a windscreen; the tactile warning was implemented by a vibrating accelerator pedal (Figure 6); and the visual-tactile warning was their synchronous combination. Objective behavioral measurements included warning detection rates and brake reaction times. Subjective ratings were collected regarding the pleasantness, perceptivity, and effectiveness of the warning stimuli and the participants' own opinion about their brake reaction speed.

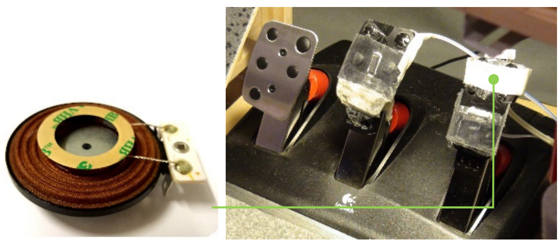


Figure 6. Vibrotactile actuator (left) and its attachment to the accelerator pedal (right) - Publication IV.

The results showed a detection rate of 100% for each warning type in each visual orientation. Brake reaction time analyses revealed that brake reactions to tactile and visual-tactile warnings varied between 623 and 630 ms and were significantly faster than those obtained for visual only warnings, which varied between 711 and 752 ms. In addition, it was found that reaction times to visual warnings were influenced by the visual orientation. Thus, significantly slower reactions were obtained while the gaze was on the right side view mirror than when it was, for example, on the road. However, the reaction times to the tactile and visual-tactile warnings were unaffected by the driver's visual orientation. Subjective ratings showed that tactile and visual-tactile warnings were preferred over visual warnings in terms of pleasantness, perceptivity, effectiveness, and reaction speed.

In general, the results of the brake reaction times corroborated those of earlier driving simulator studies showing that responses to tactile warnings can be significantly faster than for visual warnings. Moreover, the current results showed the potential of tactile and visual-tactile warnings, especially when the driver's visual attention is off the road scene ahead, that is, in situations where collision warnings are typically a matter of utmost importance.

5 Discussion

This thesis investigated the use of vibrotactile stimulations in delivering information for behavioral regulation in human-technology interaction. Publications I and II investigated *mental associations* between vibrotactile stimulations and their meanings. The results showed that vibrotactile stimulations can be designed so that users interpret their meaning in uniform fashion based on their “first impression” in a given context of use. Publications III and IV concentrated on *physical compatibility* between vibrotactile stimulations and consecutive body movements. The results demonstrated the feasibility of vibrotactile instructions in initiating body movement as an alternative or supplement to visual instructions.

The vibrotactile speed regulation instructions in Publications I and II were built on the concept of the tactile icon, that is, a brief tactile stimulus with associated meanings (Enriquez & MacLean, 2008). In our studies, the main independent variable was the vibration frequency profile of the stimuli, which was altered within a range of 50–300 Hz. The studies investigated whether ascending (from 50 to 300 Hz), constant (175 Hz), and descending (from 300 to 50 Hz) vibration frequency profiles could be naturally associated with information cueing to accelerate speed, to keep the speed constant, or to decelerate speed. The interpretation of the stimulations turned out to be uniform among the participants. Thus, the ascending, constant, and descending vibration frequencies of the stimulations were mainly associated with speed acceleration, constant speed, and speed deceleration, respectively.

In the studies, the most uniformly understood stimuli were interpreted in a similar manner at rates of 71–100%, clearly above the chance level, which was 33%. The results indicated that vibration frequency was naturally associated with speed of movement and, thus, can be used as a semantic coding, which is understandable without any teaching or guidance. One explanation for this is that the stimulations had a semantic equivalent in the physical world in relation to the perception of speed. Based on their earlier experiences, it is likely that the participants were already familiar with the idea that vibration frequency alters as a function of speed in many situations in their daily lives. Ascending and descending vibration frequencies typically occur when speed changes, for example, when accelerating and decelerating a motor vehicle, whereas constant vibration frequency is perceived when speed is unchanging.

In contrast to the *semantic coding* of the stimulations used in our experiments, previous studies have mainly used *abstract coding* of vibrotactile messages, which, by definition, requires learning before their target or meaning can be understood. Together, the results have demonstrated the high mental ability of humans to discriminate, learn, and recall abstract vibrotactile messages when allowed to first learn their meanings (e.g., Brown et al., 2006; Brown & Kaaresoja, 2006; Enriquez & MacLean, 2008).

The dual-processing model of thinking governing human cognitive processes suggests that people make decisions intuitively by using system 1, whereas system 2 is used for more effortful, rational, and memory-based deductions (e.g., Stanovich & West, 2000). In this sense, semantically coded messages can potentially be interpreted using system 1, whereas the interpretation of abstract coding requires the use of system 2. Based on Kahneman's (2003) conceptualization of intuition being thoughts and preferences that come to mind quickly, spontaneously, and effortlessly under appropriate circumstances, the participants in Publications I and II were asked to respond as quickly as possible and to rely on their first impression when deciding between the three response options. Spontaneous responding was further emphasized by stating that there are no right or wrong answers. With this treatment, the experimental setup was aimed at supporting intuitive decision making.

Given that intuitive decision making under system 1 is regarded as emotionally charged (Kahneman, 2003), subjective ratings of pleasantness and the arousability of the stimulations provided an additional viewpoint to the associative mental processes. The ratings revealed that constant frequency stimuli were experienced as more pleasant than stimuli with dynamically changing (i.e., ascending and descending) frequency profiles. Additionally, constant frequency stimuli were rated as less arousing than the two other frequency profiles. In considering the use of the stimulations in a speed regulation application such as a sports heart rate monitor, the ratings suggest that constant vibration frequency stimulations function logically in giving the exerciser a pleasant and non-arousing message that "you are doing fine – keep your speed constant." Ascending and descending frequency profiles rated as more arousing and more unpleasant would also seem functional by alerting the exerciser that "you need to change your speed – accelerate/decelerate."

This deduction can be seen as an example of the adaptive regulatory powers of emotions in guiding human behavior. Emotions play an important role in behavioral regulation by providing robust but effective signals that help to prioritize goals for subsequent action (Stanovich & West, 2000). In this sense, ratings regarding the pleasantness and arousability of the stimuli coincided appropriately with the actions suggested by the semantic content of the three speed regulation cues. This would potentially enhance the usability of this type of application.

The stimulations were delivered via wearable actuators attached to the wrist and chest. The reasoning behind choosing these locations was driven by the idea of adding haptic features to heart rate monitors. In this context, a wrist unit and heart rate monitoring chest belt provided practical (i.e., already existing) platforms for a tactile display fixed to the skin. The wrist turned out to be the more preferred stimulus location than the chest, especially by the female participants. In the post-experimental interviews, the female participants reported their chest being more sensitive than their wrist, and therefore, they experienced the chest stimuli as overly vigorous and unpleasant. The majority of the male participants, however, reported their wrist being more sensitive than their chest. These ratings are in line with Karuei et al. (2011), who found differences in touch sensitivity between genders for different body sites, for example, males detected wrist stimuli better than females.

The results of Publications I and II showed that even relatively slight changes in vibrotactile stimulation can result in significantly different perceptions in terms of emotional ratings and semantic interpretations of their meaning. For example, the change in the vibration frequency profile from ascending to descending yielded opposite meanings to the stimulations. The experiments concretely showed that vibrotactile cues for behavior regulation can be experimentally designed so that they are clearly intelligible to people with no earlier experience of the stimulations and without any teaching. In terms of potential application areas, the results suggest that carefully designed and systematically tested stimulations can be functional in delivering easy to understand feedback on how to regulate physical movement. For example, in physical exercise and rehabilitation applications, touch-based information can perhaps complete or even substitute audio-visual instructions efficiently and in an intuitive manner. This would be helpful when the distraction caused by vision and hearing–based information ought to be minimized or when they cannot be fully utilized due to the situation or impairment.

Publication III continued with the investigation of the functionality of vibrotactile stimulations in mediating the real-time guidance of physical exercise in two separate studies: one performed under controlled laboratory conditions and the other in a real exercise situation. In both studies, short (200 ms) vibration pulses applied on a leg were used to transmit information about when to initiate knee lift movement in synchrony with an instructor's example movements. The laboratory experiment concentrated on comparing knee lift RTs followed by visual, vibrotactile, and combined visual and vibrotactile instructions. Earlier RT studies have typically shown about 30–40 ms faster reactions to tactile than visual stimulations (Brebner & Welford, 1980; Hanson et al., 2009). However, RT analyses of Publication III showed reactions to vibrotactile instructions at 158–188 ms slower than visual instructions and their bimodal combination. Slightly delayed responses to vibrotactile instructions were, in fact, expected in the current experiment due to the minimalist and low-cost technical implementation, which was based on a simple accelerometer measurement and ERM actuator, and which together caused some lag in initiating the vibrotactile stimulus. As a result, the visual instructions were mediated about 200 ms prior to the vibrotactile instruction.

Subjective ratings about the timely synchronization between visual and vibrotactile instructions showed that while 42% of the respondents considered the synchrony as appropriate, 58% observed that vibration came later than visual instructions. Despite the slight lag experienced by most of the participants, the pleasantness and easiness of the exercise was rated equally positively regarding all the instruction modalities. In addition, exercising with vibrotactile instructions (both alone and when combined with visual instructions) was rated as significantly more interesting than with visual instructions.

In a follow-up study, the user experience of the exercise system was further validated in a real group exercise situation. The overall experience of the training with the system was evaluated positively by the exercisers and their instructors. The user study also revealed that the current system was suitable mainly for relatively slow-paced training. The instructors considered that faster paced exercise would require an improvement of the lag issue. Together, the results of Publication III suggested that a relatively simple and low-cost vibrotactile instruction system could open up possibilities to increase physical activity for those at risk of being excluded from organized physical exercise, which typically demands the ability to follow visual and auditory instructions. The potential of vibrotactile information has been recognized in the context of physical exercise, and a significant amount of research has been done in this field. The use of vibrotactile stimulation to mimic another person's movement, however, is still relatively new. Earlier studies have concentrated on one-to-one exercise situations whereby one instructor trains one exerciser in trunk tilt exercises or hand movement trajectories (e.g., Bark et al., 2011; Lee & Sienko, 2010; Lee et al., 2011). The current approach supported this evidence by demonstrating the functionality of vibrotactile instructions in mimicking lower extremity exercise movements in a group training situation.

Vibrotactile stimulation on a leg was also evaluated in Publication IV, where it was used to deliver emergency braking alert in a simulated driving task. Brake reactions to vibrotactile warnings were significantly faster than for visual warnings. RTs to visual warnings varied significantly, depending on the driver's visual attention being shortest (711 ms) while looking ahead and longest (752 ms) when observing the right side view mirror. However, tactile and visual-tactile RTs were unaffected by the driver's visual orientation. A body of earlier research showed that the perception of visual stimulus typically slows down as a function of increased visual angle (e.g., Strasburger, Rentschler, & Jüttner, 2011). In a driving situation, the driver's visual attention is focused diversely between the road scene and other locations both inside and outside the vehicle and can impede the utility of visual warnings, which are typically presented in a fixed position ahead of the driver.

The use of fixed-position visual warnings, most typically used in current vehicles, also contains flaws from the human factors point of view. For example, the angle of peripheral vision reduces along with age, impairing the ability to process peripheral signals and impeding driving performance (e.g., Rogé, Pébayle, Campagne, & Muzet, 2005). A reduced visual field has been found to be a key factor explaining proclivity for traffic accidents by elderly drivers (e.g., Ball, Owsley, Sloane, Roenker, & Bruni, 1993). Therefore, it is possible that touch-mediated warnings will be useful for elderly drivers in particular.

The RT analysis in Publication IV indicated that vibrotactile warnings were more compatible than visual warnings with respect to the rapidity of an emergency brake reaction. However, while a statistically significant multisensory enhancement effect, with the bimodal stimulation being reacted faster than the unimodal stimulation (e.g., Forster et al., 2002), was not obtained in the current experiment, there was a systematic trend supporting slightly faster RTs to bimodal stimulations than unimodal visual or tactile stimulations. In fact, a similar trend indicating a multisensory enhancement was also observed in Publication III.

A simplified design of the vibrotactile displays consisted of a single actuator per body location in all experiments of this thesis. This is contradictory to the body of earlier experiments dealing with touch-based body movement instructions, which have mainly used multiple actuators. They have been used to provide dynamically changing spatiotemporal patterns that indicate, for example, the desired movement direction of the body. The reasoning behind the minimalist approach in this thesis was primarily based on the tradition of experimental research whereby a simplified setup is a prerequisite for the careful control of the experimental variables. From an applications point of view, the simplicity of the design can be seen as an advantage as it usually goes hand-in-hand with the simplicity of use. Consumers more easily adopt simple user interfaces because they create a feeling of being in control rather than being controlled by the device. Simplicity achieved with minimum use components is also of essence when considering durability and low manufacturing expenses in mass-market products such as sports computers and automotive applications, which formed the focus of this thesis.

6 Conclusions

This doctoral thesis focused on situations in which the sense of touch was currently less utilized but potentially advantageous in comparison to the use of vision and hearing while interacting with technology. The chosen contexts of use included physical exercise and car driving, which both allocate visual and auditory senses for the ongoing primary task and, thus, impede their use as information channels in HTI applications. The current trend is that information technology is increasingly gaining ground in virtually all areas of life, especially those we use on the move. Seeing that people are not particularly good at multitasking due to limited amounts of cognitive and sensory resources, the attention we pay to information displays occurs at the expense of the vigilance we allocate to the environment. In traffic, for example, this increases the risk of safety hazards, which is acknowledged as a major design challenge.

In a wider scope, the current doctoral thesis can be regarded as being related to some of the most vital human functions such as keeping up physical fitness, better quality of life, and traffic safety by utilizing the possibilities of vibrotactile information delivery. The meta level goals related to body movement instructions were to investigate the functionality of vibrotactile cues in improving safe interaction in contexts in which distraction should be minimized and fast bodily reactions are desirable (i.e., physical exercise and driving) and in promoting physical health (i.e., group exercise for elderly people).

More specifically, the work examined the recognition of vibrotactile information, which communicated different types of instructions to regulate physical movement of the body. The emphasis was especially on the effortless mental processing of the meaning of the instructions as well as rapid responses to them in terms of physical movement. The results suggested that vibrotactile information was clearly understandable. Importantly, in some cases, vibrotactile instructions resulted in better performance than visual instructions.

The studies were conducted primarily in a laboratory environment to enable careful control of the experimental conditions. Typical of all the studies in this thesis was that the parameters of the stimuli were systematically varied, and their effects on the participants' objective and subjective responses were measured in controlled laboratory conditions. The results concretely demonstrated the functionality of systematic experimental research in becoming aware of the associations between touch sensations and their significance for users. By means of experimental research, it is possible to generate easily understandable touch stimulations that feel comfortable and require only few cognitive resources. This would enable better concentration on primary functions such as observing the environment to improve safety while interacting with technology.

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Publication I

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Vibrotactile Information for Intuitive Speed Regulation

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ABSTRACT

The present aim was to investigate if controlled vibrotactile stimulation can be used to inform users on how to regulate their behavior. 36 stimuli were varied by frequency modulation (i.e., ascending, constant, and descending), duration (i.e., 500, 1750, and 3000 ms), waveform (i.e., sine and sawtooth), and body location (i.e., wrist and chest), and presented to 12 participants. The participants were to evaluate without any training the meaning of each presented stimuli using three response options: 'accelerate your speed', 'keep your speed constant', and 'decelerate your speed'. Participants rated also how emotionally pleasant and arousing the different stimulations were. The results showed that the stimuli were predominantly perceived analogously with the vibration frequency modulation. The best stimuli represented 'accelerate your speed', 'keep your speed constant', and 'decelerate your speed' information in accuracies of 88, 100, and 79 %, respectively. Stimulations were experienced as more pleasant in the wrist compared to the chest location. Both ascending and descending stimulations were rated as more arousing than stimuli with constant frequency. Our results suggest that tactile stimulation could be used in real life mobile applications, for example, in sports to inform the users on how they should regulate their performance.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/methodology, Haptic I/O.*

General Terms

Measurement, Performance, Design, Experimentation, Human Factors.

Keywords

Tactile feedback, tactile icons, speed regulation, non-visual interaction.

1. INTRODUCTION

There are a growing number of human-technology interaction (HTI) applications that utilize measurement and interpretation of bodily functions for improving human physical performance. For instance, the effects of using heart rate biofeedback in guiding physical training have been proved beneficial [7]. The interpreted measurement data can currently be mediated continuously and in real time to the users in order to help them to regulate their behavior and performance throughout the physical performance like running.

Mobile sports computers have nowadays many guiding features such as functionalities for heart rate monitoring, timekeeping and navigation. Traditionally these devices provide the needed information for the user during a physical exercise (e.g., when the heart rate exceeds the set target range) using auditory alerts and/or visual feedback for adjusting the level of the performance (e.g., to slow down the speed). The full exploitation of visual and auditory feedback modalities can, however, be restricted if the user has low vision or low hearing ability.

Sometimes the access to the needed information can be prevented by situational or context related reasons as well. Taking a running exercise in urban surroundings is a rather extreme example of a context where situational constrains are faced, but at a same time, it is a common situation for the growing number of sports computers users. The noise of the traffic and the need for focusing one's attention to the environment can prevent the efficient use of both auditory and visual outputs. On the other hand, in more peaceful situations auditory feedback can be considered as disturbing either by the user or by other people around. Listening to information via earphones might be effective but not always recommendable because it could prevent the user from processing important environmental information such as hearing sounds of approaching vehicles. Due to potential safety risks, in many U.S. marathon events, for example, the entrants are prohibited from using earphones for music listening [1].

It is clear that alternative ways to mediate information on the status of human bodily functioning would be welcome. One promising solution is to extend the bandwidth by adding other modalities to mediate information to the users of mobile technology. Haptics is a modality that is gaining increasing interest supported by the latest scientific results and improved technology. The research in the field of haptics focuses on the use of the sense of touch, active touching, and haptic feedback in HTI. Tactile expression refers to technologies that are able to give tactile stimulation by using certain predefined parameters. By their sense of touch humans can interpret the tactile expressions provided by, for example, a mobile device.

Intuitively, it is apparent that presenting information via the sense of touch (i.e., haptic feedback) would have several advantages compared to the use of visual and auditory modalities in the mobile contexts of use. It would free the user from sharing the visual and auditory attention between the environment and the messaging device. In this sense the potential of having haptic feedback seems a promising way to proceed in developing safer and user-friendlier devices for mobile users.

In fact, there is evidence that the tactile sense can be used successfully in proving guidance during a physical exercise [9]. In another study, van Erp *et al.* [6] provided motion co-ordination information on the angles of the knees and the back during a set of multiple rowing exercises. Feedback was given either by visual information on the computer screen or by analogous vibrotactile information with actuators located on the back and on the knee. Co-ordination accuracies with vibrotactile and visual feedback groups were equally good, but interestingly, the vibrotactile group showed decrease on the heart rate along the experiment while in the visual group the heart rates were increasing. The authors interpreted the results so that more effort was required to maintain the optimal performance by following visual than vibrotactile information during the exercise.

Recent studies have found that tactile expression can also be used for producing iconic information by using predefined parameters. Brewster and Brown [3] introduced a concept of tactile icons (i.e., Tactons) as a communication method to complement graphical and auditory feedback at the user interface. Tactile icons are structured, abstract messages that can be used for non-visual information presentation. The authors suggest that distinguishable and identifiable information can be encoded by manipulating, for example, frequency, amplitude, duration, rhythm, and spatial location of the tactile icons. Brown *et al.* [4] created 9 two-dimensional tactile icons informing about the type of a phone alert (i.e., three different rhythms) and the priority of the alert (i.e., three different amplitude modulations within each rhythm) using advanced actuator technology. The results showed that the icons were recognized correctly with the accuracy of 71 %. Later on, Brown and Kaaresoja [5] were able to reach equal recognition rates using a standard vibration actuator of a mobile phone in creating similar iconic information.

We note, however, that in these studies it has been typical that the recognition rates for iconic information were achieved by teaching the meaning of the icons for the participants in a separate learning session before the actual experiment. Of course, it would be ideal if the tactile expression could be designed so that they can be interpreted effortlessly, or even intuitively. For this reason also studies that do not coach experimental participants are needed.

Our aim was to first investigate the possibilities of providing intuitive tactile information in carefully controlled laboratory settings with immobile participants. Only after the case that we would find that easily interpretable or intuitive feedback seems possible, we should proceed to more realistic settings and mobile users. Earlier research has shown that physical movement can attenuate the recognition accuracy of low-amplitude vibrotactile stimuli [8], and therefore it was reasonable to use relatively high stimulus amplitude for ensuring that the same stimuli could be usable also in the future studies, where physical exercise was planned to be present.

It was hypothesized that different vibration frequency profiles (i.e., dynamic and constant) could have the potential to intuitively provide the users with analogous information about the regulation of the speed. We were encouraged by the results of our pilot studies which indicated that ascending, constant, and descending frequencies could be associated with speed acceleration, constant speed, and speed deceleration, respectively. Wrist and chest were chosen for the reason that they are the locations of the main components of commonly used sports monitors (i.e., wrist unit and heart rate monitoring chest belt) and thus natural platforms for embedding haptic technology. The other stimulus parameters were selected for investigating the effects on different waveforms and stimulus durations.

Tactile expression has also been found to be associated to human emotions [10]. As the stimuli should be noticeable but preferably not too much irritating, we also wanted to measure the emotion related subjective experiences evoked by the stimuli. Earlier research has shown that the use of dimensional affective space can be effective in tracking down the emotion related responses of the participants. We decided to use subjective rating scales for arousal and pleasantness, which have been previously used, for example, by Bradley and Lang [2] and Salminen *et al.* [10].

2. METHODS

2.1 Participants

Twelve naïve and voluntary male participants took part in the experiment (mean age 22.8 years, range 19–31 years). By their self reports eleven were right-handed and one was left-handed. They all reported that they had normal sense of touch.

2.2 Apparatus

Two Engineering Acoustic Inc. (http://www.eaiinfo.com/) C-2 vibrotactile voice coil actuators were used to present Windows Waveform (WAV) audio files through a sound card of a PC computer. The diameter of the C-2 actuator was 3.05 cm (1.2”), and the diameter of the vibrating skin contactor area was 0.76 cm (0.3”). Stimuli were amplified with a Stage Line® STA 1508 eight-channel amplifier. The actuators were attached to the wrist with elastic wristband and to the chest with elastic and adjustable Polar® WearLink™ heart rate monitoring chest belt (Figure 1).

Figure 1. Wrist actuator attached under a wristband and backside view of chest actuator attachment to a chest belt.

E-Prime® 2.0 Professional experiment generator software [11] was used to control the stimulus presentation and to collect the data. Responses were given with a modified number key section of a standard computer keyboard. Three response buttons were set in a vertical layout. The uppermost button was labeled with an arrow pointing upward (↗), the middle button was labeled with an arrow pointing sideward (→), and the undermost button was labeled with an arrow pointing downward (↘). Green experiment initiation button was located on the left side of the middle button. Unnecessary buttons were removed.

2.3 Stimuli

18 different stimuli were used to present vibrotactile information on two body sites (i.e., wrist and chest). The stimuli were varied by frequency modulation, duration, and waveform of the signal. The stimuli were built upon two different waveforms (i.e., sine and sawtooth wave). These waveforms were selected based on both C-2 actuator recommendations on using sine wave stimuli (see http://www.eaiinfo.com/) and pilot tests. The pilot tests showed that sawtooth stimuli performed better in differentiating the ascending, constant, and descending frequency modulations as

compared to the use of square wave stimuli. Three different durations of the stimuli were used (i.e., 500, 1750, and 3000 ms) providing clearly distinctive temporal time frame for the stimulation. The frequency profiles of the stimuli were manipulated using three different types of frequency modulations (i.e., ascending, constant, and descending frequency). For ascending stimuli the frequency was modulated linearly from 50 to 300 Hz (Figure 2a). The frequency for the constant stimuli was kept at 175 Hz (Figure 2b). For descending stimuli the frequency was modulated linearly from 300 to 50 Hz (Figure 2c). The amplitude and phase of the signal were not altered.

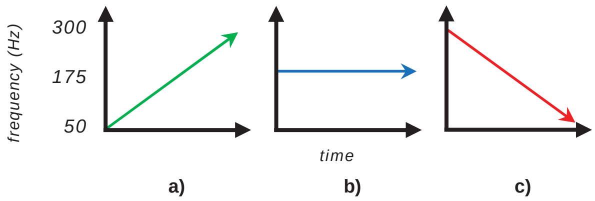

Figure 2. Frequency modulations used for ascending (a), constant (b), and descending (c) stimuli.

Audacity® audio editor and recorder software version 1.2.6 (http://audacity.sourceforge.net/) and Pure Data real-time audio synthesizer software version 0.40.3 (http://puredata.info/) were used in creating the stimuli. All the stimuli were 16-bit mono WAV files with 44.1 kHz sampling frequency. Stimulus amplitude was adjusted to 1.49 V (AC) for both channels (i.e., for wrist and chest) by measuring the voltage from the amplifier outputs with a Fluke® 87 V True RMS multimeter while the actuators were playing a constant 250 Hz sine wave calibration stimulus.

2.4 Procedure

First, the laboratory and the equipment were introduced to the participant. Then he was seated and the actuators were attached on top of the wrist of the non-dominant hand and to the chest. The actuator in the chest was located in the sagittal plane of the thorax. In order to avoid unwanted vibration resonance with the skeleton, the actuator was attached below the breastbone. To ensure this the participant was instructed to put his thumb under his breastbone and then to adjust the height of the chest belt so that the actuator was right under the thumb. The participant was informed that the heart rate data was not measured during the experiment, although the chest belt used was originally from a heart rate monitor. The non-dominant hand was laid on a table on top of a foam plastic armrest and the other hand was put on top of the response buttons. The participant was instructed to hold the non-dominant hand still and to keep the gaze on the display during the experiment. In order to block the mechanical sound of the actuators, the participant listened pink noise (i.e., $1/f$ noise) via a hearing protector headset at a comfortable sound level.

There were three sessions: stimulus familiarization session, cognitive evaluation session, and emotional rating session. The order of the sessions was fixed. The emotional rating session consisted of two sub-sessions (i.e., A for pleasantness ratings and B for arousal ratings). The order of the sub-sessions was counterbalanced between the participants so that half of them started with sub-session A and then continued with sub-session B. The other half performed the sub-sessions in reverse order. Each of the sessions and sub-sessions consisted of two separate blocks. In block A, the stimuli were presented to the wrist and in block B, the stimuli were presented to the chest. The performance order of the blocks within each session and sub-session was counterbalanced between the participants so that half of them started with block A and then continued with block B. The other half performed the blocks A and B in reverse order. The participant was allowed to take a short break between the sessions, sub-sessions and blocks. Finally, there was a structured but informal post-experimental interview, where the participant was asked questions to get additional information, for example, on the response strategy and about opinions regarding the difficultness of the experimental tasks. It took an average of one hour for conducting the whole experiment.

2.4.1 Stimulus Familiarization Session

The purpose of the first session was to allow the participant to familiarize himself in feeling the vibrotactile stimulations in the two body sites and to initiate him into the stimulus space used in the experiment. The task was simply to sit still and to feel the stimuli. After giving the instructions, the participant was allowed to start the first session by pressing the experiment initiation button. Then all the 18 stimuli were presented sequentially in a randomized order for the participant with an interstimulus interval of 3500 ms. In block A, the stimuli were presented to the wrist, and in block B, the stimuli were presented to the chest. Thus, there were a total of 36 trials. The response buttons were covered for preventing of giving any hints of the experimental task in the upcoming cognitive evaluation session.

2.4.2 Cognitive Evaluation Session

In the beginning of the second session the experimenter uncovered the response buttons and explained the purpose of the experiment. The participant was instructed to imagine that the computer was giving him instructions to either accelerate his speed, to keep his speed constant, or to decelerate his speed on the basis of the stimuli presented in the first session.

First, the participant performed three practice trials in order to train the response technique. In the practice session, three 1000 ms long practice stimuli (constant 50, 175, and 300 Hz square wave vibration) were presented one at a time in a randomized order simultaneously to the wrist and to the chest. The practice stimuli were not presented in the actual experiment.

After the practice trials, the experimenter left the room and the participant was allowed to initiate the first trial by pushing the experiment initiation button. In a trial, a text “Next stimulus” appeared on the display for 1500 ms. Then the text disappeared and a fixation point (+) appeared on the center of the display for 1500 ms. The display was blank for 500 ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the response options appeared on the display, and the participant was able to answer. The task was to evaluate the meaning of the stimulus between three response options. The uppermost button was to be pushed for ‘Accelerate your speed’ responses, the middle button was to be pushed for ‘Keep your speed constant’ responses, and the undermost button was to be pushed for ‘Decelerate your speed’ responses. The participant was instructed to give the response as quickly as possible and to rely on the first impression. After the press of a response button there was a 500 ms interval and then a new trial was initiated automatically.

Each of the 18 stimuli was presented twice to the wrist (block A) and twice to the chest (block B) in a randomized order. Thus, there were a total of 72 trials.

2.4.3 Emotional Rating Session

In the third session the task was to rate the subjective experiences evoked by the stimuli using two emotion-related nine-point bipolar scales varying from -4 to +4. In sub-session A, ratings were asked for the scale of pleasantness of the stimulus varying from unpleasant to pleasant (i.e., how unpleasant or pleasant the stimulus felt). In sub-session B, ratings were asked for the scale of arousal of the stimulus varying from relaxed to aroused (i.e., how relaxed or aroused the participant felt during the stimulus). On both of the scales, 0 represented a neutral experience (i.e., neither unpleasant nor pleasant and neither relaxed nor aroused). Ratings were given using a computer keyboard with nine keys labeled from -4 to +4.

In the beginning of both sub-sessions the participant performed three practice trials in order to practice giving the ratings. In the practice trials, three practice stimuli were rated one at a time. The practice stimuli were presented simultaneously to the wrist and to the chest. They were not presented in the actual experiment.

After the practice trials, the experimenter left the room and the participant was allowed to start rating the experimental stimuli. The participant was able to decide when to initiate a trial by pushing a space bar on the keyboard. Then a fixation point appeared on the center of the display for 1500 ms. The display was blank for 1500 ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the rating scale appeared on the display, and the participant was able to respond. After giving the response there was a 500 ms interval and then the participant could initiate a new trial.

In both sub-sessions each of the 18 stimuli were presented once to the wrist (block A) and once to the chest (block B) in a randomized order. Thus, there were a total of 72 trials.

2.5 Data analysis

The experiment was a within-subject 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) design. Repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the *F* statistic. Bonferroni corrected pairwise *t*-tests were used for post hoc tests.

3. RESULTS

Figures 3–8 show the mean responses and standard error of the means (S.E.M.s) in the cognitive evaluation session. Figures 9–12 present the mean responses and S.E.M.s in the emotional rating session.

3.1 Cognitive Evaluations

3.1.1 'Accelerate your speed' Responses

For the 'Accelerate your speed' responses (see Figures 3 and 4), a four-way 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) ANOVA showed a statistically significant main effect for the frequency modulation $F(2, 22) = 26.0$, $p < 0.001$ and for the waveform $F(1, 11) = 29.1$, $p < 0.001$. The main effects for the duration and the location were not statistically significant.

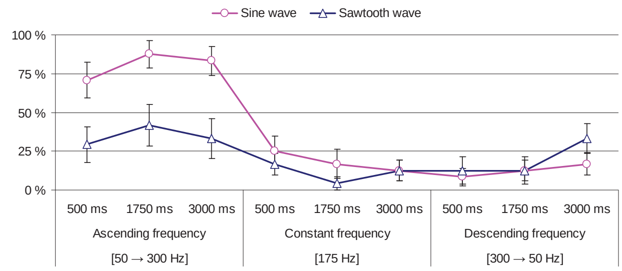

Figure 3. Mean percentages and S.E.M.s for 'Accelerate your speed' responses in wrist by frequency modulation, duration, and waveform.

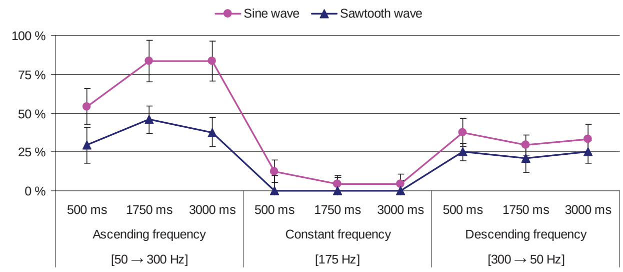

Figure 4. Mean percentages and S.E.M.s for 'Accelerate your speed' responses in chest by frequency modulation, duration, and waveform.

There was a statistically significant interaction effect between the frequency modulation and the waveform $F(2, 22) = 15.1$, $p < 0.001$, between the frequency modulation and the location $F(2, 22) = 9.3$, $p \leq 0.001$, and between the frequency modulation and the duration $F(4, 44) = 3.6$, $p < 0.05$. There were no other statistically significant interactions of the main effects.

To analyze the interaction effects in more detail, four separate one-way ANOVAs were performed. One-way ANOVAs revealed a significant effect of the frequency modulation $F(2, 22) = 26.0$, $p < 0.001$ and the waveform $F(1, 11) = 29.1$, $p < 0.001$, but the effects of the duration and the location were not statistically significant.

Post hoc pairwise comparisons showed that the participants evaluated the meaning of the stimuli with ascending frequency more frequently as 'Accelerate your speed' than the stimuli with constant frequency $MD = 0.47$, $p < 0.001$ and descending frequency $MD = 0.34$, $p < 0.01$. In addition, the meaning of the stimuli with descending frequency was evaluated more frequently as 'Accelerate your speed' than the stimuli with constant frequency $MD = 0.13$, $p < 0.01$. The sine wave stimuli were evaluated more frequently as 'Accelerate your speed' than the sawtooth wave stimuli $MD = 0.16$, $p < 0.001$. The other pairwise comparisons were not statistically significant.

3.1.2 'Keep your speed constant' Responses

For the 'Keep your speed constant' responses (see Figures 5 and 6), a four-way 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) ANOVA showed a statistically significant main effect for the frequency modulation $F(2, 22) = 88.4$, $p < 0.001$, for the duration $F(2, 22) = 6.6$, $p < 0.05$, and for the waveform $F(1, 11) = 44.1$, $p < 0.001$. The main effect for the location was not statistically significant.

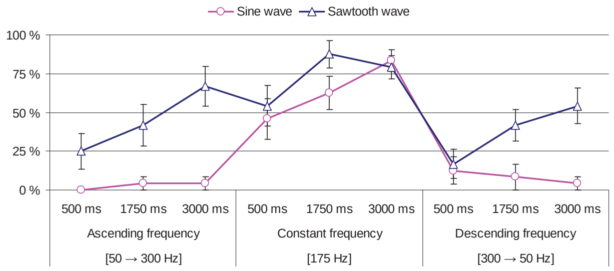

Figure 5. Mean percentages and S.E.M.s for ‘Keep your speed constant’ responses in wrist by frequency modulation, duration, and waveform.

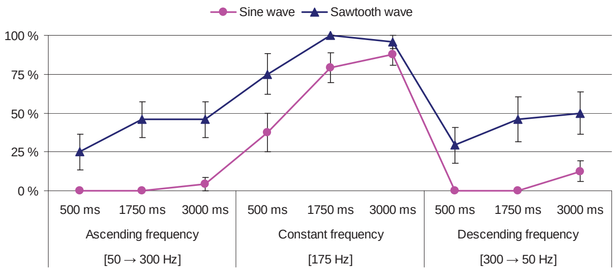

Figure 6. Mean percentages and S.E.M.s for ‘Keep your speed constant’ responses in chest by frequency modulation, duration, and waveform.

There was a statistically significant interaction effect between the frequency modulation and the waveform $F(2, 22) = 7.5$, $p < 0.01$. There were no other statistically significant interactions of the main effects.

To analyze the interaction effect in more detail, two separate one-way ANOVAs were performed. One-way ANOVAs revealed a significant effect of the frequency modulation $F(2, 22) = 88.4$, $p < 0.001$, and the waveform $F(1, 11) = 44.1$, $p < 0.001$.

Post hoc pairwise comparisons showed that the participants evaluated the stimuli with constant frequency more often as ‘Keep your speed constant’ than the stimuli with ascending frequency $MD = 0.52$, $p < 0.001$ and descending frequency $MD = 0.51$, $p < 0.001$. The sawtooth wave stimuli were evaluated more often as ‘Keep your speed constant’ than the sine wave stimuli $MD = 0.30$, $p < 0.001$. The other pairwise comparisons were not statistically significant.

3.1.3 ‘Decelerate your speed’ Responses

For the ‘Decelerate your speed’ responses (see Figures 7 and 8), a four-way 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) ANOVA showed a statistically significant main effect for the frequency modulation $F(2, 22) = 26.7$, $p < 0.001$, for the waveform $F(1, 11) = 11.4$, $p < 0.01$, and for the duration $F(2, 22) = 4.9$, $p < 0.05$. The main effect for the location was not statistically significant.

There was a statistically significant interaction effect between the frequency modulation, the duration, and the waveform $F(4, 44) = 4.1$, $p < 0.01$. In addition, there was a statistically significant interaction effect between the frequency modulation and the waveform $F(2, 22) = 10.1$, $p < 0.01$, between the frequency modulation and the location $F(2, 22) = 4.2$, $p < 0.05$, and between the duration and the waveform $F(2, 22) = 4.1$, $p < 0.05$. There were no other statistically significant interactions of the main effects.

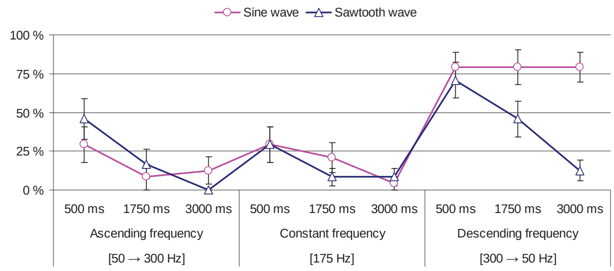

Figure 7. Mean percentages and S.E.M.s for ‘Decelerate your speed’ responses in wrist by frequency modulation, duration, and waveform.

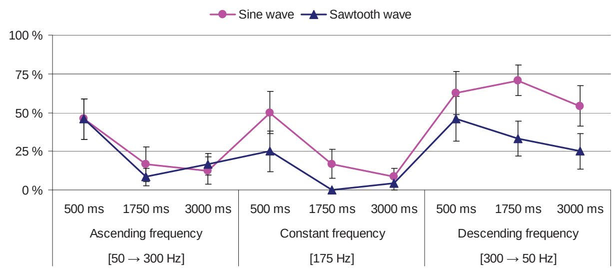

Figure 8. Mean percentages and S.E.M.s for ‘Decelerate your speed’ responses in chest by frequency modulation, duration, and waveform.

To analyze the interaction effects in more detail, three separate two-way ANOVAs and three separate one-way ANOVAs were performed. Two-way ANOVAs revealed the significant interactions between the frequency modulation and the waveform $= F(2, 22) = 10.1$, $p < 0.01$, and between the duration and the waveform $= F(2, 22) = 4.1$, $p < 0.05$, but not between the frequency modulation and the duration. One-way ANOVAs revealed a significant effect of the frequency modulation $F(2, 22) = 26.7$, $p < 0.001$ and the waveform $F(1, 11) = 11.4$, $p < 0.01$, but the effect of the location was not statistically significant.

Post hoc pairwise comparisons showed that the participants evaluated the stimuli with descending frequency more frequently as ‘Decelerate your speed’ than the stimuli with ascending frequency $MD = 0.33$, $p < 0.01$ and constant frequency $MD = 0.38$, $p < 0.001$. The sine wave stimuli were evaluated more frequently as ‘Decelerate your speed’ than the sawtooth wave stimuli $MD = 0.13$, $p < 0.01$. The other pairwise comparisons were not statistically significant.

3.2 Emotional Ratings

3.2.1 Pleasantness

For the ratings of pleasantness (see Figures 9 and 10) a four-way 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) ANOVA showed a statistically significant main effect for the duration $F(2, 22) = 5.8$, $p < 0.05$ and for the location $F(1, 11) = 7.4$, $p < 0.05$. The main effects for the frequency modulation and the waveform were not statistically significant, and there were no statistically significant interactions of the main effects.

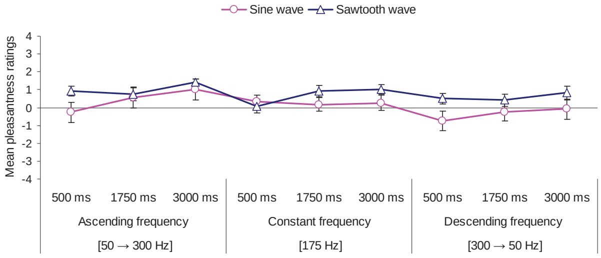

Figure 9. Mean ratings and S.E.M.s for pleasantness of the stimuli in wrist by frequency modulation, duration, and waveform.

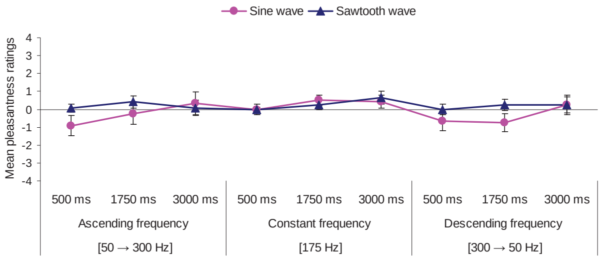

Figure 10. Mean ratings and S.E.M.s for pleasantness of the stimuli in chest by frequency modulation, duration, and waveform.

Post hoc pairwise comparisons showed that the participants rated the 3000 ms long stimuli as significantly more pleasant than the 1750 ms long stimuli $MD = 0.29$, $p < 0.05$. In addition, the stimuli were rated as significantly more pleasant in the wrist than in the chest $MD = 0.38$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

3.2.2 Arousal

For the ratings of arousal (see Figures 11 and 12) a four-way 3 × 3 × 2 × 2 (frequency modulation × duration × waveform × location) ANOVA showed a statistically significant main effect for the frequency modulation $F(2, 22) = 59.6$, $p < 0.001$, for the duration $F(2, 22) = 5.8$, $p < 0.05$, and for the waveform $F(1, 11) = 44.2$, $p < 0.001$. The main effect of the location was not statistically significant.

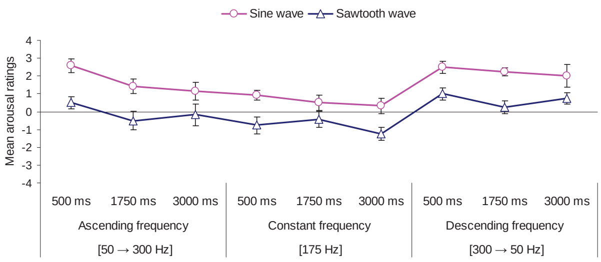

Figure 11. Mean ratings and S.E.M.s for arousal of the stimuli in wrist by frequency modulation, duration, and waveform.

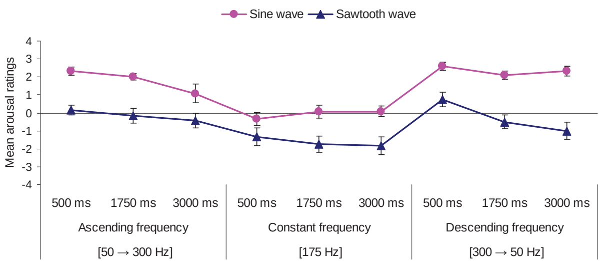

Figure 12. Mean ratings and S.E.M.s for arousal of the stimuli in chest by frequency modulation, duration, and waveform.

There was a statistically significant interaction effect between frequency modulation and the location $F(2, 22) = 4.0$, $p < 0.05$. There were no other statistically significant interactions of the main effects.

To analyze the interaction effect in more detail, two separate one-way ANOVAs were performed. One-way ANOVAs revealed a significant effect of the frequency modulation $F(2, 22) = 59.6$, $p < 0.001$, but the effect of the location was not statistically significant.

Post hoc pairwise comparisons showed that the participants felt less aroused during the stimuli with constant frequency than during the stimuli with ascending frequency $MD = -1.31$, $p < 0.001$ and descending frequency $MD = -1.73$, $p < 0.001$. In addition, the participants felt less aroused during the sawtooth wave stimuli than during the sine wave stimuli $MD = -1.81$, $p < 0.001$. The other pairwise comparisons were not statistically significant.

3.3 Post-experimental Interviews

The most central findings in the interviews were the following. Five of the total of twelve participants thought that the task in evaluating the stimuli between the response options was easy rather than difficult, and one participant was caught between the two options. The rest thought that the task was difficult rather than easy, but two of them said that the task became easier during the experiment.

When asked about the used response strategies, none of the participants reported giving answers purely on random basis. The most common response strategy was based on the analogy with the perceived frequency modulation. Ten participants reported that they were able to recognize three types of frequency dynamics, and that they based their answers mainly on that. In addition, two of them mentioned that they also used stimulus duration in associating the shortest stimuli with ‘Decelerate your speed’ responses. Two participants based their responses mainly on the stimulus duration.

Whereas eight participants considered the wrist as a more sensitive location for feeling the stimuli, the chest was regarded as more sensitive by the rest. When asked about their preference between the two locations, nine reported rather feeling the stimuli in the wrist than in the chest, and three voted for the chest. None of the participants reported hearing the mechanical sound of the stimuli.

4. DISCUSSION AND SUMMARY

Our results showed that our hypothesis was well supported, as the meanings of the stimuli were predominantly perceived and evaluated analogously with the vibration frequency modulation without teaching. The best performing stimuli could represent information for accelerating the speed, for keeping the speed constant, and for decelerating the speed in accuracies of 88, 100, and 79 %, respectively. These accuracies were clearly above the 33.3 % chance level. In general, sine wave stimuli outperformed sawtooth wave stimuli in representing ‘Accelerate your speed’ and ‘Decelerate your speed’ information, but at the same time sawtooth wave stimuli functioned better in representing ‘Keep your speed constant’ information compared to the sine wave stimuli. Differences between different stimulus durations were not statistically significant, although there was a tendency for associating the shortest (i.e., 500 ms) stimuli with ‘Decelerate your speed’ responses and longer (i.e., 1750 and 3000 ms) stimuli with ‘Keep your speed constant’ responses. There were no statistically significant differences in the stimulus evaluations between the wrist and chest locations. The empirical results were supported by post-experimental interviews, where the majority of the participants reported that they had created a response strategy which was in analogy with the perceived frequency modulation of the stimuli. Most of the participants thought that the task felt rather difficult, especially in the very beginning, but that at the same time, as the experiment proceeded, it became easier.

To summarize the results from the statistical analysis of the cognitive evaluation data (see Figures 3-8), we would recommend using an ascending frequency sine wave stimulus with long duration for presenting information on speed acceleration. On the contrary, a constant frequency sawtooth wave stimulus with medium duration should be used for presenting information on keeping the speed constant. Descending frequency sine wave stimuli with short duration would perform well in presenting information on speed deceleration.

Emotional ratings (see Figures 9–12) for arousal and pleasantness showed that stimuli with constant frequency were evaluated as less arousing than stimuli with ascending and descending frequency. Although, the sine wave stimuli were evaluated as more arousing than the sawtooth wave stimuli, there were no differences in the pleasantness ratings between the two waveforms. This is interesting because in the earlier study by Salminen *et al.* [10], tactile stimuli rated as arousing, were also rated as unpleasant, and respectively, relaxing stimuli were rated as pleasant. In stimulus discrimination tasks of the same study, more arousing stimuli were also reacted faster and they appeared to be more distinguishable than less arousing stimuli.

In the current experiment, the participants rated the longest stimuli (i.e., 3000 ms) as more pleasant than the stimuli with shorter durations (i.e., 500 and 1750 ms). In general, all stimuli were also evaluated as more pleasant in the wrist than in the chest. This result was supported by the post-experimental interviews where the majority of the participants preferred wrist more than chest. Further, most participants reported that their wrist was more sensitive for feeling the stimuli than their chest. Even so, there seemed to be individual differences in the touch sensitivity between the two locations as one of the participants verbalized that some stimuli felt ‘too thrilling’ in the chest. Generally speaking, our stimuli were, however, rated as fairly neutral in respect of their pleasantness, even though relatively high stimulus amplitudes were used in order to be able to provide detectable stimuli for the real life contexts and physically active users.

The results were promising because they indicated that it is possible to provide interpretable information to guide the user’s performance without loading the user’s visual and auditory channels. We argue that we were able to convey information intuitively in the sense that in the particular context we did set for our participants, the stimuli could be interpreted naturally and coherently. This happened despite the fact that the meaning of the stimuli was not taught for the participants at any point of the experiment. An interesting detail was that one of the stimuli (i.e., constant frequency / 1750 ms / sawtooth wave) was evaluated in the chest as ‘Keep your speed constant’ in the rate of one hundred percent.

Based on the current results it seems that in respect to the idea of being effortlessly interpretable or intuitive, our stimulations functioned in quite promising way. Given that the factual intuitiveness of the stimuli requires further research, we are executing a follow-up study using two groups with both female and male participants. In one group the participants are first trained the meaning of the different stimuli in the beginning of the experiment. Similarly to the present study, the other group is not taught or coached in any way. By comparing the response rates between these groups, we will be able to get a better understanding of the intuitiveness of the stimuli. We can also analyze if there are any differences between the responses of women and men. Finally, we are planning to move on outside the laboratory and test how the system would work in a realistic sports computer use. This way we will be able to evaluate if tactile expression works better as a support to visual and auditory feedback or would it be the case that tactile expression is fully sufficient on its own.

5. ACKNOWLEDGMENTS

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Publication II

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Intuitiveness of Vibrotactile Speed Regulation Cues

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Interpretations of vibrotactile stimulations were compared between two participant groups. In both groups, the task was to evaluate specifically designed tactile stimulations presented to the wrist or chest. Ascending, constant, and descending vibration frequency profiles of the stimuli represented information for three different speed regulation instructions: "accelerate your speed," "keep your speed constant," and "decelerate your speed," respectively. The participants were treated differently so that one of the groups was first taught (i.e., primed) the meanings of the stimuli, whereas the other group was not taught (i.e., unprimed). The results showed that the stimuli were evaluated nearly equally in the primed and the unprimed groups. The best performing stimuli communicated the three intended meanings in the rate of 88% to 100% in the primed group and in the unprimed group in the rate of 71% to 83%. Both groups performed equally in evaluating "keep your speed constant" and "decelerate your speed" information. As the unprimed participants performed similarly to the primed participants, the results suggest that vibrotactile stimulation can be intuitively understood. The results suggest further that carefully designed vibrotactile stimulations could be functional in delivering easy-to-understand feedback on how to regulate the speed of movement, such as in physical exercise and rehabilitation applications.

Categories and Subject Descriptors: H.1.2 [**Models and Principles**]: User/Machine Systems—*Human factors, human information processing*; 5.2 [**Information Interfaces and Presentation**]: User Interfaces (D.2.2, H.1.2, I.3.6)—*Haptic I/O*; J7 [**Computer Applications**]: Computers in Other Systems—*Consumer products*

General Terms: Design, Experimentation, Human Factors

Additional Key Words and Phrases: Human-computer interaction, heart rate monitor, haptic feedback, iconic information, priming, intuitive decision making

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1. INTRODUCTION

Interaction with mobile devices relies mainly on auditory and visual feedback modalities, although it is known that cognitive processing of auditory and visual information in mobile situations can be problematic (e.g., Oulasvirta et al. [2005]). Problems regarding parallel processing of technology-mediated information and the environment stem from the limitations of the human mental capacity, which is emphasized in situations where divided attention is required (e.g., while moving in rough terrain or

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in traffic) [Lamble et al. 1999]. Especially in sports, visual and auditory attention often needs to be focused primarily on the environment and on the ongoing performance, and all intervening or competitive information from a mobile device may distract and expose both the user and the other people nearby to potential safety risks.

Utilizing the human sense of touch (i.e., haptic modality) as an information channel is a promising alternative to visual and auditory information in mobile and visually demanding situations [Raisamo et al. 2009]. Touch-based stimulation can convey the needed information while allowing the user to focus the vision and hearing exclusively on the surroundings and on the primary task, such as an ongoing workout. For example, Ho et al. [2005] found that reactions to vibrotactile warning signals presented to the torso were significantly faster and also somewhat more accurate as compared to warning signals presented in auditory and visual modality in a dual-task condition (i.e., while performing an attention-demanding visual task).

Haptic feedback that is informing about a status of mobile devices (e.g., alarm for an incoming phone call) is most commonly provided with vibrotactile actuators that vibrate the device and provide tactile sensations by activating mechanoreceptors in the user's skin. In addition to mobile phones, some of the latest sports heart rate monitors are equipped with a vibration function as an alternative to auditory alarms. Although vibration can potentially grasp the exerciser's attention effectively, privately, and in an unobtrusive way, a binary type (i.e., on/off) alarm is limited in the sense that it is incapable of conveying the actual meaning of the alarm signal. Therefore, after noticing the vibration, there is still a need to refer to visual information to confirm whether to slow down or to speed up the exercise.

With haptic stimulation, it is possible to provide richer information than just binary alarms. Brewster and Brown [2004] introduced tactile icons—structured, abstract messages that can be used for presenting information via the sense of touch. They suggested that distinguishable and identifiable iconic information can be encoded by manipulating, for example, frequency, amplitude, duration, rhythm, and spatial location of the haptic stimulation. Using a vibrotactile actuator of a mobile phone, Brown and Kaaresoja [2006] created nine two-dimensional tactile icons informing about the type of a phone alert (i.e., three different rhythms) and the priority of the alert (i.e., three different amplitude modulations within each rhythm). The results showed that the icons were recognized correctly with an accuracy of 72%.

Iconic haptic feedback has been investigated in physical training as well. Rovers and van Essen [2006] introduced a crosstrainer gym device with haptic features. The handles of the device were equipped with multiple vibrotactile actuators mediating iconic guidance information by stimulating the user's palms. The icons were designed to inform the user of factors such as a hearbeat that is too low or too high. For example, an overly extensive workout was represented as a heartbeat signal consisting of a strong beat at the center of the palm and a weaker afterbeat at the lower palm. The results showed that the icons were noticeable during the exercise, but their interpretation required first referring to visual information to understand and eventually learn their meanings.

Enriquez and MacLean [2008] found that vibrotactile icons (e.g., for going faster and slower) can be learned and recalled after a 2-week delay with 80% accuracy regardless of whether their meanings were purely arbitrarily chosen or self-chosen by the participants. Even then, it would seem probable that using arbitrarily or subjectively predefined haptic icons in commercial products holds some concerns. This is because, in all likelihood, many end-users would not interpret the meanings of the icons in a way that the designer has originally intended.

In conclusion, there is evidence that haptic stimulation can complement or even substitute visual and auditory feedback, not only for alarming purposes but also in mediating the needed information with relatively high recognition accuracies. We note, however, that in all of the noted studies, the participants were provided with guidance or a chance to first learn the meanings of the iconic stimulations. This type of individual priming is, of course, impossible when considering the everyday use of haptic icons in consumer devices. It is also known that most typically, people want to learn to use new devices and applications first based on their intuition, and manuals are often referred to only when anything else does not seem to solve the problem [Rettig 1991]. Hence, it would be ideal if haptic information could be interpreted intuitively so that the device could be introduced “out of the box” without any extensive learning or adjustments of its functions. Motivated by the reasons mentioned earlier, we started investigating possibilities of providing simple and easily interpretable haptic information for the needs of mobile users. The aim of an initial experiment [Lylykangas et al. 2009] was to study whether three types of iconic speed regulation cues could be recognized in an intuitive manner—that is, without a priori teaching or coaching. The vibrotactile stimuli were varied, for example, by a vibration frequency profile to investigate if stimuli with ascending, constant, and descending vibration frequency profiles could be associated naturally and analogously with information cueing to accelerate the speed, to keep the speed constant, and to decelerate the speed, respectively. The wrist and chest were chosen for the stimulus locations because the main components of the most heart rate monitors—a wrist unit and a chest strap—could serve as natural platforms for embedding haptic technology and enabled permanent contact to the skin. The results showed that the stimuli were predominantly perceived in congruence with the three different vibration frequency profiles in both body locations. The best recognized ascending, descending, and constant frequency stimuli represented “accelerate your speed,” “decelerate your speed,” and “keep your speed constant” information in accuracies of 88%, 79%, and 100%, respectively. The results indicated promisingly that it could be possible to provide interpretable information via the sense of touch to guide the user’s performance without any teaching. In this respect, it seemed that conveying speed regulation information with haptic icons might really be intuitive.

The present aim was to further test the learnability and, particularly, the possible intuitiveness of the three types of haptic speed regulation cues. Intuitiveness is frequently referred to as an important factor in human-technology interaction [Naumann et al. 2007], but controlled experimental research in this area seems to be virtually nonexistent. We decided to put intuition to the test by comparing a condition where participants were primed by first teaching the intended meaning of the stimulation against one where participants were unprimed (i.e., not taught). By comparing the response rates between these two groups, it would be possible to get a better understanding of the actual intuitiveness of the associations in the decision making.

Because this was the first test of this type of experimental design, we decided to conduct the initial study in laboratory settings with immobile participants in order to minimize the effects of uncontrolled variables to the results. Knowing that physical movement can attenuate the recognition accuracy of low-amplitude vibrotactile stimuli [Pakkanen et al. 2008; Post et al. 1994], we used relatively high stimulus amplitude to ensure that the stimulations could be functional in future studies with mobile participants. Karuei et al. [2011] found that negative effects of movement artifacts on vibration perception can be compensated by sufficient stimulus intensity and appropriate body location. There are several examples showing that vibrotactile displays can provide guidance information during physical movement in various sports, such as snowboarding [Spelmezan et al. 2009], rowing [Van Erp et al. 2006], and swimming [Bächlin et al. 2009].

Tactile stimulation has been found to be associated with human emotions [Salminen et al. 2008]; therefore, we also measured the emotion-related subjective experiences evoked by the stimuli. Earlier research has shown that the use of dimensional affective space can be effective in tracking down experiences evoked by visual and auditory stimulations [Bradley and Lang 1994, 2000]. Because haptic stimuli in mobile situations should be clearly noticeable, yet preferably not irritating, subjective ratings on arousability and pleasantness of the stimuli were collected.

Fig. 1. Attachment of C2 actuators inside a wristband and a chest strap (left), and their locations in a body (right). Pictures of the chest strap with permission of Polar Electro Oy.

Based on the results of our earlier study [Lylykangas et al. 2009], it was expected that responses are mostly given in congruence with the vibration frequency profile of the stimuli regardless of the experimental condition (i.e., primed or unprimed group).

2. METHOD

2.1 Participants

Twenty-four volunteers took part in the experiment after signing informed consent forms. Twelve of the participants were female (mean age 29 years, age range 19–57 years) and 12 were male (mean age 23 years, age range 19–30 years). The participants were students of the University of Tampere. They all were naïve with respect to the purpose of the experiment and reported having a normal or corrected-to-normal vision and normal sense of touch. By self-reports, 23 participants were right-handed and 1 participant was left-handed.

2.2 Apparatus

Experimental hardware was identical to our previous study [Lylykangas et al. 2009]. Two Engineering Acoustic Inc. C2 voice coil actuators were used to present vibrotactile stimulations through a sound card of a personal computer. The diameters of the actuator and its vibrating skin contactor area were 3.05cm (1.2in) and 0.76cm (0.3in), respectively. Stimuli were amplified with a Stage Line® STA 1508 audio amplifier. The actuators were attached to a soft textile wristband and to a Polar® WearLink™ chest strap (Figure 1).

E-Prime® 2.0 Professional experiment generator software [Schneider et al. 2002] was used for controlling the stimulus presentation and data collection. Responses were given using a computer keyboard. The buttons for "accelerate your speed," "keep your speed constant," and "decelerate your speed" responses were set in a vertical layout and labeled with an arrow pointing upward, sideward, and downward, respectively. An experiment initiation button was located on the left side of the middle button. In addition, nine response buttons for giving emotional ratings were set in horizontal layout and labeled from −4 to +4.

2.3 Stimuli

A subset of 18 stimuli was selected from the previous study [Lylykangas et al. 2009]. The stimuli were varied by 3 × frequency profile, 3 × duration, and 2 × stimulus location. The frequency profiles of the stimuli (Figure 2) were created in the following way: (a) for ascending stimuli, the frequency was modulated linearly from 50 to 300Hz; (b) the frequency for the constant stimuli was kept at

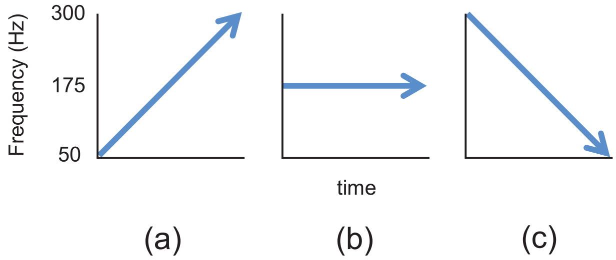

Fig. 2. Vibration frequency profiles of (a) ascending, (b) constant, and (c) descending stimuli.

175Hz; and (c) for descending stimuli, the frequency was modulated linearly from 300 to 50Hz. Three different durations of the stimuli were 500, 1750, and 3000 ms, which provided clearly distinguishable stimulations. The stimuli were built upon sine waveform based on C2 actuator recommendations (http://www.eaiinfo.com/). The amplitude and phase of the signal were not manipulated.

Audacity® audio editor and recorder software version 1.2.6 (http://audacity.sourceforge.net/) and Pure Data real-time audio synthesizer software version 0.40.3 (http://puredata.info/) were used in creating the stimuli. All of the stimuli were 16-bit mono Windows Waveform (WAV) audio files with a 44.1kHz sampling frequency. Stimulus amplitude was adjusted to 1.49V (AC) for both wrist and chest by measuring the voltage from the amplifier outputs with a Fluke® 87V True RMS multimeter while the actuators were playing a constant 250Hz sine wave calibration stimulus.

2.4 Procedure

After introducing the laboratory and the equipment, the participant was seated and the actuators were attached on top of the wrist of the nondominant hand and to the chest (Figure 1). The actuator in the chest strap was located in the sagittal plane of the thorax. In order to avoid vibration resonance with the skeleton, the actuator was attached below the breastbone. Because the chest strap was originally from a heart rate monitor, the participant was informed that the heart rate data was not measured during the experiment. The nondominant hand was laid on a soft armrest, and the other hand was put next to the response buttons. The participant was instructed to hold the nondominant hand still and to keep the gaze on the display during the experiment. To block the mechanical sound of the actuators, the participant listened to pink noise via a hearing protector headset at a comfortable sound level.

The experiment consisted of two experimental conditions. In the primed condition, the participants (six females and six males) were first trained to learn the meanings of the stimuli. In the unprimed condition, the participants (six females and six males) were not taught the meaning of the stimuli. Both conditions included three sessions: (1) priming/familiarization, (2) recognition, and (3) rating. The order of the sessions was fixed. The rating session consisted of two subsessions: pleasantness rating and arousability rating. The order of the subsessions was counterbalanced so that half of the participants started with pleasantness rating and then continued with arousability rating. The other half performed the subsessions in reversed order. Each of the sessions and subsessions consisted of two separate blocks. In one block, the stimuli were presented to the wrist; in the other block, they were presented to the chest. The order of the blocks within each session and subsession was counterbalanced.

The participant was allowed to take a short break between the sessions, subsessions, and blocks. Finally, there was a structured postexperimental interview, where questions were asked to get additional information on the easiness/difficulty of the recognition task and on the used response strategies. The two stimulus locations were also ranked in terms of touch sensitivity and preference. The experiment finished with a debriefing, in which the participants were explained the purpose of the experiment. It took an average of 1 hour to conduct the whole experiment.

2.4.1 Session 1: Priming/Familiarization. The objective of the first session was to create two experimental treatments: a condition with primed participants and a condition with unprimed participants. In the primed condition, the purpose of the session was to teach the participants the intended meanings of the stimuli. They were first told that ascending, constant, and descending vibration frequency meant speed acceleration, constant speed, and speed deceleration, respectively, and that the stimulus duration did not make any difference in this respect. The task was to sit still, feel the stimulations, and learn their meanings. The participants would see a text in the screen that indicated the meaning of the stimuli before and after each stimulus presentation (e.g., "The upcoming stimulus means: Accelerate your speed" and "The stimulus meant: Accelerate your speed"). In the unprimed condition, the purpose of the session was to allow the participants to familiarize themselves with feeling the vibrotactile stimuli in the two body sites and to initiate them into the stimulus space used in the experiment. They were instructed simply to sit still and feel the stimuli. In both conditions, participants started the session by pressing the experiment initiation button. Then the nine wrist stimuli and the nine chest stimuli were presented in separate blocks sequentially in a random order with an interstimulus interval of 3500ms. The response buttons were covered in both conditions to prevent hints to the experimental task in the upcoming session.

2.4.2 Session 2: Recognition. In the beginning, the experimenter uncovered the response buttons. At this point, the actual meaning of the experiment was revealed and explained to the participants. They were instructed to imagine that the computer was giving them instructions to either accelerate their speed, keep their speed constant, or decelerate their speed by using the stimuli presented in the previous session. The primed group was instructed to respond as quickly and as accurately as possible according to what was taught in the previous session. However, according to Kahneman's [2003] characterization of intuition being thoughts and preferences that come to mind quickly, spontaneously, and effortlessly under appropriate circumstances, the unprimed group was instructed to respond as quickly as possible by relying on the first impression. Otherwise, the procedures in the primed and unprimed groups were identical. First, the participant performed three practice trials in order to rehearse the response technique. In the practice session, three 1000ms-long practice stimuli (constant 50, 175, and 300Hz square wave vibration) were presented one at a time in random order. In contrast to the experimental stimuli, the training stimuli were presented simultaneously to the wrist and chest. The practice stimuli were not presented in the actual experiment. After the practice trials, the experimenter left the room and the participant initiated the first trial by pushing the experiment initiation button. In a trial, a "Next stimulus" text appeared on the display for 1500ms. Then, the text disappeared and a fixation point (+) appeared on the center of the display for 1500ms. The display was blank for 500ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the response options appeared on the display, and the participant was able to answer. The uppermost button was to be pushed for an "accelerate your speed" response, the middle button was to be pushed for a "keep your speed constant" response, and the lowest button was to be pushed for a "decelerate your speed" response. After the response, there was a 500ms interval and then a new trial was initiated automatically. Response times were calculated from the stimulus offset. Each of the nine wrist stimuli and nine chest stimuli were presented twice in a random order in separate blocks, resulting in a total of 36 trials in the session.

2.4.3 Session 3: Rating. The task in the third session was to rate the stimuli using two emotion-related nine-point bipolar scales varying from -4 to $+4$. The procedure was the same in the primed and the unprimed conditions. Ratings were asked for the scale of pleasantness of a stimulus (i.e., how unpleasant or pleasant the stimulus felt), varying from unpleasant to pleasant, and for the scale of arousability of a stimulus (i.e., how relaxed or aroused the participant felt during the stimulus), varying from relaxed to aroused. On both scales, 0 represented a neutral experience (i.e., neither unpleasant nor pleasant, and neither relaxed nor aroused). Ratings were given using the keyboard. In the beginning of both pleasantness and arousability ratings, the participant performed three practice trials in order to rehearse the rating procedure. Three practice stimuli not included in the actual experiment were rated one at a time. The practice stimuli were presented simultaneously to the wrist and chest. After the practice trials, the experimenter left the room and the participant was allowed to start rating the experimental stimuli. The participant initiated a trial by pushing a space bar on the keyboard. Then, a fixation point appeared on the center of the display for 1500ms. The display was blank for 1500ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the rating scale appeared on the display, and the participant was able to respond. After giving the response, there was a 500ms interval and then the participant could initiate a new trial. Each of the 18 stimuli was presented once for both the pleasantness and the arousability rating scales in separate blocks in a random order. Thus, there were a total of 36 trials in the session.

2.5 Data Analysis

The data of the average response percentages in the second session were analyzed using a four-way mixed model Analysis of Variance (ANOVA) with experimental condition (i.e., primed and unprimed group) as a between-subjects factor, and stimulus properties (i.e., frequency profile, location, and duration) as within-subjects factors. The analysis was conducted separately for each of the three response options.

Response times in the second session were analyzed with a two-way mixed model ANOVA with experimental condition as a between-subjects factor and stimulus location as a within-subjects factor. The main interest was to study the possible effects of these two factors; therefore, response times were averaged over the frequency profiles and stimulus durations to simplify the analysis. In addition, data were averaged over the three response options in order to avoid a bias caused by the fixed order of the response buttons. Response time analysis included both congruent and incongruent responses.

The main scope of the emotional ratings in the third session was to study possible effects of gender, frequency profile, and stimulus location. Thus, to avoid overly complex analysis, the data were averaged over the experimental conditions and stimulus durations. A three-way mixed model ANOVA with gender as a between-subjects factor and frequency profile and location as within-subjects factors was used for the analysis.

Greenhouse-Geisser–corrected degrees of freedom were used to validate the F statistic, if the sphericity assumption of the data was violated. Bonferroni-corrected t-tests were used for pairwise post hoc tests.

3. RESULTS

Figure 3 shows the mean responses and Standard Error of the Means (SEMs) in the second session. Figures 4 and 5 present the mean responses and SEMs of the emotional ratings of pleasantness and arousability in the third session.

3.1 "Accelerate Your Speed" Responses

For the "accelerate your speed" responses (Figure 3(a)), a four-way $2 \times 3 \times 2 \times 3$ (experimental condition $\times$ frequency profile $\times$ location $\times$ duration) mixed model ANOVA showed a statistically significant

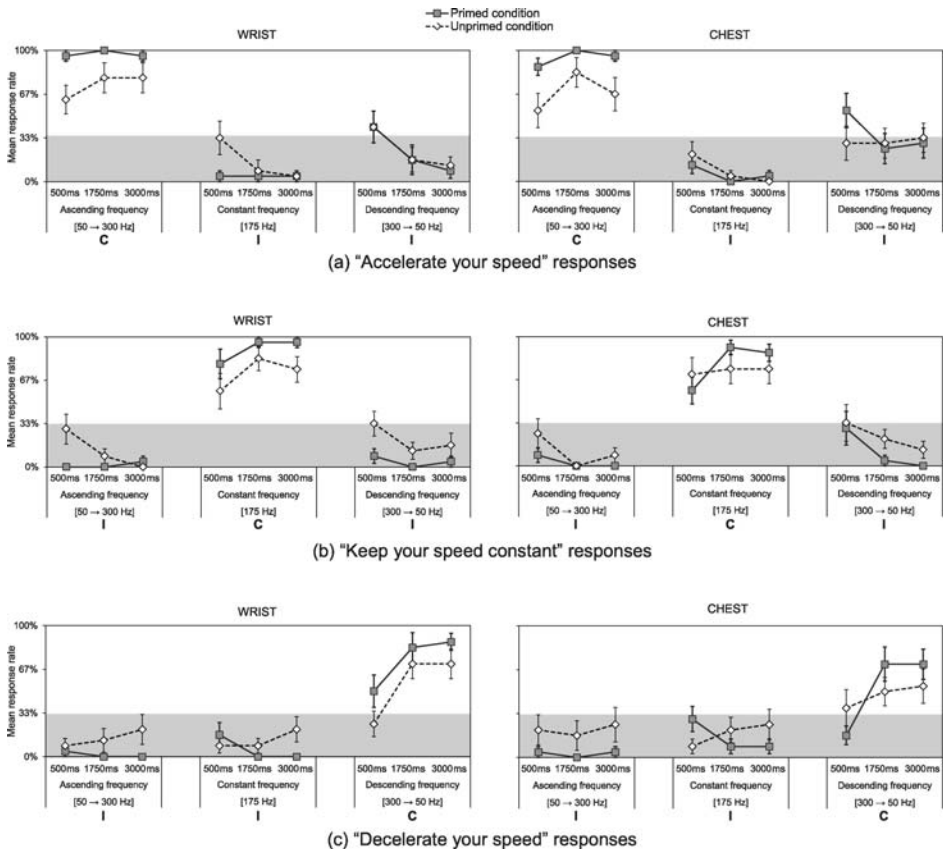

Fig. 3. Mean percentages and SEMs of (a) "Accelerate your speed" responses, (b) "Keep your speed constant" responses, and (c) "Decelerate your speed" responses for wrist and chest stimuli by experimental condition, stimulus duration, and frequency profile. The grey area indicates the range of the chance level. C, congruent stimuli; I, incongruent stimuli.

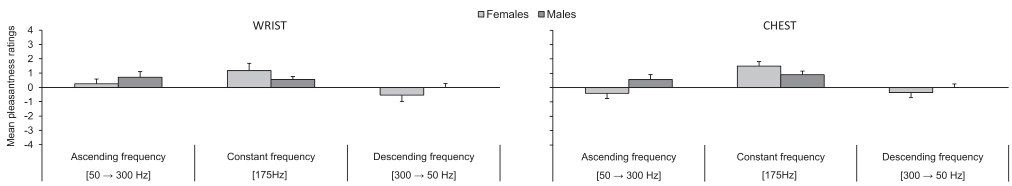

Fig. 4. Mean pleasantness ratings and SEMs of wrist stimuli (left) and chest stimuli (right) by gender and frequency profile.

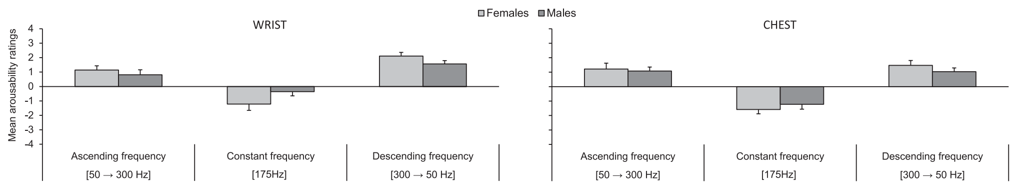

Fig. 5. Mean arousability ratings and SEMs of wrist stimuli (left) and chest stimuli (right) by gender and frequency profile.

main effect of frequency profile [$F(2, 44) = 113.2$, $p < 0.001$] and two-way interactions between frequency profile and experimental condition [$F(2, 44) = 5.1$, $p \leq 0.01$], frequency profile and location [$F(1.6, 35.2) = 4.3$, $p < 0.05$], and frequency profile and duration [$F(2.4, 53.6) = 7.56$, $p \leq 0.001$]. Main effects of experimental condition, duration and location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the mean rate of "accelerate your speed" responses given to congruent (i.e., ascending frequency) stimuli (83.3%) was significantly higher as compared to incongruent (i.e., constant frequency [$MD = 75.0\%$, $p < 0.001$] and descending frequency [$MD = 55.2\%$, $p < 0.001$]) stimuli.

In order to analyze the interaction between frequency profile and experimental condition in more detail, three separate one-way ANOVAs (i.e., one for each frequency profile with experimental condition as an independent between-subjects factor) were conducted. The analyses showed that the interaction was due to the fact that response rates between primed and unprimed participants were similar for incongruent (i.e., constant and descending frequency) stimuli, but they differed significantly for congruent (i.e., ascending frequency) stimuli [$F(2, 22) = 12.7$, $p < 0.01$]. In Figure 3(a), it can be seen that primed participants gave "accelerate your speed" responses for ascending frequency stimuli more frequently than unprimed participants [$MD = 25.0\%$].

The interaction between frequency profile and location came from the fact that response rates of wrist and chest stimuli were similar, except for descending frequency stimuli, where response rates were slightly, although not significantly, higher in the chest than in the wrist [$MD = 10.4\%$, $p = 0.079$]. The reason for the interaction between frequency profile and duration can be seen in Figure 3(a), which shows that response rates of 500ms stimuli were lower in congruent responses and higher in incongruent responses as compared to 1750 and 3000ms stimuli.

3.2 "Keep Your Speed Constant" Responses

For the "keep your speed constant" responses (Figure 3(b)), a four-way $2 \times 3 \times 2 \times 3$ (experimental condition $\times$ frequency profile $\times$ location $\times$ duration) mixed model ANOVA showed a statistically significant main effect of frequency profile [$F(1.4, 29.9) = 198.7$, $p < 0.001$]. Two-way interactions were found between frequency profile and experimental condition [$F(1.4, 29.9) = 6.1$, $p < 0.05$] and frequency profile and duration [$F(2.7, 60.1) = 10.2$, $p < 0.001$]. Main effects of experimental condition, duration and location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the rate of "keep your speed constant" responses given to congruent (i.e., constant frequency) stimuli (78.8%) was significantly higher as compared to incongruent (i.e., ascending frequency [$MD = 71.9\%$, $p < 0.001$] and descending frequency [$MD = 64.2\%$, $p < 0.001$]) stimuli.

To analyze the interaction between frequency profile and experimental condition, three separate one-way ANOVAs (i.e., one for each frequency profile with experimental condition as an independent between-subjects factor) were performed. The analyses showed that the interaction was due to the fact that response rates between primed and unprimed participants were similar for congruent (i.e., constant frequency) stimuli but differed significantly for incongruent stimuli. Unprimed participants gave "keep your speed constant" responses more frequently to ascending and descending frequency stimuli than primed participants [$MD = 9.8\%$, $p < 0.05$ and $MD = 13.9\%$, $p < 0.05$, respectively].

The explanation for the interaction between frequency profile and duration can be seen in, Figure 3(b) where response rates of 500ms stimuli is lower in congruent responses and higher in incongruent responses as compared to 1750 and 3000ms stimuli.

3.3 "Decelerate Your Speed" Responses

For the "decelerate your speed" responses (Figure 3(c)), a four-way $2 \times 3 \times 2 \times 3$ (experimental condition $\times$ frequency profile $\times$ location $\times$ duration) mixed model ANOVA showed a statistically significant main effect of frequency profile [$F(1.5, 33.9) = 40.8$, $p < 0.001$] and stimulus duration [$F(1.4, 30.3) = 4.6$, $p < 0.05$]. A three-way interaction was found between experimental condition, frequency profile, and duration [$F(4, 88) = 2.6$, $p < 0.05$]. Two-way interactions were found between frequency profile and location [$F(1.5, 32.1) = 9.7$, $p < 0.001$] and frequency profile and duration [$F(4, 88) = 10.9$, $p < 0.001$]. Main effects of experimental condition, location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the rate of "decelerate your speed" responses to congruent (i.e., descending frequency) stimuli (57.3%) was significantly higher as compared to incongruent (i.e., ascending frequency [$MD = 47.6\%$, $p < 0.001$] and constant frequency [$MD = 44.4\%$, $p < 0.001$]) stimuli. Despite the main effect of stimulus duration, pairwise comparisons did not reveal significant differences between the durations.

To investigate the three-way interaction between experimental condition, frequency profile, and duration, two-way 3×3 (frequency profile $\times$ duration) ANOVAs were performed separately for primed and unprimed groups. The results showed that the interaction resulted from the fact that frequency profile interacted with duration in the primed group [$F(2.3, 25.3) = 12.9$, $p < 0.001$] but not in the unprimed group. Figure 3(c) shows that response rate of 500ms stimuli in the primed group fluctuated in response to frequency profile; thus, in ascending, constant, and descending frequency, it was either equal, lower, or higher, respectively, in relation to 1750- and 3000ms stimuli.

The interaction between frequency profile and location was due to the fact that congruent responses were given more often for the wrist than chest stimuli [$F(1, 23) = 7.0$, $p < 0.05$], but incongruent responses to constant frequency stimuli were given more frequently when presented to the chest than the wrist [$F(1, 23) = 6.4$, $p < 0.05$]. The explanation for the interaction between frequency profile and duration can be seen in Figure 3(c), which shows that response rates of 500ms stimuli were lower in congruent responses as compared to 1750 and 3000ms stimuli, but in incongruent responses, the response rates were similar for the three stimulus durations.

3.4 Response Times

The grand mean of the response times in the second session was 1597ms. A two-way 2×2 (experimental condition $\times$ stimulus location) mixed model ANOVA showed a statistically significant main effect of stimulus location [$F(1, 20) = 12.1$, $p < 0.01$]. The main effect of experimental condition and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the mean response time to wrist stimuli (1463ms) was significantly faster as compared to the responses given to chest stimuli [$MD = 269$ms].

3.5 Pleasantness Ratings

For the ratings of stimulus pleasantness (Figure 4), a three-way $2 \times 3 \times 2$ (gender $\times$ frequency profile $\times$ location) mixed model ANOVA showed a statistically significant main effect of frequency profile [$F(2, 44) = 17.2$, $p < 0.001$] and a significant two-way interaction effect between gender and frequency profile [$F(2, 44) = 5.3$, $p < 0.05$]. The main effects of gender and location were not statistically significant, and there were no other statistically significant interactions of the main effects. Post hoc pairwise comparisons showed that constant frequency stimuli were rated as more pleasant than ascending frequency stimuli [$MD = 0.7$, $p < 0.05$] and descending frequency stimuli [$MD = 1.3$, $p < 0.001$]. In addition, ascending frequency stimuli were rated as more pleasant than descending frequency stimuli [$MD = 0.5$, $p < 0.05$].

The interaction between gender and frequency profile was analyzed in more detail with two separate one-way ANOVAs (i.e., one for both genders with frequency profile as an independent within-subjects factor). The results showed that the interaction was due to the fact that frequency profile had a statistically significant effect for females' responses [$F(2, 22) = 24.8$, $p < 0.001$] but not for males' responses. Post hoc pairwise comparisons showed that females rated constant frequency stimuli as significantly more pleasant than ascending frequency stimuli [$MD = 1.4$, $p \leq 0.01$] and descending frequency stimuli [$MD = 1.8$, $p < 0.001$].

3.6 Arousability Ratings

For the ratings of stimulus arousability (Figure 5), a three-way $2 \times 3 \times 2$ (gender $\times$ frequency profile $\times$ location) mixed model ANOVA showed a statistically significant main effect of frequency profile [$F(2, 44) = 56.3$, $p < 0.001$] and location [$F(1, 22) = 6.9$, $p < 0.05$]. The main effect of gender and interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that both ascending and descending frequency stimuli were rated as significantly more arousing than constant frequency stimuli [$MD = 2.2$, $p < 0.001$ and $MD = 2.6$ $p < 0.001$, respectively]. In addition, wrist stimuli were rated as significantly more arousing when compared to chest stimuli [$MD = 0.3$, $p < 0.05$]. The other pairwise comparisons were not statistically significant.

4. DISCUSSION

In general, the vibrotactile speed regulation stimuli were clearly intelligible for both primed and unprimed participants. Figure 3 showed that the average rates of congruently (i.e., according to our hypothesis) given responses were clearly above the 33% chance level, and incongruent responses were given at lower rates. At their best, the three different speed regulation cues could be evaluated congruently in the rates of 88% to 100% and 71% to 83% by primed and unprimed participants, respectively. To the best of our knowledge, these were the first results showing proof on behalf of intuitive judgments of vibrotactile iconic information by using a method where the performances of primed and unprimed participants were compared in a controlled experimental setup.

The hypothesis of the congruence between the vibration frequency profiles and the response options was mainly supported, because unprimed participants performed equally to primed participants in evaluating the stimuli with constant and descending frequency profiles congruently. Ascending frequency stimuli, however, were evaluated congruently (i.e., as "accelerate your speed" information) more frequently by primed than unprimed participants. Even then, as seen from Figure 3(a), the mean rate of congruent responses of unprimed participants for ascending frequency stimuli (83.3%) is commensurate with their congruent responses for constant and descending frequency stimuli. Considering that primed participants succeeded exceptionally well (i.e., in accuracy of 100% or close) in evaluating ascending frequency stimuli, the significant difference can be partly explained by the good performance of primed participants rather than by the low rate of congruent responses by unprimed participants. Taken together, the results of the unprimed participants replicated the significant findings of our previous experiment [Lylykangas et al. 2009]. Added to this, the predominantly coherent performance of both primed and unprimed participants in the present study gave evidence that the stimuli were intuitively associated to their intended meanings.

In postexperimental interviews, many participants criticized that evaluating the shortest (i.e., 500ms) stimuli was difficult. This opinion was supported by the significant interaction effects found between frequency profile and stimulus duration within each response option. Figures 3(a)–3(c) shows that the 500ms stimuli were evaluated congruently to a lesser degree when compared to longer stimulus durations. Thereby, it seems that the 1750 and 3000ms stimuli would provide speed regulation information more efficiently than the 500ms stimuli.

Response times were similar between primed and unprimed groups. Both groups, however, responded significantly faster to wrist stimuli than to chest stimuli. The statistical analysis did not reveal a coherent result on the superiority of neither wrist nor chest stimulation; therefore, it seems unlikely that the difference of the response times was due to difficulty in perceiving the chest stimuli. One possible explanation can be related to results of Tipper et al. [1998], which show that visual perception on the haptically stimulated body site can facilitate reaction times as compared to a situation where the body site cannot be seen. Thus, faster response times in the wrist found in the present study could be related to the fact that the participants were able to see their wrist but not their chest during the stimulation.

Subjective ratings of the stimuli revealed that constant frequency stimuli were generally evaluated as more pleasant than stimuli with ascending and descending frequencies. Further, the ratings of arousal showed that constant frequency stimuli were rated as less arousing than the other frequency profiles. Thinking from the application point of view, this result suggests that constant vibration frequency stimulation could function nicely in informing nonarousingly that "you are doing fine—keep your speed constant." The other two frequency profiles rated as more arousing would also function well by first alerting that one needs to make a change and then informing whether one should accelerate or decelerate the speed.

Although the pleasantness of wrist and chest stimuli was rated in an equal way by both genders, postexperimental interviews (see the Appendix) revealed that females preferred wrist stimulation over chest stimulation almost unanimously. The wrist was preferred also by males but not as clearly as among females. The females' greater favor of wrist stimuli could be due to gender difference in touch sensitivity, because females, more often than males, reported their chest area being more sensitive than their wrist. Therefore, some of them relayed the experience of chest stimuli as overly vigorous and thus unpleasant. Unlike females, however, the majority of males reported their wrist being more sensitive than their chest in feeling the stimuli. This result is in line with Karuei et al. [2011], who found differences in touch sensitivity between genders across different body sites. For example, they found that wrist stimuli were detected better by males than females. To sum the results of the interviews of the current study, the wrist was preferred over the chest in feeling the stimuli by both genders, yet males showed more interpersonal variation in their most preferred stimulus location. In subjective evaluations of Karuei et al. [2011], wrist stimulation was also found as a preferred body site for vibrational exercise cues.

In conclusion, the current results demonstrated that vibrotactile cues can evoke coherent and intuitive associations for regulating behavior in a certain manner. A wearable heart rate monitor with carefully designed haptic signals would enable an inconspicuous medium capable of providing private information and guidance in an easily interpretable manner. This could serve as an alternative medium for both visual and auditory alarms, which can be cumbersome due to environmental or user-related reasons. For example, a noisy environment can prevent the user from hearing auditory signals. Auditory signals can also be awkward in social situations. Especially, information considered as private by its nature (e.g., heart rate and physical condition) may not be desirable to be shared in the presence of others. Visual signals can easily be neglected in high luminance conditions, and naturally, people with sensory impairments may not benefit from visual or auditory feedback at all.

Tactile information as an alternative to visual and auditory modalities could be appreciated among a variety of heart rate monitor users. In sports such as running and cross-country skiing, where upper limb coordination plays a central role, the stimuli introduced in the present study would not interfere with the user's optimal hand trajectories, because one would not need to take glances at the display to interpret the alarms. Intuitive vibrotactile stimulations might be functional in home-based cardiac rehabilitation applications (e.g., Bidargaddi and Sarela [2008], Gay et al. [2009], and Su et al. [2010]) by informing the patient unobtrusively on safe strain levels and the status of the blood vascular system during light exercise, daily routines, and even in overnight monitoring. In comparison to visual and auditory information, simple and comprehensible haptic feedback signals especially could come up to the expectations of the technologically unoriented, weak-sighted, and hearing-impaired users. It is likely that the results could be applicable in other contexts as well, such as motion training, car driving, and gaming, in which haptic speed regulation cues could be beneficial in complementing or substituting audiovisual information in an intuitive manner.

In thinking of the ecological validity, there is evidence that wearable vibrotactile displays can provide users with perceivable and understandable information during physical exercise (e.g., Bächlin et al. [2009], Spelmezan et al. [2009], and Van Erp et al. [2006]). However, future work should include testing the stimuli suggested by our current results in mobile settings outside the laboratory. In fact, the perceptual cycle model by Neisser [1976] suggests that these stimuli might function even better in the actual speed regulation task than in the current laboratory setup. This is because in the present approach, the participants' information processing cycle was incomplete in the sense that the feedback on the correctness of the responses was missing from the information processing loop. In realistic settings, the speed regulation stimuli would be directly consequential in respect to the individual user's actions. In terms of Neisser's thinking, this would enable users to gradually build up an inner schema about the haptic code during the exercise. Following this, the schema could actually make it easier to recognize the stimuli.

The significant findings of the current research provide a fertile ground for future investigations with regard to intuitive decision making. For example, more diverse speed regulation information could potentially be designed using more rich variations of stimulus parameters. As one possibility, both short- and longer-term stimulation could be intuitively associated with quick and slow speed shift, respectively. In summary, the present results suggest that the use of carefully designed and tested haptic stimulation is a promising direction in which to proceed when developing future applications that aim at intuitive behavioral regulation.

APPENDIX. POSTEXPERIMENTAL INTERVIEWS

After the experiment, the majority of the primed participants (8/12) and nearly half of the unprimed participants (5/12) reported that the task of evaluating the meanings of the stimuli was easy rather than difficult. In proportion, two primed and five unprimed participants considered that the task was difficult. In both conditions, two participants thought that the task was neither easy nor difficult. The most frequent reason for the difficulties was related to the shortest (500ms) stimuli, which were considered problematic by nine primed and two unprimed participants.

Nearly all primed participants (11/12) reported the ability to respond according to the response logic introduced in the beginning of the experiment, regardless that many of them had some difficulties in evaluating the meaning of the shortest stimuli. Among the unprimed participants, the most prevalent response strategy was related mainly to frequency profile of the stimuli (10/12) according to what was hypothesized. One participant came up with response logic in which stimulus duration was the determinant for assessing the meanings, and one reported being unable to create any meaningful response strategy during the experiment.

Almost half of the females (5/12) stated that their chest was more sensitive in feeling the stimuli than the wrist. Another five females felt that their wrist was more sensitive than the chest. The majority of the males (9/12) considered their wrist more sensitive than the chest, whereas only two males rated their chest as more sensitive than the wrist in feeling the stimuli. The rest did not feel a difference in the sensitivity of the wrist and chest locations.

Almost all females (11/12) preferred their wrist to the chest in feeling the stimuli. Only one female was fonder of the chest stimuli. With male participants, the preferences of feeling the stimuli were more evenly distributed between the locations, as seven voted for the wrist and five for the chest.

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Research Article

Vibrotactile Stimulation as an Instructor for Mimicry-Based Physical Exercise

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The present aim was to investigate functionality of vibrotactile stimulation in mimicry-based behavioral regulation during physical exercise. Vibrotactile stimuli communicated instructions from an instructor to an exerciser to perform lower extremity movements. A wireless prototype was tested first in controlled laboratory conditions (Study 1) and was followed by a user study (Study 2) that was conducted in a group exercise situation for elderly participants with a new version of the system with improved construction and extended functionality. The results of Study 1 showed that vibrotactile instructions were successful in both supplementing and substituting visual knee lift instructions. Vibrotactile stimuli were accurately recognized, and exercise with the device received affirmative ratings. Interestingly, tactile stimulation appeared to stabilize acceleration magnitude of the knee lifts in comparison to visual instructions. In Study 2 it was found that user experience of the system was mainly positive by both the exercisers and their instructors. For example, exercise with vibrotactile instructions was experienced as more motivating than conventional exercise session. Together the results indicate that tactile instructions could increase possibilities for people having difficulties in following visual and auditory instructions to take part in mimicry-based group training. Both studies also revealed development areas that were primarily related to a slight delay in triggering the vibrotactile stimulation.

1. Introduction

Structured physical group exercise is typically based on seeing and listening to instructions of a trainer and then modeling them by trainees who try to do the same movements in synchrony with the trainer. There are many groups, however, like aged and disabled people who cannot benefit or get the full utility from such activities if their sensory or cognitive impairments inhibit them from following visual and auditory instructions. Utilizing the sense of touch as an information channel could partly replace the requirements of the full functionality of visual and auditory perception (see [1] for a review). Following this, touch mediated instructions could increase the achievability of group exercise for special groups and it could actually complement the exercise even in the case of fully functional sensory systems.

Motor response to a touch sensation is an innate trait for human beings, and the sense of touch has some advantages over the other senses [2]. For example, reaction times (RTs) to tactile stimuli have been found to be faster than RTs to visual stimuli (e.g., [3]). As compared to auditory RTs, tactile RTs have been found to be less affected by distractions such as a concurrent secondary task (e.g., [4]). This is probably because, in contrast to visual and auditory events, tactile events are in direct physical contact with the organism and thus evoke more readily the interest of an organism [5]. Mechanisms to react to tactile stimulation are among the first ones to develop as evidenced by the palmar grasp reflex of fetuses [6]. Furthermore, the importance of the sense of touch has been shown by, for example, remaining of motor responses to tactile stimulation, while the patients are unresponsive to other types of stimulations like visual and auditory stimulations [7].

Relatively recent experimental research has shown that technology-mediated vibrotactile stimulation (i.e., cutaneous stimulation produced by a vibration actuator) can be successfully used in assisting physical rehabilitation and exercise by means of sensory substitution and augmentation. Wearable vibrotactile feedback systems have proven to be usable, for example, in gait retraining [8], body balance control [9], rowing [10], snowboarding [11], and even swimming [12]. There is also evidence that appropriately designed vibrotactile signals can be intuitively associated with cues suggesting, for example, to accelerate and decelerate the speed of movement [13]. The evidence on intuitive associations between tactile stimulation and human behavior suggests that tactile stimulation might also function as a substitute for another person's visual demonstration of bodily movements. Lee and his colleagues [14, 15] have empirically tested body balance training with tactile information in the mimicry frame of reference, but otherwise using tactile stimulation in providing interpersonal, mimicry-based behavioral regulation information seems to be still largely unstudied. In a preliminary study by Lee and Sienko [14] the task was to replicate prerecorded trunk tilt movements consisting of a 20° anterior tilt followed by a 6 s long static hold and a 20° posterior trunk tilt back to the upright starting position. The tilt movements were performed at a rate of about 1.12°/s. The instructions were either visual, tactile, or combined visual-tactile cues. Visual instruction was provided with a side-view illustration of a virtual avatar representing the prerecorded example movements of an instructor. Tactile instructions were provided with two separate vibration actuators placed on trunk midline in the navel and back indicating the anterior and posterior tilts, respectively. End of the vibration communicated the attainment of the desired tilt angle. The results showed that the example tilts were mimicked significantly more accurately and faster with combined visual-tactile and tactile instructions as compared to visual instructions. In a follow-up study [15] the speed of the example movement was varied, and this time only tactile instructions were provided. The results showed that slow (approximately 1.12°/s) example movements were mimicked more accurately as compared to medium (approximately 2.0°/s) and fast (approximately 4.0°/s) example movements. Together the results of Lee and colleagues [14, 15] indicate a serious potential of using tactile instructions to mimic physical movement of another person in eyes- and hands-free fashion. However, more research is needed to assess the functionality of the concept in other types of mimicry-based physical training.

In contrast to earlier work, our aim was to broaden the scope from personal (i.e., one-to-one) balance training towards faster-paced rhythmic knee lift exercise often performed in group training situations. Clearly, the characteristics and requirements of the relatively slow-paced trunk tilt exercise performed in the earlier studies and the rhythmic knee lift exercise (e.g., marching in place) with many participants deviate from each other in many respects. For example, the precise postural mimicry of the angular magnitude of the instructor's movement considered essential in the earlier trunk tilt studies was not recognized as a central factor in the rhythmic knee lifting task. This is because comfortable lift height range may be widely varied within the exercise group depending on the participants' physical condition. Accurate temporal mimicry enabling rhythmic synchrony, however, is essential in this type of an exercise in order to keep the group in the same phase. So, in contrast to the instructions given in balance training, it is more vital to communicate the start time rather than end point of the movement. Another change considered necessary for the current investigation was the replacement of the virtual avatar used in [14] by a human instructor to meet the facilities of a typical group exercise situation. Importantly, we also addressed the exercisers' subjective experiences on how they considered touch information in the context of physical exercise.

We designed a system that measured an instructor's leg movements and, on the basis of these measurements, tactile stimulations were wirelessly routed to a leg of a participant to instruct the moments to perform leg lifts. Two versions of a wireless and wearable prototype system were designed in an iterative fashion for investigation. In Study 1, the first prototype version was tested in controlled laboratory conditions with individual adults participating in a simulated exercise situation to get basic information on the functionality of the system and to reveal main development areas. In Study 2, the second prototype version with modified construction and increased functionality needed in actual training situation was tested in realistic conditions with a potential target group consisting of geriatric participants taking part in a structured group exercise. In both studies the participants performed mimicry-based tasks with visual and tactile guidance and then evaluated their experiences of performing the exercise.

2. Study 1: Laboratory Experiment

2.1. Introduction. The aim of the first experiment was to evaluate how a wireless tactile guidance application functions in comparison to conventionally used visual demonstration in a knee lift exercise. Typically in such exercise an instructor shows how and when a knee should be lifted, and the exerciser's task is to mimic the demonstration movements in the same phase with the instructor.

We used prerecorded video instructions in giving the visual guidance stimuli to provide consistent and comparable test conditions. A reflection symmetry motor paradigm by Bavelas et al. [16] was used to instruct the participant to imitate the instructor's demonstration movements shown in the video so that the participant and the instructor were facing each other and the task was to respond to the instructor's knee lift as if watching one's own image reflected by a mirror.

Tactile guidance was provided with vibration stimulation on a leg. Tactile stimulus was based on a push metaphor [11, 17]. This means that the task was to withdraw the leg away from the stimulus located in the dorsal side of the leg above crook as though the vibration would "push" the limb to an opposite direction. The stimulus-response compatibility between push versus pull stimulation and consecutive body movements has been studied to some extent (e.g., for wrist rotation direction studied in Jansen et al. [17]), but so far established guidelines for optimal stimulus locations, for example, for a knee lift movement, seem to be nonexistent. Location, duration, vibration frequency, and amplitude of the tactile stimulation were chosen based on a pilot test where six participants evaluated vibratory stimulations in different leg locations while performing a knee lift exercise. The overall preference of the two metaphors was almost equally distributed and thus the decision was based on the slightly more affirmative stimulus amplitude ratings given to the push metaphor stimulations.

There were three modality conditions to provide knee lift instructions: visual (V), tactile (T), and visual-tactile (VT) guidance. Knowing that a slight delay between the onsets of visual and tactile stimuli will inevitably be present due to an acceleration threshold-based triggering of the tactile stimulus (i.e., the instructor's leg movement needed to exceed a certain magnitude to set on the tactile stimulus in the exerciser's leg) as well as operating latency of the vibrotactile actuator, we focused on comparing the knee lift RT between the modality conditions. RT was considered as an important measure because synchronous-enough timing between the onsets of instructor's demonstration movement and the tactile guidance stimulus would be a prerequisite for a successful group exercise especially with visually impaired exercisers. We also investigated possible effects of tactile stimulation on the leg's acceleration magnitude to study the movement dynamics between the different instruction modalities in more detail. In addition to the objective measures of the knee lift RT and acceleration, the participants' subjective experiences were inquired to assess how they rated the tactile instructions in this type of activity.

2.2. Methods

2.2.1. Participants. Twelve voluntary participants (3 female and 9 male) between the ages of 19 and 48 years ($M = 26$ and $SD = 9$) took part in the study after signing informed consent forms. They were students or staff of the University of Tampere. All reported having normal sense of touch and normal or corrected to normal vision. Eleven of them were right legged and one was left legged by their own report. The study was approved by a local research ethics committee.

2.2.2. Stimuli. The knee lift guidance stimuli were presented in three modality conditions. In V modality condition the stimuli were provided with an exercise video (320 × 240 pixel resolution, ~30 Hz sampling rate) where an instructor facing towards the participant produced the stimuli by demonstrating left knee lift movements (Figure 1).

In VT modality condition, a 200 ms long and 285 Hz vibration stimulus in the participant's right thigh was coupled with each knee lift event presented in the exercise video.

Figure 1: A screenshot of the exercise video showing the instructor performing a demonstration movement.

The current stimulus duration has been earlier used in wearable vibration systems for body movement instructions by, for example, Sienko et al. [9] and Jansen et al. [17]. The vibration frequency was within the best sensitivity range of Pacinian corpuscle mechanoreceptors around 10–500 Hz [18] and was found to be well perceived in the preexperimental pilot test. The vibration was provided in an early phase of the demonstration knee lift movement as soon as the instructor's leg acceleration exceeded a triaxial sum vector threshold of 0.75 g calculated as

$$\sqrt{(gX^2) + (gY^2) + (gZ^2)} \quad (1)$$

in a baseline-corrected data. The baseline was the mean of the first 200 samples from the beginning of the measurement while the instructor was standing still. The threshold was determined by inspecting accelerations of the demonstration movements shown in the exercise videos. The data showed that the current threshold was required to be exceeded in order to reliably detect the upward phase of each of the demonstration movements. In consequence of the acceleration threshold there was an average of 203 ms ($SD = 31$ ms) delay between the instructor's initial leg movement and the onset of the tactile stimulus. In T modality condition the vibration stimuli were identical to those in VT, but the visual instructions (i.e., the exercise video) were excluded. In order to reduce the predictability of stimulus onset time, interstimulus interval (ISI) was varied randomly within three durations: 3 (short), 6 (medium), and 9 (long) seconds, approximately. Three separate exercise videos (i.e., one for each modality condition) with differently arranged ISI occurrence were used to eliminate possible learning effect regarding the running order of the short, medium, and long ISI trials.

2.2.3. Apparatus. The first prototype device (Figure 2) was built on Arduino Duemilanove prototyping board that was used for processing the data from an accelerometer, controlling a vibration motor and communicating wirelessly with a PC over Bluetooth. The prototyping board, Bluetooth module, and 9 V battery used to power the device were enclosed to a box and placed into a belt bag. Precision Microdrives

(a) (b)

Figure 2: (a) Wearable parts of the apparatus including electronics in the enclosure box (middle), accelerometer inside the round housing (right), and vibration motor inside the tube housing (left). Scale is indicated by a coin in diameter of 20 mm. (b) The belt bag containing the enclosure box and the leg band equipped with the accelerometer and vibration motor worn by a participant.

vibration motor (model 304-111) encapsulated in a plastic tube was used for stimulating a leg. The typical operating characteristics of the vibration motor included a lag time of 16 ms and a rise time of 28 ms. A 3.3 V output of the Arduino board was used together with a bipolar transistor to drive the vibration motor. The transistor was controlled over the digital output of the prototyping board. Dimension Engineering DE-ACCM3D triaxial accelerometer sensor encapsulated in a plastic housing measured the acceleration of a participant's leg movement. The accelerometer featured a ±3 g sense range and 500 Hz bandwidth for x-axis, y-axis, and z-axis. An analog input of the prototyping board was used to read the output of the accelerometer. The vibration motor and the accelerometer were attached to a leg band. The PC and the prototype device communicated with the BlueSMiRF Silver module over serial port. A USB-Bluetooth adapter was used for translating the wireless communication in a sampling rate of 60 Hz. The PC was used for sending the tactile instruction stimulation and presenting the video instructions to the participant and for storing the received acceleration data from the participant's leg using custom software programmed in Processing.org language. The software was used for receiving acceleration data over the wireless communication from the prototype device and for storing the time stamped data to a file for later analysis. The instructions were based on prerecorded acceleration measurements that were recorded with the device and stored together with the recorded exercise video in synchronization. Visual instructions were presented through a 24″ Samsung SyncMaster display.

2.2.4. Procedure. After wearing the belt bag including the electronics, the leg band was fastened around the participant's right thigh so that the accelerometer was located in the ventral side about 10 cm above the kneecap and the vibration motor was in the dorsal side of the thigh (Figure 2(b)). Then a hearing protector was put on and two 200 ms long test stimuli were presented to confirm that the participant was able to feel the vibration and unable to hear the vibration sound. The participant was guided to about 120 cm distance from the computer display of which center point was 155 cm above the floor. Then the experimenter gave verbal instruction and a visual example of the exercise movement. The task was to lift the right knee until the thigh angle was parallel with the floor, at the maximum, and immediately after that to lay the leg down back in the starting position. The lift was instructed to be done as soon as the visual instruction on the video and/or tactile stimulus was perceived. This instruction was given once before the actual experimental trials. Running order of V, T, and VT conditions and the three exercise videos was fully counterbalanced between the participants. A similar procedure was followed in V, T, and VT conditions apart from the following attributes:

(i) In V condition, the video was turned on and the vibration motor off.

(ii) In T condition, the video was turned off and the vibration motor on.

(iii) In VT condition, both the vibration motor and the video were turned on.

After the experimenter had left the room, each condition started with an initiation trial excluded from the analysis and was followed by 21 experimental trials consisting of seven short, medium, and long ISI trials. An experimental trial started with a randomly chosen short, medium, or long ISI which was followed by V, T, or VT instruction stimulus depending on the modality condition. The participant's task was to immediately respond to the instruction stimulus by a knee lift and then start to wait for a next trial. One condition took about 2.5 minutes. After completing a condition, the experimenter returned to the testing room and the participant was allowed to have a short break. Then the experimenter announced the instruction modality of the upcoming condition. After performing all the three modality conditions the participant assessed them with rating scales. In accordance with Mehrabian and Russell [19] and Bradley and Lang [20] the scales were bipolar nine-point scales varying from −4 to +4. Ratings were asked for the pleasantness of the task (varying from unpleasant to pleasant), easiness of the task (varying from difficult to easy), and interest of the task (varying from boring to interesting). On each scale, 0 represented a neutral experience (e.g., neither unpleasant nor pleasant). Ratings were given using pen and paper.

Finally, the participant was asked to rate the tactile stimulation regarding its amplitude (too weak, appropriate, or too strong) and duration (too short, appropriate, or too long). In addition, the temporal uniformity of the timing of the tactile stimulations in relation to the visual instructions (too early, appropriate, or too late) presented in the VT condition was asked to validate the subjective experience of the lag caused by the technical implementation of the tactile stimulus.

2.2.5. Data Analysis. RTs and peak accelerations of the knee lifts were analyzed with a one-way repeated measures analysis of variance (ANOVA) with modality condition as a within-subjects factor. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate F statistic. Bonferroni corrected pairwise t-tests were used for post hoc tests. RTs were measured from the moment when the instructor's demonstration knee lift exceeded the 0.75 g acceleration threshold to the moment when the participant's knee lift movement reached its peak acceleration. Peak acceleration sum vector was defined as the highest value during an upward phase of the participant's knee lift event using a similar baseline definition and formula as in determining the threshold for stimulus onset in the exercise video. A total of 33% of the RT and acceleration data (i.e., 4, 5, and 3 participants in V, T, and VT conditions, resp.) was excluded due to technical reasons causing noisy acceleration signal and replaced by a condition specific series means in the analyses. Prior to the imputation, the normality of the obtained RT and peak acceleration data was confirmed using Shapiro-Wilk test of normality. The tests suggested that the assumption of normal distribution was met in the V, T, and VT conditions regarding RT (S-W = 0.95, df = 8, and $p = 0.67$; S-W = 0.95, df = 7, and $p = 0.76$; S-W = 0.97, df = 9, and $p = 0.91$, resp.) and peak acceleration data (S-W = 0.90, df = 8, and $p = 0.28$; S-W = 0.95, df = 7, and $p = 0.72$; S-W = 0.87, df = 9, and $p = 0.13$, resp.).

Ratings of pleasantness, easiness, and interest were analyzed with three separate Friedman tests. If the Friedman test showed a significant effect, Wilcoxon Signed-Rank tests were used for pairwise comparisons.

2.3. Results. Means and standard error of the means (SEMs) for the RTs and peak accelerations of knee lifts are presented in Figure 3. Nobody missed any knee lift stimuli in the V, T, and VT conditions.

2.3.1. Reaction Times. A one-way repeated measures analysis of variance (ANOVA) showed a statistically significant effect of modality: $F(1.27, 14.00) = 15.66$; $p \leq 0.001$. Post hoc pairwise comparisons between the modalities showed that the RTs were significantly faster in V and VT conditions as compared to T condition: MD = 158 ms and $p < 0.05$ and MD = 183 ms and $p < 0.001$, respectively. RT difference between V and VT conditions was statistically nonsignificant.

2.3.2. Peak Accelerations. A one-way ANOVA showed a statistically significant effect of modality: $F(2, 22) = 5.91$; $p < 0.01$. Post hoc pairwise comparisons between the modalities

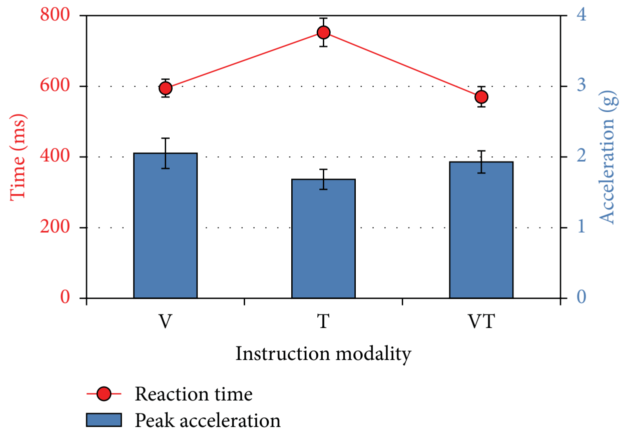


Figure 3: Mean RTs and mean peak accelerations of knee lifts in visual (V), tactile (T), and visual-tactile (VT) modality conditions. Error bars represent SEMs.

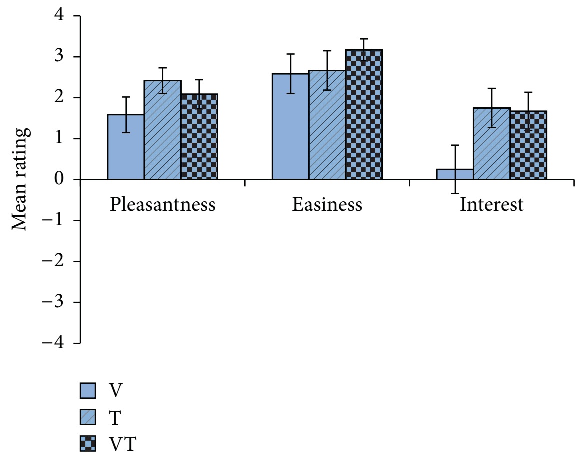


Figure 4: Mean ratings for pleasantness, easiness, and interest of the knee lift tasks in visual (V), tactile (T), and visual-tactile (VT) modality conditions. Error bars represent SEMs.

showed that the peak leg accelerations were significantly greater in VT condition when compared to T condition: MD = 0.25 g and $p \leq 0.05$. Other pairwise comparisons were statistically nonsignificant.

2.3.3. Subjective Ratings. Means and SEMs of the subjective ratings are shown in Figure 4. Friedman test showed a statistically significant effect for the ratings of interest: $\chi^2 = 9.66$; $p < 0.01$. For the ratings of pleasantness and easiness, the Friedman test revealed no statistically significant effects. Wilcoxon Signed-Rank tests showed that the task was considered in T and VT conditions as significantly more interesting than in V condition: $Z = -2.51$ and $p < 0.05$ and $Z = -2.45$ and $p < 0.05$, respectively. Difference between T and VT conditions was not statistically significant.

Vibration amplitude was considered as appropriate by each of the twelve participants. No one reported the vibration being too weak or too strong. Vibration duration was assessed as appropriate by eleven participants, while one considered that the vibration was too long. Nobody considered the vibration too short. In VT condition the vibration timing (i.e., synchrony) with respect to the knee lift shown in the instruction video was agreed as appropriate by five participants and the remainder considered that the vibration came too late. Nobody thought that the vibration was too early with respect to the video.

2.4. Discussion. The results of Study 1 showed that tactile instruction channel was functional in a knee lift exercise both alone (i.e., T condition) and when combined with visual instructions (i.e., VT condition). It seems that the parameters (i.e., duration, vibration frequency, amplitude, and location) of the tactile stimulus were applicable because nobody missed any tactile stimuli. In addition, the findings in the subjective ratings and postexperimental interviews showed favorable assessments of tactile instructions. In the interviews stimulus amplitude and duration were considered as appropriate almost unanimously. The temporal synchrony of the visual and tactile instruction in VT condition, however, polarized the opinions, as more than half of the participants thought that the vibration came too late with respect to knee lift shown in the video.

The experienced asynchrony was likely due to the relatively robust acceleration threshold causing the 203 ms delay and the 16 ms onset latency of the vibration actuator, which together resulted in a minimum of about 220 ms delay from the instructor's initial leg movement to the onset of the tactile stimulus in the participant's leg. In consequence, the instructor's leg movement was already visible in the video when the tactile stimulus started. The delay can also explain why the mean RT (i.e., time to reach the peak leg acceleration) in T condition was 158.2 and 182.5 ms slower as compared to V and VT conditions, respectively.

If the tactile stimulus onset had been created in exact synchrony with the instructor's initial leg movement, the RTs in T and VT conditions could, in fact, have been about 40–60 ms faster than those in V condition. This conclusion is based on subtraction of the lag caused by the technical implementation from the mean RT of T condition and supported by earlier findings showing about 30–40 ms shorter RTs to tactile than visual stimuli (e.g., [3, 5, 21]). Following this, tactile instructions would seem to have the potential to enable even faster knee lift reactions than conventionally used visual instruction provided that the onset of the tactile stimulus could be reliably situated to the initial phase of the instructor's leg movement. However, the aim of the present study was to assess the functionality of tactile instruction system in a realistic exercise situation, where a robust-enough onset method would be required to prevent the instructor from giving false-positive instruction stimuli resulting, for example, from minor or unintentional leg movements between the repetitions. Thus, lowering the acceleration threshold to diminish the onset delay would require further studies to find an acceptable trade-off between the speed and accuracy of providing the tactile instructions.

Instruction modality also had an effect to the acceleration magnitude of the leg movements. VT instruction resulted in significantly higher peak acceleration than T instruction. Despite the fact that the mean peak acceleration was the highest in V condition and the lowest in T condition, the difference did not reach statistical significance. As it can be seen in the SEM error bars of Figure 3, this was due to the larger deviation of acceleration magnitude in V condition compared to those found in T and VT conditions. This result may indicate that tactile stimulation stabilized the acceleration of leg movement and enabled more consistent repetitions.

Ratings of the pleasantness, easiness, and interest of the exercise task were clearly positive in each modality condition which indicates that tactile instruction channel was well accepted in the current context along with conventionally used visual instructions both unimodally and when combined with visual instruction modality. This was despite the fact that the participants were fully capable of following visual instructions and, therefore, did not necessarily need tactile instructions in this type of activity. Moreover, tactile stimulation provided in T and VT conditions increased significantly the participants' interest of the task when compared to V condition. This finding suggests that such a device may be of interest to exercisers also in real training situations, which in turn would be important in the light of earlier studies showing that interest towards the training is a central factor in increasing the motivation and exercise adherence (e.g., [22]).

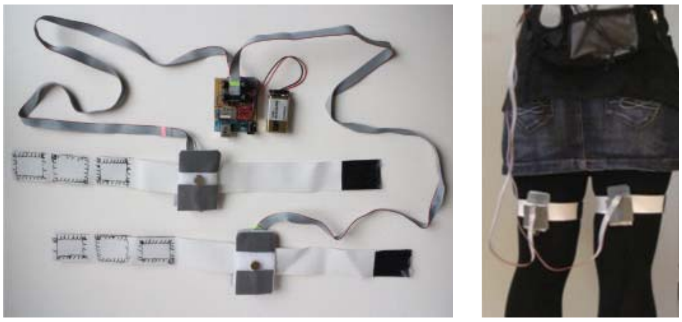
3. Study 2: User Experience and Acceptance of a Vibrotactile Exercise Device among Elderly Participants

3.1. Introduction. In a follow-up user study, the wearable tactile device used in Study 1 was iterated further and redesigned to be used in a group exercise situation with elderly participants. This approach was chosen based on a recent trend that has been shifting increasingly from one-to-one personal training to group exercise and training programs [23]. Supervised group exercise is often favored in public and institutional healthcare, because it is clearly more time-effective and cost-effective in comparison to personal training and it has been found to be beneficial in promoting not only physical fitness [24] but also social and mental well-being and overall quality of life [25].

A new version of the device allowed an instructor to activate an exerciser's legs with tactile stimulation automatically and in real time (i.e., in conjunction with the instructor's demonstration movements) via a wireless link. The main goal of this user study was to evaluate acceptance and user experience (UX) of the tactile exercise device in a context of recreational group exercise among a potential target population. The approach had three main research questions:

(1) How do elderly participants experience the use of a tactile device in a group exercise context?

(2) How does it differ from conventional session without tactile instructions?



(a) (b)

Figure 5: (a) Wearable parts of the exercise device and (b) their attachment locations.

(3) Do the elderly participants accept the use of tactile stimulation in a group exercise context?

The user study consisted of exercise sessions both with and without the device, UX questionnaires, and interviews inquiring the exercisers' as well as the instructors' impressions, experience, and acceptance of using the device.

3.2. Methods

3.2.1. Participants. Participants and premises for the study were provided by a service center for elderly people. The targeted user group consisted of relatively healthy elderly volunteers without any major cognitive disabilities to ensure that they were fully able to answer questionnaires and take part in an interview. They were also required to be able to take part in the physical exercise tasks, including knee lifting used in Study 1. Two male and six female exercisers and two female instructors took part in the study after signing informed consent forms. The exercisers were between the ages of 73 and 92 years (M = 83 and SD = 7). The instructors were 27 and 39 years old. One of the instructors had a formal education in physical therapy. The study consisted of two within-subjects exercise groups, each with one instructor and four exercisers. The study was approved by the local research ethics committee.

3.2.2. Apparatus. The tactile device consisted of two elastic leg bands and a belt bag (Figure 5). Both the leg bands included a tactile actuator and accelerometer, while the belt bag contained an Arduino board and a 9 V battery. The components in the leg bands were connected to the board via flat cables. The study was done with two identical devices. One device worn by an instructor functioned in a "master" mode and the other worn by an exerciser was set in a "slave" mode. The devices communicated via Bluetooth with a PC acting as host and routing the communication between the devices. A more detailed description of the system's operation principle is given in [26]. The major change from the users' view point was the fact that, contrary to the device used in Study 1, leg bands were attached to both limbs. In addition, the vibration actuator type was replaced with Solarbotics VPM2 Vibrating Disk Motor due to its closed structure. There was a mechanical delay of 60 ms, on average, measured from the onset of the applied voltage (3 V) to the beginning of the actuation from the motor using a GW Instek GDS-2104A oscilloscope. The accelerometers were relocated above the actuators in the dorsal side of the legs. Together these revisions enabled a more compact design of the leg bands.

3.2.3. User Experience Questionnaire. The UX questionnaire was used for studying the research questions 1 and 2. The questionnaire had two variants: one for evaluating the exercise experience while wearing the device and another without it. They had nearly identical scales and distinctive instructions on what to evaluate. The questionnaires were based on UX model by Hassenzahl [27]. The semantic differentials were selected from two different questionnaires: AttrakDiff 2 [28] and Attrak-Work [29]. AttrakDiff 2 questionnaire consists of seven-point semantic differential scales, which are divided into pragmatic qualities (PQ), hedonic qualities of stimulation (HQS) and identification (HQI), and attractiveness (ATT). The Attrak-Work adds a task and goal achievement (TGW) quality, which is essential in work-related contexts. The pragmatic scales are close to the traditional definition of usability (usefulness, utility, and usability). If a product is stimulating, it provides possibilities to gain new knowledge and self-development, while identification can be explained as social self-expression through physical objects and possessions. Three device-centric scales were omitted from the questionnaire without the device: impractical, practical; makes exercise harder, makes exercise easier; and slows down the exercise, speeds up the exercise. A few scales were selected for each of the five themes to keep the questionnaire length on one page. Moreover, some scales had to be left out as they were presumed to be inapplicable to this study due to the context and nature of the device. The selected scales for each quality are presented in Table 1.

3.2.4. Interview. The group interviews concentrated on qualitative information on the participants' general impressions of tactile instructions and the device. The interviews were semistructured and started with free-form description of the participants' impressions of the user experience. This was followed by a discussion about the exercise with and without

Table 1: Qualities and scales used in the UX questionnaires.

Quality	Scale	ID
Pragmatic	Complex, simple	PQ_2
	Impractical, practical	PQ_3
	Challenging, effortless	PQ_4
	Confusing, clear	PQ_6
Hedonic: stimulation	Conventional, original	HQS_1
	Unimaginative, creative	HQS_2
	Dull, absorbing	HQS_5
Hedonic: identification	Unprofessional, professional	HQI_2
	Poor quality, high quality	HQI_4
	Noninclusive-Inclusive	HQI_5
	Separates me from people, brings me closer to people	HQI_6
Attractiveness	Unpleasant, pleasant	ATT_1
	Unattractive, attractive	ATT_3
	Bad, good	ATT_5
	Discouraging, motivating	ATT_7
Task and goal achievement	Makes exercise harder, makes exercise easier	TGW_1
	Slows down the exercise, speeds up the exercise	TGW_4
	Difficult to control, easy to control	TGW_7

the device, acceptance, and other ideas for the device and applications both the exercisers and instructors might have.

3.2.5. Procedure. The exercisers' task was to follow and repeat the exercise guided by the instructor. The exercise consisted of moving legs in seated and standing positions, including various leg lifting tasks, stationary marching, and dancing. The whole exercise was done with background music. The sessions were designed and carried out by the instructors as normally as possible but with emphasizing on legs and lower part of the body. The exercise sessions began with an introduction to the purpose of the user study and a brief explanation of the device. The exercisers were told that the instructor's device sent tactile instructions to the exerciser's device as an additional signal to start performing the exercise movements. Tactile stimuli were produced concurrently in both the instructor's device and the exerciser's device, thus enabling the instructor to confirm a successful sending of a tactile instruction. Due to the limited amount of devices, the exerciser's device was rotated between the four exercisers in the group. Every 15 minutes the exercise was paused to switch the device to a next exerciser. As a result, each exerciser got to wear and exercise with the device for about 15 minutes during the 1-hour session. The instructor wore the other device for the whole exercise session. Halfway through the session, the exercisers filled the UX questionnaires evaluating the subjective experience of exercising in the group. The first two exercisers to try the tactile device filled the questionnaire "exercise with the device," and the other two filled the questionnaire "exercise without the device." This was repeated at the end of the session but this time vice versa. At the end, each exerciser in the group evaluated the exercise with and without wearing the device. The instructors in both groups evaluated the user experience of exercising with the device after the session. Following the session, the group (including the instructor) took part in 30-minute-long interview.

3.3. Results

3.3.1. User Experience Questionnaire. The exercisers' ratings given to the UX questionnaire (Figure 6(a)) showed that the exercise both without and with the device was experienced mainly in a positive way. They evaluated the exercise with the device to be more motivating than that without the device (ATT_7), but otherwise the SEM ranges of the ratings were overlapping between the two exercise situations indicating potentially nonsignificant differences. Ratings of the three items reflecting the device use situation only were also positive; the exercisers considered that the device was more practical than impractical (PQ_3), made the exercise somewhat easier (TGW_1), and speeded up the exercise (TGW_4). Interestingly, the instructors' ratings of the device in Figure 6(b) were mainly outside the SEM range of those given by the exercisers shown in Figure 6(a). One or both of the instructors rated the device more positively than the exercisers regarding 8 items (i.e., PQ_2, PQ_6, HQS_1, HQS_2, HQI_2, HQI_5, HQI_6, and ATT_7) and more negatively regarding 10 items (i.e., PQ_3, PQ_4, HQI_4, ATT_1, ATT_3, ATT_5, ATT_7, TGW_1, TGW_4, and TGW_7). Consensus was found only for item HQS_5; the exercise with the device was found equally absorbing by the exercisers and the two instructors. However, no statistical analysis was performed for the questionnaire data due to low number of the participants.

3.3.2. Interview: Exercise Experience with and without the Device. Exercisers' expectations of the exercise with the device were summarized into three groups: (1) no expectations, (2) slightly nervous or afraid, and (3) interested. Majority of the exercisers were slightly nervous or afraid of trying a device they did not have any experience with. However, after the exercisers tried the device, many of the expectations were changed in a positive way as exemplified by following quotations:

> *"I was nervous about this thing we were supposed to wear. Then I saw how simple it was and the fear vanished," an exerciser said.*

> *"At first I was nervous and surprised. I didn't expect it to be this easy," an exerciser said.*

On the other hand, one exerciser commented that his/her expectations did not change, and another one had expected much stronger stimulation.

First impressions of exercise with the tactile device, for both the exercisers and instructors, were positive and even surprising. These consisted of positive and neutral descriptions, such as nice, pleasant, easy, fun, ordinary, different (i.e.,

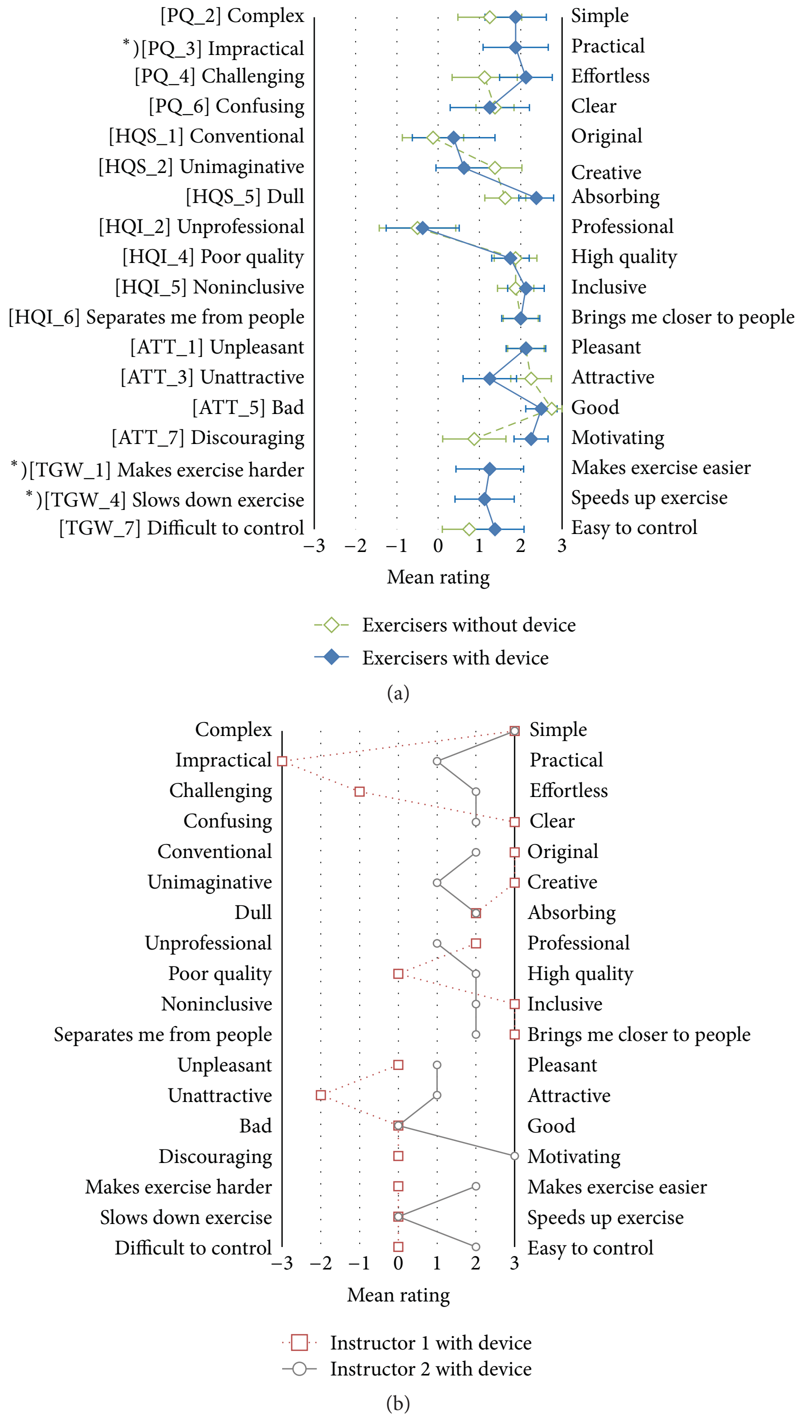


Figure 6: Mean ratings for the UX questionnaires on 7-point semantic differential scale given by (a) the exercisers and (b) the instructors. Items labeled with *) in (a) were excluded from the "exercise without the device" questionnaire. Error bars in (a) represent SEMs.

something new), and effortless. The emphasis on the easiness was frequent in the comments. Once the device was put on, the exercisers did not need to concentrate on operating the device. The majority of the exercisers also quickly understood the purpose of the device with a very short introduction. Two of the exercisers needed further instructions. One exerciser had major difficulties in recognizing the tactile stimulation and another was so concentrating on following the tactile instructions that she forgot to pay attention to the actual exercise. The tactile stimuli and the form-factor of the wearable device were comfortable and pleasant according to the exercisers. However, one of the instructors said that wearing the device for an hour became uncomfortable because of the frequent tactile stimulation.

In addition to the positive reaction, the tactile exercise device seemed to bring something new to the exercise. Variation to the usual exercise was considered positive and refreshing. The exercisers and instructors said that the device encourages and motivates one to exercise. The instructors explained that the device also created a new kind of bond between them by enabling remote and hands-free touch stimulation. Even though the exercisers reported mainly focusing on the visual and auditory guidance, the tangible and intuitive feel of the rhythm of the exercise was said to be motivating. Citations below illustrate new possibilities and insights inspired by the device:

> *"I teased a little bit by sending [tactile] stimulation also outside the exercise tasks," an instructor said.*

> *"I instinctively moved my leg when I got the [tactile] stimulation," an exerciser said.*

3.3.3. Interview: Wearing and Using the Device. Although the exercise experience was mainly positive, the actual device got mixed feedback. The device was found usable in both seated and standing positions, which is important for the groups consisting of elderly participants with varying physical conditions. Although the leg bands and waist-mounted electronics were connected with cables, it did not restrict the movements during the exercise. As a drawback, the exercisers needed help in putting the device on.

The instructors stated that the device was capable of displaying slow rhythm to the exercisers, but faster rhythms were not distinguishable as the device would then vibrate constantly. The delay between the two devices was also said to be too long and creating an out-of-sync issue between the different instruction modalities.

The main problem recognized was the stimulation model of the current implementation, which provided tactile stimulation only for a limited set of leg exercise movements. Slow and static exercise moves (e.g., when the leg is moved very slowly and kept still to exercise muscles) resulted in either excess stimulation or no stimulation at all. In consequence of the simple and robust stimulation model, the usefulness of the device was found limited in the exercise context of this study.

3.3.4. Interview: Acceptance. Despite the encouraging user experience, the interview questions related to acceptance did not get as positive responses. The responses were divided by the groups: the first group would not use the tactile device in exercise and background music was preferred over it and the second group would use the device occasionally to bring variety to the exercise groups. Both groups were suspicious of the actual benefits of using such system. The delay and constricted stimulation model issues were also raised as a major drawback affecting the acceptance. However, the exercisers and instructors also commented that the device should be used more comprehensively to be able to better evaluate its acceptance and usefulness:

> *"If used too often, it might create a feeling that I cannot do the exercise without aiding devices," an exerciser said.*

> *"Would bring variety and sustain the interest in the exercise if the device is used from time to time," an exerciser said.*

3.3.5. Interview: Further Development and Research Ideas. The interviews spawned few development ideas for the device. Overall, the device should support a more comprehensive set of exercise moves. The instructors proposed a stimulation model based on the activation of large muscle groups for slower paced muscle exercises. Also the information about range of motion would be useful, as one of the exercise goals is to improve it on the elderly exercisers. It was also suggested that the delay should be minimized or the tactile stimulation could be generated based on the rhythm of the music to avoid delay issues. Finally, amplitude of the tactile stimulation could be adjustable to suit the exercisers' varying levels of touch sensitivity. The potential of the device was identified also in remote exercise context where some or all exercisers can be in different locations.

3.4. Discussion. The results of Study 2 showed that the device got mostly positive responses from the elderly exercisers. However, the current implementation of the stimulation method (i.e., onset of tactile stimulus was triggered based on the instructor's leg acceleration data) caused slight delay and thus did not support real-time exercise situation very well. In particular the instructors brought up the delay as an issue that should be further developed.

The user study resulted in encouraging user experience findings. Regarding the research questions 1 and 2, the device was perceived to be easy to learn and pleasant to use. The UX questionnaire revealed that the exercisers thought that the device increased motivation to exercise. Otherwise the experience of the exercise session was rated quite similarly both with and without the device.

The third research question about acceptance got mixed responses. Usefulness of the device was questioned by the exercisers and instructors. This was probably because all the elderly participants of the current study were in relatively good physical condition and able to follow visual demonstrations and verbal instructions. In consequence, they had no absolute need for tactile instructions. The exercisers preferred to train with background music and were ready to use the device from time to time. For the instructors, the stimulation model, which was restricted to recognize only rapid leg movements, and delay limited the contents of the exercise in excess and thus the device with the current design was not considered very useful within the current context and participants. Based on these findings, future work should concentrate on refining the tactile stimulation model so that it would support better a fast-tempo exercise by minimizing the delay and the fact that the system would function also in slow and long term movements such as muscle stretching.

4. General Discussion

The results of Studies 1 and 2 showed that tactile stimulation can be used successfully in mediating real-time instructions to perform leg movements in simulated laboratory conditions as well as in realistic group exercise situation. Tactile instructions were found applicable in both complementing (Studies 1 and 2) and substituting (Study 1) the typically used visual exercise instructions. With this regard the results are in line with earlier studies showing that tactile stimulation (e.g., vibration) can be practical in various contexts of physical exercise (e.g., [10–12]) and rehabilitation (e.g., [8, 9]). However, typical set up in the earlier concepts has been that tactile stimulation provides feedback derived from the exerciser's own actions in the context of self-contained exercise. In contrast to this, our aim was to study tactile support specifically in a motor-mimicry frame of reference. That is to say, in the current approach, the source and the communicative function of the tactile stimulation was movement of another human being. To our knowledge, along with the work by Lee and colleagues [14, 15], this was among the first approaches to study technology-mediated touch information in the context of mimicry-based behavioral regulation in physical exercise. In this framework, our results showed a potential for utilizing real-time tactile communication between a human instructor (in contrast to an avatar used in [14]) and exerciser(s) in rhythmic physical exercise. As an additional complement to earlier work, the current approach obtained the exercisers' subjective experiences.

Physical measurements conducted in Study 1 showed that tactile instruction modality diminished the deviation of peak acceleration magnitude of the knee lift movements in comparison to visual-only instructions. It is noted that this effect took place with healthy and relatively young participants. The result may indicate that tactile stimulation stabilized motor responses and thus enabled better control to perform exercise movements in a consistent way even for exercisers with fully functional sensory system and motor coordination. This could be a useful supplement in various motion training exercises where repeatable and precise control of movement is of the essence. Noisy acceleration data caused rejection of objective data from 3 to 5 participants in the three stimulus conditions. However, each participant performed 21 trials in each condition and thus the total amount of data in one condition was based on relatively high number of 147–189 trials. The stability of the results was indicated by normally distributed values across the RT and acceleration of the obtained data.

Subjective evaluations of Study 1 revealed that tactile instruction modality both alone and when combined with visual instructions was found to be as equally pleasant and easy as visual-only instructions. Importantly, tactile stimulation increased significantly the interest of the exercise task. The delay between the visual instruction and the onset of tactile stimulation reported in both studies showed that the tactile stimulation model was found suitable mainly for simple and slow-paced exercise in its current form. The exercise phase of Study 1 can be regarded as relatively slow as the interval between successive knee lifts varied between 3 and 9 seconds. In these circumstances the temporal synchrony between visual demonstration and concurrent tactile stimulation was experienced as appropriate by nearly half of the participants. Even so, the fact that the slim majority found the delay being too long shows that there is still room for improving the onset model of the tactile stimulus. This finding recurred also in the actual exercise situation of Study 2, where in particular the instructors commented that the delay limited the pace of the exercise.

In Study 2 the elderly exercisers' general experience of the device was clearly positive and in some respects it improved the experience compared to their normal exercise situation. This finding is in line with earlier results by Mitzner et al. [30] showing that, contrary to popular stereotypes, older adults have mainly positive attitude towards technological devices especially when the technology is easy to use and it supports their activities, enhances convenience, and contains useful features. Applying new interactive technologies (e.g., body controlled gaming interfaces such as Microsoft Kinect) for regular use presumes additionally that the technologies connect with routines and spaces that people inhabit [31]. These conditions were met in the present study seeing that the user interface was virtually invisible for the exercisers and the system was integrated with already familiar activity, space, and people.

Few doubts related to usefulness amongst the participants in Study 2 boiled down to a need for development of the stimulation model and brought up topics for future research. For example, evaluating the usefulness of the device with disabled people (e.g., visually, aurally, and cognitively impaired and those with difficulties in initiating limb movements) would provide more insight into which special groups would potentially benefit most from tactile instruction channel.

In fact, one interesting topic would be a deeper investigation of blind people's imitation behavior using tactile instruction modality. There is evidence that the human mirror neuron system, which is argued to play a central role in visuomotor imitation learning [32], allocates same resources regardless of sensory modality [33]. Findings by Ricciardi et al. [33] demonstrate that visual experience is not a prerequisite for the mirror system development and that even congenitally blind people without vision-based imagery can "see" the actions of others by recruiting the same network of cortical areas activated by action observation in sighted subjects. The authors suggest that the mirror system stores a motor representation of others' actions that can be evoked through supramodal sensory mechanisms. Research on mimicry-based learning activated by tactile stimuli (in comparison to those perceived via visual modality) could open new insights into motor learning amongst the visually impaired.

In addition to tactile instructions, a wide range of physical exercise and therapy methods would benefit from objective measurement and analysis of physical movement. It is known that objective feedback from one's own performance can contribute favorably to learning of motor skills [23] and maintain motivation to continue the training program [34]. However, conventional physical activity monitoring devices, such as pedometers and motion sensors, are incapable of assessing exerciser's performance such as RT, intensity, and rhythmic synchrony of body movements with respect to instructor's demonstration movements. In this context, our concept could provide more insight by quantifying exercise performance for both online monitoring and further analysis. This would enable the instructor to observe multiple exercisers' individual performances in an equal manner and to reliably follow their long term progress.

Altogether, there is a clear need for new actions to improve the current situation where ageing people and people having disabilities are at risk of serious health problems associated with lack of physical activity. In USA, for instance, adults with disability are twice as likely to be physically inactive as compared to those with no disability [35], and only about 16% of the ≥65 years old meet the recommended amount of physical activity [36, 37].

Taken together, the current objective and subjective data suggest that a rather simple and inexpensive tactile instruction system could open up possibilities to increase physical activity for those being at risk to be excluded from organized group exercise that typically demands the ability to follow visual and auditory instructions. The possibility to use the device remotely (e.g., from one's home) could help in overcoming transportation difficulties and finally quantified and unbiased information of the performance could give an additional boost and motivate people to continue with regular training.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Publication IV

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Responses to visual, tactile and visual–tactile forward collision warnings while gaze on and off the road

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ABSTRACT

The objective of the current driving simulator study ($N = 20$) was to assess brake reaction time (BRT) and subjective experiences of visual (V), tactile (T), and visual–tactile (VT) collision warnings when the drivers' visual orientation was manipulated between four locations (i.e., road and three different mirror locations). V warning was a blinking light in a windscreen, T warning was implemented by a vibrating accelerator pedal, and VT warning was their synchronous combination. The results showed that all the warning stimuli were detected in 100% accuracy in all visual orientations, but T and VT warnings produced significantly faster BRTs when compared to V warning. It was found that BRT to V warning was the slowest while observing the furthermost side mirror. However, BRTs following T and VT warnings remained unaffected by the visual orientations. Both the objective BRT measurements and subjective evaluations indicated a superiority of T and VT warnings against a sole V warning, not only in general terms, but also separately for different visual orientations.

1. Introduction

Forward collision warning (FCW) systems have been developed to prevent and reduce the seriousness of front-to-end crashes typically caused by inattentive driving and insufficient safe-headway (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). The warnings are designed to alert the driver in advance to facilitate response times to apply brakes and/or make evasive steering maneuvers. Even though the usefulness of the FCW system as such may be evident, it is not fully clear what is the most efficient way to deliver this information so that it is accurately detected and results in fast actions of the driver to avoid the potential accident (Spence & Ho, 2008).

FCW stimulation is of critical importance especially when a driver's attention is off the road scene ahead. Although there are visual FWC stimulus systems, the stimuli are typically presented in front of the driver. Following this the warnings can go unnoticed when looking at a mirror because the stimulation is in the periphery of the visual field. Even when noticed, visual stimulus in peripheral vision can be responded slower than when seen in the foveal vision (e.g., Brebner & Welford, 1980; Strasburger, Rentschler, & Jüttner, 2011).

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Therefore, visual FCW is typically complemented with auditory warning signal. The advantage is that auditory warning can be perceived regardless of the driver's visual orientation. Response times have also found to be inherently faster to auditory than visual stimuli (Brebner & Welford, 1980). However, similarly to visual stimuli, the efficiency of auditory warning depends on the state of the driver's situational awareness. For example, engaging secondary tasks such as a problem-solving assignment or phone conversation have been found to significantly slow down response times to a warning sound (Bueno, Fabrigoule, Ndiaye, & Fort, 2014; Mohebbi, Gray, & Tan, 2009). In the other extreme, auditory warnings can become totally useless due to hearing impairments.

Utilizing the human sense of touch (i.e., haptic modality) as a communication channel can be a functional alternative to visual and auditory modalities when the ability to process sensory information is reduced, for example, due to ageing, physical impairment, or situation (Raisamo et al., 2009). Previous research has shown that tactile stimulation (e.g., vibration) would be a potential modality to be used in FCW (e.g., Spence & Ho, 2008). One advantage found in driving simulator studies is the faster response time to tactile stimulation compared to visual stimulation (e.g., De Rosario et al., 2010; Scott & Gray, 2008). There is also evidence that in comparison to auditory stimuli, response times to tactile stimuli are less affected by driver distraction (Mohebbi et al., 2009). However, to date tactile FCWs have not been used in vehicles as frequently as visual and auditory FCWs.

In order to enhance the efficiency of warning signals, investigating a stimulus–response (S–R) compatibility between the warning and its expected consequence is of essence (e.g., De Rosario et al., 2010; Wang, Proctor, & Pick, 2003). S–R compatibility has been long studied in psychology, and in general it refers to the fact that some S–R pairings are easier to use than others (Umiltá & Nicoletti, 1990). High level S–R connection has been shown to facilitate speed and accuracy of a performed task in comparison to those with lower level S–R connection.

More specifically, a spatial type of S–R compatibility occurs when the position of the stimulus indicates the position of the required response (Umiltá & Nicoletti, 1990). According to this, visual FCW implemented by a head-up display (HUD) in a windscreen (e.g., Lind, 2007) would appear to have a high spatial S–R compatibility by orienting a driver's vision toward the direction of a threat. Visual orienting to unexpectedly occurring salient cue such as blinking warning light is reflexive by its nature and, thus, it happens automatically and can be resilient to other concurrent visual information (Jonides, 1981; Müller & Rabbitt, 1989). Following this analogy, FCW presented down in a cluster panel, for example, would be spatially incompatible by prompting the driver's attention toward an inappropriate location in respect to the threatening event. Evidence pro this was reported by Lind (2007) who found that the HUD warning had the highest detection rate, resulted in shortest brake response time, and was also the most preferred in comparison to other visual warnings located either in cluster panel or steering wheel. So, when studying visual FCWs it seems that HUD would be a rational starting point to be adopted in the experimental design.

Tactile stimulation and motor response can also have high spatial compatibility as exemplified by an automatic reaction to quickly withdraw a limb away from unexpected touch sensation such as static electricity shock. Regarding an FCW provided in tactile modality the spatially congruent S–R association would suggest that stimulation should be presented to the body location that is primarily required for the response (De Rosario et al., 2010). Right foot is typically used for the accelerator and brake pedals and hence it would seem rational to stimulate that area for an FCW. As compared to vibrational warnings applied by waist belt (e.g., Scott & Gray, 2008), seat (e.g., Higuchi & Raksincharoensak, 2010), or steering wheel (e.g., Chun et al., 2012), a vibrating accelerator pedal would seem to have a stronger S–R compatibility. This is because apart from a sole attentional alarming effect it may also result in motor preparation for a quick release of the foot from the vibrating accelerator and applying brakes (Scott & Gray, 2008).

Another central factor that affects to the detection of warning signals relates to the focus of attention. The drivers' visual attention is concentrated diversely between on the road scene and other locations both inside and outside the vehicle. As mentioned earlier, this behavior makes the perceptivity of visual warnings highly dependent on the situation. Additionally, there is evidence that gaze direction can influence the perception of tactile stimuli as well. For example, reaction time to tactile stimulation has been found to be faster when looking toward than away from the stimulated body site (e.g., Lloyd, Bolanowski, Howard, & McGlone, 1999; see also Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002 for contradictory results). Nevertheless, the effect of variation in the visual focus (gaze on vs. off the road) to a perception time of visual and tactile FCWs has not been systematically investigated. Ho, Gray, and Spence (2014) found that response time to vibrotactile warning signal applied in the waist was significantly faster when looking forward than when head was turned either left or right for looking back. However, possible differences in the actual perception times between the head position conditions remained unclear. This is because the longer response time in the head turn conditions probably cumulated due to an additional visual discrimination task and the fact that the participants had to turn their head forward before giving the response, whereas neither of these tasks was involved in the forward looking condition.

Including concurrently presented bimodal visual–tactile warning becomes highly reasonable in the light of earlier laboratory studies showing proof on behalf of a facilitation effect known as multisensory enhancement (Diederich & Colonius, 2004). It has been found that multimodal stimuli can produce faster reaction times than unimodal stimuli (e.g., Burke et al., 2006; Diederich & Colonius, 2004; Forster et al., 2002; Higuchi & Raksincharoensak, 2010), which would naturally be an advantageous feature for an imminent warning signal such as FCW. However, possible sensorimotor facilitation effects of visual–tactile warnings in the varying driving conditions are still largely unstudied.

In summary, the earlier studies indicate the potential of tactile warning modality either alone or when combined with visual and/or auditory modalities (e.g., Spence & Ho, 2008). Touch-based stimulation seems to be especially advantageous when participants are exposed to some type of distraction (e.g., Bueno et al., 2014; Mohebbi et al., 2009). A large body of literature shows that the reaction time to visual stimuli perceived in peripheral vision is impaired (e.g., Strasburger et al., 2011) but the relationship between gaze direction and the perception of tactile stimulation seems to be more ambiguous (e.g., Forster et al., 2002; Lloyd et al., 1999). In addition, high-level S–R compatibility (e.g., Umiltá & Nicoletti, 1990) as well as multisensory enhancement effect of the stimulations (e.g., Diederich & Colonius, 2004) have been shown to facilitate reaction times. Empirical evidence on these isolated effects as a whole, however, appears relatively scarce in the context of FCW systems for the present.

The objective of this study was to assess perception of visual, tactile, and visual–tactile FCWs when the drivers' visual orientation was not distracted (i.e., observing road scene ahead) and while being distracted (i.e., observing mirrors). In order to concentrate purely in quantifying perception time of the warnings in the varying visual orientations, simple reaction time measurement was adopted as an independent variable in terms of brake response time (BRT) defined in Society of Automotive Engineers (SAE) Recommended Practice J2944 (2012).

In addition to the objective BRT measurements, also subjective experiences reflecting, for example, the S–R compatibility of the warning stimuli were investigated separately for each visual orientation. Rating scales inquired self-assessed speed of the braking reaction and assessments of the pleasantness, perceptivity, and effectiveness of the warning stimuli. Rankings and general opinions of the different FCWs were collected in a post-experimental interview. At first sight, pleasantness and preference may seem rather irrelevant features for a high priority emergency alert such as FCW. At the same time, however, overly annoying warning systems come with a risk of being rejected or disabled by the users, and therefore, a trade-off between pleasantness and urgency of the warning should also be taken into consideration (Wiese & Lee, 2004). For example, the vibrating waist belt warning in Scott and Gray (2008) turned out to be efficient in terms of response time, but at the same time 37.5% of the participants preferred it least (in comparison to visual and auditory warnings) because they did not like the vibratory sensation in their abdomen.

2. Method

2.1. Participants

Twenty voluntary participants (10 female) all having a valid driving license took part in the study (mean age 27 yrs, range 19–51 yrs). Two of them were left-handed and one was ambidextrous by self-reports. Five participants were recruited from staff and the rest were students of the authors' University attending to an introductory course of interactive technology. The students received a course credit for their participation. All had normal or corrected to normal vision, and normal hearing and sense of touch by their own report. No-one had previous experience on FCWs. All the participants were fully informed for the purpose of the study and signed informed consents prior to the experiment.

2.2. Apparatus and the experimental setup

A fixed-base driving simulator was implemented in a laboratory. A PC ran a lane change test (LCT) driving simulator software (ISO 26022, 2010) showing a simulated roadway with no other traffic. The simulator was run either on a 55″ LCD display (Samsung UNES7005) or on one of a total of three 17″ LCD displays (Acer LCD AL732) at medium contrast and brightness in a well-lit laboratory. The 55″ display provided the on the road view for the simulator and the 17″ displays provided the simulated visual orientations for two exterior mirrors and one interior mirror. A plexi-glass windscreen measuring $1200 \times 800 \times 4$ mm (width $\times$ height $\times$ thickness) was set in about 35° angle. Simulated driving sound of the LCT was played via a Creative 3.1 speaker system through a PC soundcard at a comfortable sound level. Logitech G27 Racing Wheel and pedal pad were used to simulate the driving equipment.

Visual warnings were provided with a HUD implemented in accordance with Lind (2007). It consisted of a stream of 23 red light emitting diodes (LEDs) (Wah Wang WW05A3SRP4-N2) spaced out over a total length of 172 mm. Each LED had a relative luminance of 1.5 a.u. at 30 mA and hence this was used as the base brightness parameter for the visual stimulation. The LED strip was hidden behind a cover so that only the light reflected via windscreen was visible for the participant (Fig. 1 (a)). A HiWave HIAX25C10-8/HS (Tectonic TEAX09C005-8) voice coil actuator was attached to the rear of the accelerator pedal to provide the vibrotactile stimulation, whereas two linear micro switches (KW 1 21), one fitted onto both the accelerator and brake pedals provided information regarding the participant's foot movement (Fig. 1(b)). The actuators were powered by a pulse-width modulation amplifier and a signal generator.

Physical dimensions of a cockpit in terms of relative distances between a seat, steering wheel, pedals, mirror center points, and windscreen were replicated from a left-hand drive Volvo XC60 vehicle.

A multimodal triggering and data logging software, controlled by the experimenter, provided the warning stimuli at random inter-trial intervals. The software logged the response times from the stimulus onset to brake pedal contact.

2.3. Stimuli

Three types of warning stimuli were used: visual (V), tactile (T), and visual–tactile (VT). Parameters of the V warning were adopted from Lind (2007). The warning lasted for 1.2 s and it consisted of five 150 ms light flashes separated by 100 ms

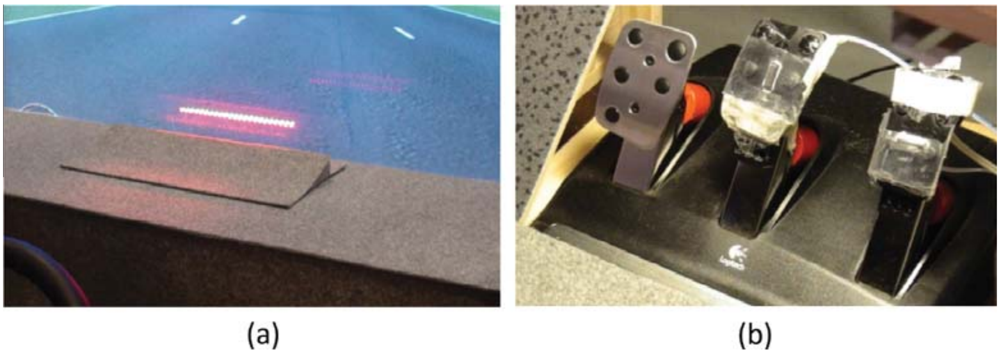

Fig. 1. (a) Visual warning stimulus reflected to the windscreen and (b) pedal set with footrest. Vibrotactile actuator producing tactile warning stimulus is located behind the accelerator pedal.

interval between each flash. T warning was provided by sinusoidal wave at 220 Hz and amplitude value of 18.8 V (peak to peak) and shared identical on/off timing parameters with V warning. VT warning was a synchronized combination of V and T warnings.

2.4. Procedure

In the beginning, the laboratory and the equipment were introduced to the participant. It was explained that the purpose of the experiment was to study collision warnings provided via flashing light, vibrotactile stimulation, and their combination. The experiment was carried out without shoes to enable equal conditions for vibration perception.

Before the experiment began, the seat was personally adjusted and a hearing protector headset playing pink noise was put on to mask the sound of the vibrotactile stimulation. Then the participant was introduced with the V, T, and VT warning stimuli by presenting them once without a driving task.

Next, the participant was familiarized with driving and braking task on the driving simulator. They were instructed to use their right foot for using both the accelerator and brake pedals. The left foot was held on a foot rest next to the pedals. The participant practiced by driving the simulated car accelerator pedal fully depressed at a pre-limited speed of 60 km/h and then braking until the car was completely stopped. At this point, no warning stimuli were provided. The participant practiced the braking task for at least 5 times until completing at least 3 successful brakings.

After the practice the experiment continued with four experimental blocks. In each block a different visual display was used to present the view of the driving simulator in order to control the participants' visual orientation. The 55″ display in front of the participant was used as a *gaze on the road scene ahead* (On-the-road) visual orientation. Three *gaze off the road scene ahead* visual orientations were implemented by the 17″ displays imitating the positions of the left mirror (L-mirror), center mirror (C-mirror), and right mirror (R-mirror). In the On-the-road block the 17″ displays were turned off. In the L-, C-, and R-mirror blocks only the 17″ display specific to the visual orientation showed the driving scene. The other two 17″ displays were turned off and On-the-road display showed only a still image of the driving scene to provide constant background luminance conditions for the V stimulus in each block (see Fig. 2). The order of the visual orientation exposures were fully counterbalanced amongst the participants.

Each visual orientation block consisted of a practice session, BRT measurement session, and subjective rating session. The purpose of the practice session was to familiarize the participant with the warnings and driving while viewing the visual orientation in question. In the practice session, V, T, and VT warning stimulus was presented once in a randomized order as follows. In the beginning of a practice trial the participant accelerated and drove a pre-limited speed of 60 km/h accelerator pedal fully depressed in a middle of a three-lane road. Then, after a randomly chosen 5–36 s interval a warning stimulus was presented. Then, the task was to release accelerator pedal and brake as quickly as possible. When the car had fully stopped, the participant was to release the brake pedal and start a new practice trial in a similar fashion. After completing the three practice trials, the participant proceeded to the actual BRT measurement session, which proceeded similarly to the practice session except that V, T, and VT warning stimuli were presented three times each in a randomized order resulting in a total of 9 experimental trials. The actual lane change task of the LCT driving simulator was omitted from the procedure.

The BRT measurement session was followed by the subjective rating session where the participants reported their experiences of the warnings with respect to the current visual orientation. For this purpose, the participant performed three additional braking tasks, one for each warning modality presented in a randomized order. Immediately after a warning stimulus was presented and the participant had completed a full braking, a questionnaire with four bi-polar, nine-point

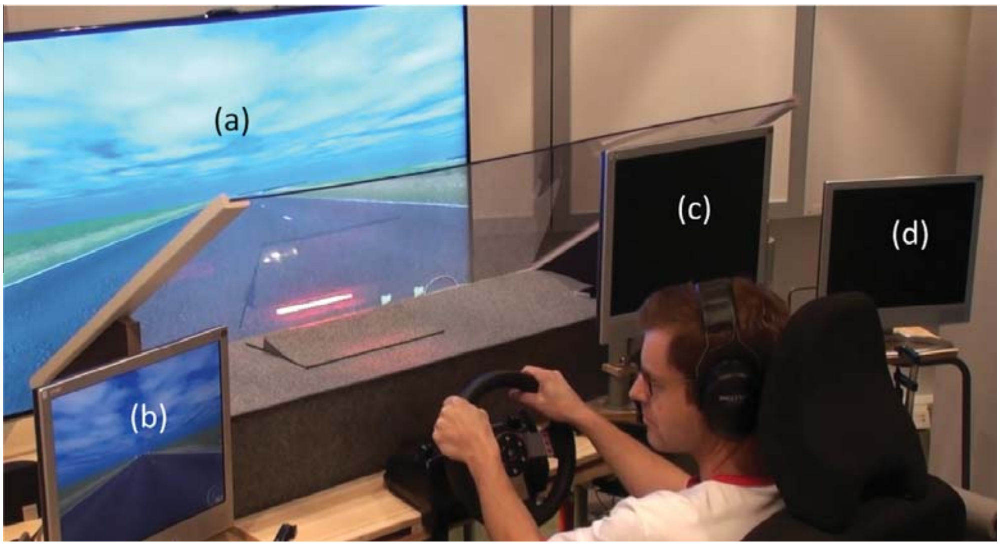

Fig. 2. Participant in the L-mirror visual orientation block. V stimulus is reflected to a lower part of the windscreen against the On-the-road display showing a still image of a driving scene. Displays used for manipulating the participant's visual orientation: (a) On-the-road, (b) L-mirror, (c) C-mirror, and (d) R-mirror.

rating scales varying from 1 to 9 was given to the participant. The scales were (1) speed of the brake reaction (varying from slow to fast), (2) pleasantness of the warning (varying from unpleasant to pleasant), (3) perceptivity of the warning (varying from unnoticeable to noticeable), and (4) effectiveness (varying from ineffective to effective). On each scale a midpoint (i.e., value (5) represented a neutral experience (e.g., neither slow nor fast). After rating the V, T, and VT warnings, a new visual orientation block was initiated. This was repeated in a similar fashion until all the four visual orientation blocks were completed.

At the end of the experiment the participants were shortly interviewed. They were asked to rank which (if any) of the warnings was the most pleasant one and which (if any) they would rather have in their car. Finally, the participants were asked if they heard any sound of the T warning stimuli in order to guarantee the functionality of the hearing protection. Conducting the experiment took approximately 45 min.

2.5. Data analysis

BRTs were analyzed with 3×4 (warning modality $\times$ visual orientation) repeated measures analysis of variance (ANOVA). BRT was calculated from warning stimulus onset to the initial touch of the brake pedal according to the SAE Recommended Practice J2944 (2012). If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the *F* statistic. Pairwise Bonferroni corrected *t*-tests were used for post hoc tests. Shapiro–Wilk test of normality test suggested that the assumption of normal distribution was met regarding the BRT data S–W = .95, df = 20, $p = .43$. The subjective rating data was analyzed with Friedman tests for the effects of warning modality and visual orientation. Wilcoxon signed-ranks tests were used for pairwise comparisons. The rating scale of 1–9 was transformed to (-4)–$(+4)$ for Fig. 4 to illustrate the negative–positive dimensions of the bi-polar scales.

3. Results

3.1. Perception of the stimuli

Participants were able to detect and respond to all warning stimuli in each visual condition. No-one reported hearing the sound of the T warnings.

3.2. Brake response times

Mean ratings and standard error of the means (*S.E.M.s*) for BRTs are presented in Fig. 3. A two-way 3×4 (warning modality $\times$ visual orientation) ANOVA showed a statistically significant main effect of the warning modality $F(1.40, 26.56) = 365.37$, $p < .001$, $\mu^2 = .74$, and visual orientation $F(3, 57) = 4.27$, $p = .009$, $\mu^2 = .01$. In addition, the interaction of the main effects was statistically significant, $F(2.60, 49.26) = 4.85$, $p = .007$, $\mu_p{}^2 = 0.20$.

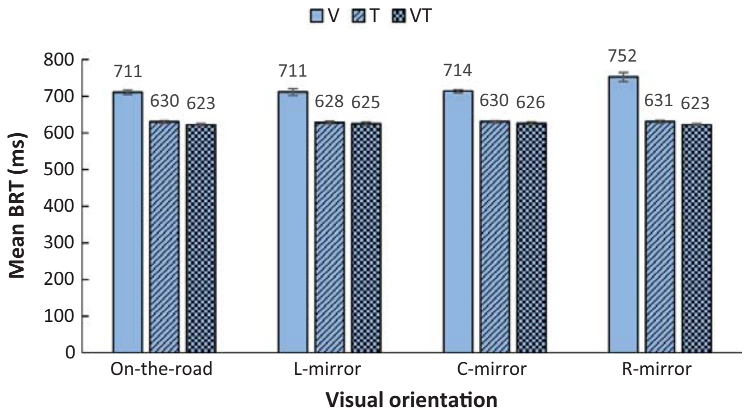

Fig. 3. Mean BRTs by warning modality and visual orientation. Error bars represent *S.E.M.s*. Note: V = visual; T = tactile; VT = visual–tactile.

To further analyze the interaction of the main effects, four one-way ANOVAs were performed to study the effect of warning modality separately in each visual orientation. ANOVAs showed that the modality affected to BRTs in all visual orientations as follows: On-the-road $F(1.54, 29.21) = 147.88$, $p < .001$, $\mu^2 = .81$, L-mirror, $F(1.41, 26.79) = 66.94$, $p < .001$, $\mu^2 = .68$, C-mirror $F(2,38) = 203.64$, $p < .001$, $\mu^2 = .87$, and R-mirror, $F(1.21, 23.12) = 94.82$, $p < .001$, $\mu^2 = .77$. Post hoc pairwise comparisons showed that participants braked significantly faster after T than V warnings in all visual orientations: On-the-road, $MD = 81$ ms, $p < .001$, $r = .94$, L-mirror, $MD = 83$ ms, $p < .001$, $r = .89$, C-mirror, $MD = 83$ ms, $p < .001$, $r = .97$, and R-mirror, $MD = 122$ ms, $p < .001$, $r = .91$. The participants also braked significantly faster after VT than V warnings in all visual orientations: On-the-road, $MD = 88$ ms, $p < .001$, $r = .97$, L-mirror, $MD = 86$ ms, $p < .001$, $r = .90$, C-mirror, $MD = 88$ ms, $p < .001$, $r = .97$, and R-mirror, $MD = 129$ ms, $p < .001$, $r = .93$. The difference between T and VT warnings was not statistically significant in any of the visual orientations.

To further investigate the interaction, three one-way ANOVAs were performed to analyze the effect of visual orientation within each warning modality. The ANOVAs revealed that the interaction was due to the fact that visual orientation affected to BRT for V warnings, $F(1.92, 36.40) = 5.87$, $p = .007$, $\mu^2 = .18$, whereas no significant effect was found for T and VT warnings. Post hoc pairwise comparisons showed that the BRT was significantly slower to V warnings in R-mirror orientation than when orienting to On-the-road, $MD = 41$ ms, $p = .011$, $r = .64$ and C-mirror, $MD = 39$ ms, $p = .038$, $r = .58$. The other pairwise comparisons were not statistically significant.

3.3. Subjective ratings

Fig. 4 shows an overview of the subjective ratings averaged over the visual orientation conditions. Results of more detailed, scale-specific analysis are presented in the following sections.

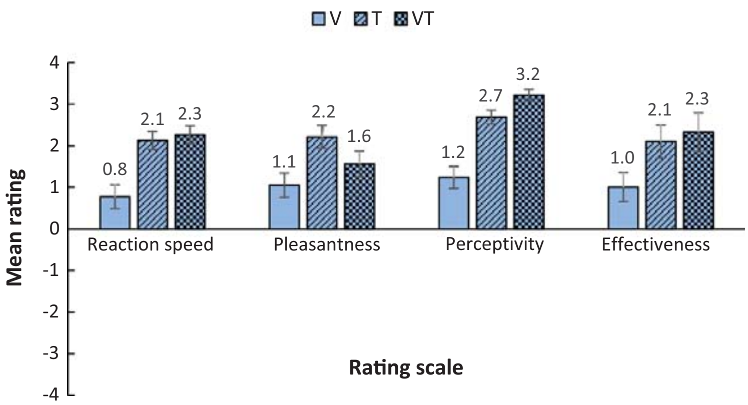

Fig. 4. Mean ratings averaged over visual orientations by warning modality and rating scale. Error bars indicate *S.E.M.*s. Note: V = visual; T = tactile; VT = visual–tactile.

Table 1
Reaction speed ratings. Wilcoxon *Z* test statistics for the pairwise comparisons of the warning modalities by visual orientation. Modality rated to produce faster reaction is indicated by bolded abbreviation.

Visual orientation	Faster reacted modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** ($Z = 3.18$)***	**VT** ($Z = 2.87$)**	*ns*
L-mirror	**T** ($Z = 3.36$)***	**VT** ($Z = 3.77$)***	*ns*
C-mirror	**T** ($Z = 3.57$)***	**VT** ($Z = 3.77$)***	*ns*
R-mirror	**T** ($Z = 3.15$)**	**VT** ($Z = 2.97$)**	*ns*

ns = $p > .05$.
* $p \leqslant .05$.
** $p \leqslant .01$.
*** $p \leqslant .001$.

3.3.1. Reaction speed

Friedman tests showed that warning modality had a statistically significant effect to the reaction speed ratings in all visual orientation conditions as follows: On-the-road, $\chi^2 = 15.39$, $p < .001$, L-mirror, $\chi^2 = 27.91$, $p < .001$, C-mirror, $\chi^2 = 27.03$, $p < .001$, and R-mirror, $\chi^2 = 15.74$, $p < .001$. Results of Wilcoxon signed-ranks tests are in Table 1.

Friedman tests did not reveal statistically significant effect of visual orientation to the reaction speed ratings for any warning modality.

3.3.2. Pleasantness

Friedman tests revealed that warning modality affected significantly to the pleasantness ratings in all visual orientation conditions: On-the-road, $\chi^2 = 16.75$, $p < .001$, L-mirror, $\chi^2 = 8.28$, $p = .016$, C-mirror, $\chi^2 = 7.32$, $p = .026$, and R-mirror, $\chi^2 = 8.79$, $p = .012$. Results of Wilcoxon signed-ranks tests can be seen in Table 2.

Friedman tests did not show statistically significant effect of visual orientation to the pleasantness ratings for any warning modality.

3.3.3. Perceptivity

Friedman tests showed that warning modality affected the perceptivity ratings in all visual orientation conditions: On-the-road, $\chi^2 = 18.00$, $p < .001$, L-mirror, $\chi^2 = 29.43$, $p < .001$, C-mirror, $\chi^2 = 28.73$, $p < .001$, R-mirror, and $\chi^2 = 28.48$, $p < .001$. Table 3 shows results of Wilcoxon signed-ranks tests.

Friedman tests did not show statistically significant effect of visual orientation to the perceptivity ratings for any warning modality.

3.3.4. Effectiveness

Friedman tests showed that warning modality affected the effectiveness ratings significantly in all visual orientation conditions: On-the-road, $\chi^2 = 19.58$, $p < .001$, L-mirror, $\chi^2 = 20.80$, $p < .001$, C-mirror, $\chi^2 = 15.27$, $p < .001$, R-mirror, $\chi^2 = 14.40$, $p = .001$. Results of Wilcoxon signed-ranks tests are shown in Table 4.

Friedman tests did not yield significant effect of visual orientation to the effectiveness ratings for any warning modality.

3.4. Warning modality rankings

Post-experimental interviews revealed that 11 participants considered T warning as the most pleasant, 6 voted for VT, 1 found V warning as the most pleasant, and 2 could not decide. Typical reasoning included a clear association between T warning and braking, and complains of V warning being distracting or too vigorous especially when presented alone.

Table 2
Pleasantness ratings. Wilcoxon *Z* test statistics for the pairwise comparisons of each warning modality in all visual orientation. Modality rated as more pleasant is indicated by bolded abbreviation.

Visual orientation	More pleasant modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** ($Z = 2.93$)**	**VT** ($Z = 2.31$)*	**T** ($Z = 2.35$)*
L-mirror	**T** ($Z = 2.76$)**	**VT** ($Z = 1.98$)*	**T** ($Z = 2.20$)*
C-mirror	**T** ($Z = 2.03$)*	*ns*	**T** ($Z = 1.99$)*
R-mirror	**T** ($Z = 2.59$)**	*ns*	*ns*

ns = $p > .05$.
* $p \leqslant .05$.
** $p \leqslant .01$.
*** $p \leqslant .001$.

Table 3
Perceptivity ratings. Wilcoxon Z test statistics for the pairwise comparisons of the warning modalities for each visual orientation. Modality rated as more noticeable is indicated by bolded abbreviation.

Visual orientation	More noticeable modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** ($Z = 2.39$)*	**VT** ($Z = 3.33$)***	**VT** ($Z = 2.72$)**
L-mirror	**T** ($Z = 3.23$)***	**VT** ($Z = 3.76$)***	**VT** ($Z = 2.81$)*
C-mirror	**T** ($Z = 3.32$)***	**VT** ($Z = 3.75$)***	**VT** ($Z = 2.49$)*
R-mirror	**T** ($Z = 3.66$)***	**VT** ($Z = 3.67$)***	*ns*

ns = $p > .05$.
* $p \leqslant .05$.
** $p \leqslant .01$.
*** $p \leqslant .001$.

Table 4
Effectiveness ratings. Wilcoxon Z test statistics for the pairwise comparisons of the warning modalities by visual orientation. Modality rated as more effective is indicated by bolded abbreviation.

Visual orientation	More effective modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** ($Z = 2.98$)**	**VT** ($Z = 3.45$)***	**VT** ($Z = 2.24$)*
L-mirror	**T** ($Z = 3.17$)**	**VT** ($Z = 3.45$)***	*ns*
C-mirror	**T** ($Z = 2.47$)*	**VT** ($Z = 2.32$)**	*ns*
R-mirror	**T** ($Z = 3.07$)**	**VT** ($Z = 3.12$)**	*ns*

ns = $p > .05$.
* $p \leqslant .05$.
** $p \leqslant .01$.
*** $p \leqslant .001$.

Ten participants considered that they would rather use T warning while driving, 8 would prefer VT, 1 would use V warning, and 1 could not decide. When asked why, the participants considered that T and VT warning was able to catch the attention efficiently. In addition, they found that vibration reflected the needed reaction (i.e., clear association for lifting the leg from the pedal) well. Similarly to the pleasantness ratings the excessive intensity of V warning was the most frequent reason for its low popularity.

4. Discussion

In general, the 100% detection accuracy showed that the FCW stimuli were functional in capturing attention in all the currently used visual orientations. Statistical analysis revealed significant differences between the responses to different warning modalities by showing that responses to T and VT warnings were significantly (i.e., 81–122 and 86–129 ms, respectively) faster as compared to V warnings throughout all visual orientations. Theoretically, when driving at a speed of 100 km/h this would enable an advantage to react about 2.3–3.6 m earlier in comparison to V only warnings. Moreover, the participants' subjective ratings of their reaction speed supported the BRT results. The objective BRT results concurred with earlier studies showing that tactile collision warning stimulus can be responded significantly faster as compared to visual stimulus (e.g., De Rosario et al., 2010; Scott & Gray, 2008). Significant multisensory enhancement effect of VT stimuli producing faster reactions than T stimuli found in earlier laboratory studies (e.g., Diederich & Colonius, 2004; Forster et al., 2002) was not obtained. However, Fig. 3 shows that BRTs to VT warnings were systematically, yet not significantly, shorter compared to T warnings. This tendency can also be considered as somewhat consistent with subjective data showing that VT warnings were rated as more noticeable and efficient than T warnings in some visual orientations.

The found effect of visual orientation provided new and more detailed insights regarding the perceptivity of FCWs in different visual orientation conditions. Fig. 3 clearly shows that BRTs to V warnings were slower in R-mirror orientation as compared to the other visual orientations, whereas BRTs to T and TV warnings remained intact. This can be explained by the fact that in the R-mirror condition the participant was exposed to the largest angular change between the visual orientation and the visual stimulus location. A body of earlier research has shown that perception of visual stimulus typically slows down as a function of increased visual angle (e.g., Strasburger et al., 2011). Concentrating gaze on L- and C-mirrors spatially closer to the visual stimulus did not lead to significantly different BRTs as compared to On-the-road orientation. This result indicates that the HUD implementation of V warning was perceived equally efficiently within the range of angular displacement of the On-the-road as well as L-mirror, and C-mirror orientations.

The fact that BRTs were unaffected by visual orientation when tactile warning modality was involved demonstrates the potential of T and VT warnings especially when visual attention is concentrated off the road scene ahead, that is, in situations when FCW is typically with the utmost urgency. Given that reduced visual field is common especially amongst elderly drivers it is also noted that the ability to perceive a unimodal V warning in the off the road visual orientations would probably be deteriorated in the average driving population as compared to the current sample consisting of relatively young participants with normal peripheral vision, typically around 180° wide horizontally. As an example, the minimum requirement of about 100–120° wide horizontal visual field is a precondition for a driving license in many countries (Bron et al., 2010). This visual field would probably have been insufficient for perceiving the currently used V warning stimulus in the R-mirror orientation in the current study. Actually, narrowed visual field has been found to be a key factor explaining proclivity for traffic accidents by elderly drivers (e.g., Ball, Owsley, Sloane, Roenker, & Bruni, 1993). Thus, it is possible that the potential benefits of tactile FCW would turn out to be especially significant amongst the elderly drivers.

Fig. 4 shows that subjective ratings as a whole were favorable regarding each warning modality yet intermodal differences were also found. T modality was clearly more preferred than V in all visual orientations, but in the other modalitywise comparisons visual orientation had a significant effect on the pleasantness ratings. For example, T and VT were rated equally pleasant in R-mirror orientation, but in the other spatially closer visual orientations T was experienced as more pleasant. Post-experimental interviews revealed one possible explanation for this result by showing that many participants considered the V warning being too intense. The intensity of the V warning probably diminished to a more acceptable level in the R-mirror orientation due to large angular displacement; V stimulus seen in peripheral visual field possibly made the stimulus appear less intense and thus more pleasant. Pleasantness ratings of V and VT warnings were similar in the C- and R-mirror visual orientations. Interestingly, however, in the spatially closer On-the-road as well as in L-mirror orientations VT was rated as more pleasant than sole V warning. This may indicate that the unpleasant experience of the excessive intensity of the visual stimulation was attenuated by the concurrent tactile stimulation. In the post experimental interviews nobody reported any discomfort of the vibrating accelerator pedal. This result is contradictory to Scott and Gray (2008) where unpleasant experiences of the vibrating waist belt warning were frequently complained.

In the S–R compatibility frame of reference both the objective and subjective results suggest that T and VT stimuli were more compatible with the braking response than a sole V stimulus in the varied gaze directions. However, it is noted that in a realistic driving situation the cognitive processes taking place between a warning stimulus and brake response can be more complex than in the current study, particularly when gaze is off the road. In addition to the motor reaction of lifting a foot from the accelerator, a natural reaction would include a visual shift toward the road scene ahead before hitting the brakes. The visual confirmation prior to a brake response is needed for making a decision whether to brake and/or steer to avoid collision, or perhaps do neither, for example, in case of a false alarm. Thus, despite the fact that the results of T and VT warnings were much alike, it would seem rational to rather use VT stimulation to enable a more optimum S–R compatibility for an FCW; The tactile component of the bimodal warning would enable quick foot response whilst the concurrent visual component would prompt visual attention toward the windscreen. Otherwise it might be possible that a sole T warning would actually shift the driver's gaze inappropriately toward the pedals.

Being aware of the constraints of the controlled experimental setups virtually always present in the automotive domain (e.g., Aust, Engström, & Viström, 2013), we chose to first concentrate on plain perception times of the warning modalities by means of simple reaction time measured using a standard of BRT. This approach will also allow to relate the current results to other studies using the same standardized performance measures (Green, 2012). Our results obtained in the four visual orientations can serve as a basis for further investigations to substantiate the promising feasibility of the foot vibrating warnings in more applied fashion and against other vibration locations such as seat and seatbelt.

Intelligent safety technologies advance and emerge rapidly in the automotive domain, and in addition to FCWs also fully automated braking systems able to take control over the driver in near-to-collision situations are already available. However, their impact on driving safety has been found twofold; On one hand they can prevent accidents, but on the other hand there is evidence that situational awareness and driving performance may actually decline along with increased level of automation, for example, due to overreliance on the technology (Strand, Nilsson, Karlsson, & Nilsson, 2014; Young & Stanton, 2007). This suggests that as long as the human operator in the vehicle is in response of the driving safety, there is still a need for investigations and development of more efficient, yet not overly annoying warning methods that rather assist than replace the driver in hazardous situations.

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