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Enhancing personal communication with spatial haptics: Two scenario-based experiments on gestural interaction

Jani Heikkinen [a,*], Jussi Rantala [b], Thomas Olsson [a], Roope Raisamo [b], Jani Lylykangas [b], Jukka Raisamo [b], Veikko Surakka [b], Teemu Ahmaniemi [c]

[a] *Human-Centered Technology, Department of Software Systems, Tampere University of Technology, P.O. Box 589, FIN-33101 Tampere, Finland*
[b] *Tampere Unit for Computer–Human Interaction (TAUCHI), Department of Computer Sciences, University of Tampere, FIN-33014 Tampere, Finland*
[c] *Nokia Research Center Tampere, Visiokatu 1, 33720 Tampere, Finland*

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ABSTRACT

Haptic gestures and sensations through the sense of touch are currently unavailable in remote communication. There are two main reasons for this: good quality haptic technology has not been widely available and knowledge on the use of this technology is limited. To address these challenges, we studied how users would like to, and managed to create spatial haptic information by gesturing. Two separate scenario-based experiments were carried out: an observation study without technological limitations, and a study on gesturing with a functional prototype with haptic actuators. The first study found three different use strategies for the device. The most common gestures were shaking, smoothing and tapping. Multimodality was requested to create the context for the communication and to aid the interpretation of haptic stimuli. The second study showed that users were able to utilize spatiality in haptic messages (e.g., forward–backward gesture for agreement). However, challenges remain in presenting more complex information via remote haptic communication. The results give guidance for communication activities that are usable in spatial haptic communication, and how to make it possible to enable this form of communication in reality.

1. Introduction

The sense of touch is an integral part of our sensory system we use extensively when interacting with the environment and people. It guides our motor system, provides unique information or replaces other senses when they cannot be used. Touch is also important in communication as it can convey non-verbal information.

In addition to touch, gestures are commonly used in face-to-face communication. They can be used to manipulate objects, as well as to describe various kinds of information during discussion [1,2]. The manipulative gestures have been studied together with haptics in virtual reality systems [3,4]. However, uniting the communication gestures with haptic communication is a novel approach.

Using haptics as a part of remote communication has been studied to some extent. Chang et al. [5] developed a haptic device, ComTouch, by which its users can send and receive vibrotactile feedback over distance. The feedback was received and initiated by the fingers and the hand, but it did not contain any gesturing. The haptic modality proved to be meaningful and several use strategies were found together with speech. It was also possible to send some of the audible information via the haptic modality. However, users requested more than one channel for the haptic feedback. Brown et al. [6] present another view for haptic communication.

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* Corresponding author.
E-mail address: jani.heikkinen@tut.fi (J. Heikkinen).

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Their Shake2Talk prototype-enriched discrete audio messages with haptic feedback. Here, messages were created by gestures, such as tapping or twisting the device. However, these prototypes relied on a single haptic actuator to present the received information to the user. A more complex haptic device prototype was presented by Hoggan et al. [7]. They used multiple haptic actuators to create rich haptic feedback on a mobile device. The results showed that multiple actuators could be used to render traditional graphical user interface elements through the haptic modality, but communication applications were not studied.

The sense of touch is highly spatial by its nature. While hearing and seeing are both based on specialized receptors spontaneously capturing audiovisual information cues from the environment, tactile sense depends on the physical contact to an object. The receptors involved in the sensation are the cutaneous receptors in the skin all over the body. These react to the direct skin stimulation, including lateral and orthogonal forces, and the receptors in muscles and joints registering the kinesthetic information arising from body movements with respect to the stimulus [8]. Therefore, spatial characteristics of the object are perceived by active exploration of the object with hands or other body parts and continuously receiving information from several skin receptors.

Creating a virtual spatial stimulus in tactile dimension is challenging. The kinesthetic mechanism can be approached with force feedback devices such as Phantom [9] and force feedback mouse [10]. However, the devices are limited in degrees of freedom of the input. Also, the common force feedback systems provide the tactile feedback through a single rigid probe, limiting the information bandwidth and forcing the user to explore the object step by step to comprehend its spatial features. Another approach is to provide several stimuli simultaneously to the skin by a set of tactile actuators. This method can create an illusion of spatial object touching the skin without actual movement. This kind of ‘virtual spatial touch’ is the aim of the current study, and it is referred to using the term *spatial haptics*.

Despite the importance of touch and gesturing in face-to-face communication, they are not yet utilized in remote communication. Our interest lies in studying further the possibilities and restrictions in remote haptic communication. We conducted two experiments to study the creation of spatial haptic stimuli in communication contexts with gestural input. The first experiment focused on the users’ needs and free-form gestures in varying use scenarios. No technological restrictions were imposed in the first study; only a non-functional device mock-up was used as an imaginary and omnipotent haptic device. The second experiment repeated the gesture creation experiment, but with a device detecting the gestures and using multiple haptic actuators to create the output stimuli.

Next, we present background for gestural interaction, gesture-sensing technologies, and haptic feedback technologies. Following that, the goals and used scenarios are presented. The two experiments, their methodology and results are presented individually starting with the technology-free experiment followed by the functional spatial haptic communication study. Finally, the findings from both studies are discussed.

2. Related work

Gestures and haptic feedback are closely related on the physical level. In addition to the different receptors in skin, our joints and muscles contain kinesthetic receptors providing us with information about our body location in three-dimensional space. Exploiting these by gesturing can be used as an alternative input method. Data from gestural movements can be gathered using various sensors, e.g., accelerometers and gyroscopes. Through further processing this sensor data can be translated to haptic output where the movements are presented using multiple, spatially arranged actuators. Combining these two modalities opens up new possibilities in remote communication. Even if spatial creation and rendering of haptic stimuli is a novel approach in interpersonal communication, there has been previous research in the areas of gestural interaction, sensing technologies, and haptic interaction that were used as a starting point of the present study. Gestural interaction and the related sensing and tactile feedback technologies are presented below.

2.1. Gestural interaction

User interfaces in the present mobile devices are based on the same Windows, Icons, Menus and Pointing (WIMP) paradigm [11] as in desktop computers. As a result, these user interfaces can be difficult to use on small screens, keyboards and in mobile context. Interaction based on gestures can combine multiple parameters (operator, operands and qualifiers) into a single gesture [12]. A gesture is defined here as movement in three-dimensional space, stroking on a touch-sensitive surface or by means of other input methods such as squeezing. This spatial type of interaction is used for example in virtual environments [11].

According to Quek et al. [1] gestures can be divided into two types: *manipulative gestures* used in controlling entities (pointing, navigation and direct-manipulation) and *semaphoric gestures*, which are a limited set of discrete symbolic gestures in certain applications identified by recognition systems. Semaphoric gestures do not share the feedback or physical limitations of manipulative gestures. The latter can be further elaborated to *conversational gestures*, which are performed for communication purposes without the physical aspect of manipulating gestures.

Cassell et al. [2] present another view for categorizing these conversational gestures. They introduce various types of gestures that are used in face-to-face communication process. *Emblematic gestures* often convey the message even without words, e.g., making “V for victory” or “thumbs up” gesture. These gestures are, however, few, they are dependent on culture and seldom used as part of face-to-face communication. *Propositional gestures* are conscious, intentional gestures that convey a part of information of the message (e.g., indicate place, size or the object one is speaking of). For example, pointing at a chair and then pointing at another spot and saying "move that over there".

The majority of gestures, often unconscious and unintentional, are spontaneous gestures that can further be divided in four types: (1) *iconic gestures* depict by the form of the gesture some feature of the subject being described (e.g., drawing a box while talking about one); (2) *metaphoric gestures* try to represent something that has no physical form with a common metaphor (e.g., rolling gesture with hands when talking about an ongoing process); (3) *deictic gestures* spatialize aspects of the discourse in the physical space in front of the narrator, e.g., illustrating "before" and "nowadays" by moving hands from side to side. These may also function as an interactional cue, indexing which person the speaker is addressing or indexing some kind of agreement between the speaker and listener; (4) *beat gestures* serve a pragmatic function by indicating and separating the relevant parts of the speech and, e.g., by firmly snapping a finger on the palm of the other hand [2].

Currently, gestures used in user interfaces are mostly semaphoric, e.g., mouse gestures. Also, gestures in user interfaces lack the physical entity being manipulated and the resulting feedback is often visual [1]. However, using the visual system for information presentation is not always the most effective modality. O'Neill et al. [13] found that their system in Accident & Emergency Department in hospital, based on semaphoric gestures, was used more efficiently when the visual modality was not present. This system offered seven hospital-related services, which were accessed by performing strokes in different compass directions. The group with visual display took significantly more time to complete the task compared to the group without display. Amount of incorrect gestures was similar between the groups. It has been found that error tolerance of semaphoric gestures is dependent on interaction context, recognition performance of the system and user goals [14]. Error rates in recognition can be as much as 40% before changing the input method. However, this tolerance was measured in ubiquitous scenarios. In desktop scenarios the tolerance is lower and traditional input technologies are preferred.

Gestures are an essential part of human–human communication. When coupled with haptic feedback in a communication device, they can potentially bring novel communication abilities besides the methods for conveying factual information [15]. In such systems, the gestures must not be semaphoric to allow expressive communication.

Overall, the semaphoric gestures have been studied more carefully than manipulative ones. However, it is argued that semaphoric gestures are not good for interaction because of their discrete nature as they are merely function keys presented in another domain [16]. Instead, the continuous and more natural manipulative gestures should be supported, but they are more challenging for the system and application designers.

2.2. *Gesture-sensing technologies*

Traditionally, keypads and pens have widely been used to operate handheld devices. More recently, these input devices have been partly substituted with larger touch screens designed to be used with bare fingers. However, in certain situations keypads, pens, and touch screens may need supplementation as they cannot make use of the inherent potential of mobile devices; with physical manipulation, e.g., rotating, tilting, and shaking, the devices themselves can be used as input devices [17].

Augmenting mobile devices with light-weight and inexpensive sensors to gather input data has been an active theme of research during the recent years [18–20]. With sensors, single hand operation of devices is possible as separate input devices are not required [21]. This can be of advantage especially when a user is simultaneously engaged in real-world activities, such as walking, and thus cannot pay full attention to the interaction with the device. According to Hinckley et al. [22], sensors have the potential to improve the use of mobile devices in two ways. First, sensors can provide information on the context of the user, therefore making it possible to adapt the interaction to suit the current task. Second, naturally occurring gestures, e.g., picking the device up, looking at it, and putting it away, can be integrated into the interaction using sensor data. This latter point is more of interest for us as our focus in this study is on active manipulation of the mobile device. Thus, this section mainly covers sensing technologies suitable for gesturing and other physical manipulation.

Accelerometers have been frequently used in previous studies to gather input data by sensing the movement of the host device. These sensors detect the tilt of a device relative to the constant acceleration of gravity, and some may also detect linear accelerations that can result, e.g., from shaking the device [22]. Accelerometers have been used for various purposes, such as, creating audiotactile feedback from gestures [20,23], automatically zooming and scaling an interface [24], recording motional activities of a person [25], rotating a display according to viewing orientation [22,26], controlling a virtual ball in a game by tapping [27], and shaking a device to hear and feel informational content [19].

Accelerometers are not the only available solution for sensing movement of a device. Harrison et al. [17] used an electrolyte bordered on two sides by a pair of conductive plates to get a crude tilt measure for implementing a list scrolling interface. Furthermore, Rekimoto [21] utilized an electromagnetic position and orientation sensor for creating menu and navigating interfaces based on tilt data. Recently, gyroscopes measuring the angular velocity, i.e., the speed of rotation, have been used with devices [6,20,23,25]. Gyroscopes provide values for angular velocities that are independent of gravitational measures and can therefore supplement or, depending on the type of sensing needed, substitute accelerometers. The movement of a handheld device can also be detected using an integrated camera [28].

In addition to providing input data based on the movement of the device, sensors have been used to detect user's contact with the device. Harrison et al. [17] attached pressure sensors to a device to detect handedness of a user as well as explicit strokes for navigating in a document. Brown and Williamson [6] utilized different sensors, including a capacitive touch sensor fixed to the back of a mobile phone to create multimodal messages based on recognized gestures. Williamson et al. [19] used the same capacitive sensor to detect tapping of a device, which resulted in virtual balls bouncing inside the device. Murray-Smith et al. [29] embedded a piezo contact microphone in a stone-shaped device to detect touching, scratching and stroking. In an example case study different gestures were used for controlling a music player.

In general, different sensing mechanisms for mobile devices have made it possible to use a far wider range of input than what was previously possible [30]. The list of different sensing technologies presented here is by no means complete but does provide examples of situations, where interaction with mobile devices can be enhanced with physical manipulation and gesturing.

2.3. Tactile feedback technology

During the recent years, several different technologies have been used to provide users with tactile feedback. Of the tactile senses we can generally stimulate nociceptors, thermoreceptors, and mechanoreceptors, which are responsible for the feeding impulses of pain, thermal, and mechanical stimulation, respectively.

Pain is one of the most efficient ways to draw one's attention but, due to the facts that it practically provides mere one-bit resolution and that it is nearly always disliked by the users, it was not considered to be used in this study. Temperature is an interesting and less researched area in the field of haptics and a major component in determining material properties [31]. However, it has some major challenges in both generating and dissipating heat efficiently, especially concerning handheld devices.

Most of the past and present haptic appliances have used different technologies to stimulate mechanoreceptors, which are responsible for delivering most of the tactile information we process, when physically interacting with our immediate surroundings. The techniques available include simulating different physical surface structures (pin displays), applying friction forces to the skin (skin stretch), and producing vibration (vibrotactile actuators). The mechanoreceptors can also be stimulated directly using electrocutaneous stimulation what would be very cost-effective method, but the users do not often favor it. The unpleasant nature of using electricity directly derives from the difficulty to control the changes in the impedance caused by the complex interaction between skin, electrode, and used current [32], which remains to be solved properly.

There are both large- and small-scale pin displays of which the large ones use hundreds of pins to present very detailed surface textures [33], while the small ones can only be used to present simple Braille-like symbols and elementary dynamic messages [34]. The limiting factor of using the large pin displays is that they are very hard to miniaturize to fit the dimensions of a handheld device. Skin stretch [35] is still quite little researched topic but it offers interesting possibilities for providing feedback.

Most vibrotactile actuators use electromagnetic motors to drive either a linear or rotational mass to provide vibration to the skin. Motors with eccentric rotating mass are often very compact in both size and weight and they are relatively easy to control. Where they fall short of, however, is that their frequency is inherently coupled with intensity and that they take relatively long time to both spin up and slow down the mass. The linear mass actuators most often use so-called voice-coil solution familiar from classic loudspeakers. These actuators provide more control over the stimulus properties, provide better temporal resolution, and can be driven by audio signals. Different piezoelectric actuators often provide even better stimulus property control and superior temporal resolution but require rather complicated electrical control over the high-voltage current.

While human sense of touch is highly sensitive for vibration and temporal dynamics [35], we often tend to use active touching to spatially explore the objects at hand. Some of the spatial resolution, which is lost when selecting vibrotactile actuators over pin displays, can be gained back by using a multi-actuator setup to communicate spatial information. This setup gives more intensity dynamics thus providing the users with better spatial feedback.

3. Scenario-based studies on spatial haptics

The main research goals for both experiments as well as common goals are described in this chapter. Also, the used scenarios and their properties are depicted with an example.

3.1. Goals

The ultimate aim of this research is to enable spatially rendered haptic communication between people. However, as this is a novel communication method, and there are many technological options for how the inputs and actuation are utilized, we started this research with two experiments. Experiment 1 focused on studying natural haptic gestures that would be produced in each of the scenarios. The users were told not to care of any technological restrictions that might occur in a real device prototype, but to use the mock-up device in a way that was the most natural to them. The results of Experiment 1 were aimed to guidance for natural haptic communication.

Experiment 2 progressed towards real use of spatial haptics by studying the same scenarios as in Experiment 1, but at this time the communication was produced through a spatial haptic system that was able to detect certain gestures and to produce actuation in a second device. However, as this method of communication is clearly new to most users, and because the mapping of inputs to feedbacks has a great effect on the way it can be perceived we decided to carry out a within-person study. The user produced the feedback with a device in one hand and felt the spatial haptic feedback in the other device in the other hand. Participants were asked to find as natural spatial haptic sensation for a given communication activity as they thought was possible with the device setup available. Even if this resulted in having a within-person feedback loop in the creation and interpretation of the spatial haptics, it was considered as an important step towards being able to find out which kind of feedback mappings are usable and expressive in spatial haptic communication.

Both of the experiments shared the following research questions:

- What kind of gestures participants use in certain scenarios and what is the deliberation behind these gestures?
- How easy, understandable, and reasonable haptic communication is in the given scenarios?

In addition, each of the experiments had their specific questions, additional data and analysis that are explained in the following sections.

3.2. Description and classification of scenarios

Both of our studies were based on the same short textual scenarios that described possible use contexts for haptic communication. Two examples of the used scenarios are presented below:

> “You are on your way to the city center for an evening coffee with your colleagues, but you do not know where you are going to meet. You send a message asking the exact place and your colleagues suggests a nice café This place sounds good and you quickly agree by making a haptic answer.” (Scenario 3)
>
> “You have been apart from your girl/boyfriend for a month because your loved one is working abroad for a while. You both are feeling the long distance and longing. To show that you are missing her/him a lot you send a romantic haptic message...” (Scenario 5)

The scenarios used in this study can be separated to scenarios with either emotive or factual information. The scenarios and their emotional themes are listed in Table 1.

4. Experiment 1: creating gestures without technological limitations

The goal of the first study was to study how people create non-verbal gestural messages in a setting without technological limitations. In addition to the actual gestures, we wanted to find out the participants' subjective evaluations of the easiness, reasonability and general acceptability of the use cases depicted in the scenarios. Another goal was to study the reasons and background for the gestures they came up with.

In research related to haptic interaction, the gestures have often been studied in technologically restrictive settings or the user has had to choose from and evaluate predefined gestures. First, we wanted to understand what kind of gestures the users would use most naturally without narrowing down any usage affordances. Thus, we would be able to extend the view of what haptic and gesture interaction could be and what would be the most natural practices. Second, we wanted to further evaluate the presented scenarios and find out in which haptic communication is considered suitable and beneficial.

4.1. Methods

The methodology used in Experiment 1 is described below.

4.1.1. Participants

We conducted altogether 20 individual single-user interview sessions with a heterogeneous set of users. Out of the 20 participants, 12 were Finnish and one from each of the following countries: Pakistan, India, Spain, Turkey, Bangladesh, Slovakia, Canada and Czech Republic. Different nationalities were selected to bring more heterogeneity to the study. The participants were either students or staff at the local University of Technology where the study took place. 14 participants were male, 6 female and their mean age was 23.3 years ranging from 18 to 33 (st. dev. 3.3). We recruited people with experience in instant messaging, expressively creative people or people using devices with touch or gesture features. All the participants

Table 1
Overview of the scenarios used in both studies.

	Scenario	Emotional theme	Description
Emotional information	1	Excitement	Showing excitement while describing a new person to a friend.
	2	Happiness	Showing happiness to a friend after winning a surprise prize.
	5	Longing	Expressing longing to loved one over a distance.
	6	Cheering up	Encouraging and cheering a friend before important job interview.
	7	Comforting	Comforting a friend whose old and beloved pet has passed away recently.
	8	Empathy	Sympathizing with loved one's work-related stress.
	10	Displeasure	Privately reminding your noisy friend to stay quiet during interesting lecture.
Factual information	3	Agreeing	Agreeing to a friend's suggestion of a place for a casual meeting.
	4	Telling time	Agreeing to a meeting with friends, but postponing it by 1 h.
	9	Call notice	Signaling intention to call a friend soon without disturbing others.

were familiar with various mobile devices including phones, media players, laptops, cameras and mobile gaming devices. Moreover, most of the participants had some level of interest in the topic.

4.1.2. *Technical settings*

No supporting technologies or working prototypes were used in this experiment to aid the participants in gesturing. They were only given a device mock-up with no actual functionality (Fig. 1). The shape and dimensions of the mock-up (13.5 × 5.8 × 5.5 cm, length × width × height) were designed to maximize the area of skin contact while holding the device in hand. In addition, motivation behind the shape was to create a device that would not resemble any existing mobile devices, such as a mobile phone. In other words, we did not want to restrict the interaction affordances the user might perceive the device to offer.

4.1.3. *Procedure*

A semi-structured interview approach was used, which left room for fairly open discussion of new ideas, and sharing of opinions and experiences. Participants were advised to act out, physically show and explain how they would communicate in the given situations.

All participants filled in a background questionnaire at the beginning of each session. Next, the participant was shortly introduced to the haptic interaction and technologies by defining the terms used. Third, the mock-up device and its omnipotence in regard to ways of interaction were introduced. The gesture types the prototype could provide were introduced on a high level, but at the same time emphasizing that almost any kind of haptic gestures could be conveyed with the prototype of an imaginary device (for both message-like synchronic and asynchronous real-time communication). Each participant was verbally told the device could recognize smoothing, shaking, tapping, other movements and touches and send these to the receiver's identical device. We used a consistent introduction to ensure that the participants were given similar introduction so that it would not affect participants' creativity with regard to creating the gestures.

Each participant was presented with the 10 scenarios based on which he or she would create haptic input with the mock-up device to be sent to a remote recipient. The order of the scenarios was randomized in each test session to prevent biasing of the results (e.g., participants basing the new gesture on the previous scenario). Scenarios were presented both verbally and textually. The experimenter read the scenario description out loud and the participant was able to read it at the same time from the paper. If the participant did not know what to do, she or he was advised to show how the message in the given situation could be created by using the mock-up device. After each scenario the participant was shortly interviewed to inquire the reasons behind the created input, the subjective estimation of the easiness of creating it, the assumed understandability of the message and the reasonability of using haptic modality in the case given. The easiness, understandability and reasonability were asked on a scale from 1 to 7. The used questions were: "On a scale from 1 to 7, how easy it was to figure out a gesture for this purpose?", "On a scale from 1 to 7, how well do you think the receiver will understand this gesture?" and "On a scale from 1 to 7, was the haptic message a reasonable way to communicate in this scenario?" The scale was then explained by 1 being the negative and 7 being the positive end of the scale.

4.1.4. *Data analysis*

Each session had an experimenter and an assistant who took notes of the discussion with a laptop computer. The sessions were recorded with a video camera to support note taking and analysis. Qualitative results were analyzed by sorting the acquired data by scenarios and going through it scenario at a time and simultaneously identifying general needs from scenario-specific ones. We used researcher triangulation (altogether three researchers) in the analysis process to take advantage of the tacit knowledge the assistants gained while taking notes. After the qualitative data, averages and standard deviations were calculated for the most interesting quantitative questions from background and interview questions.

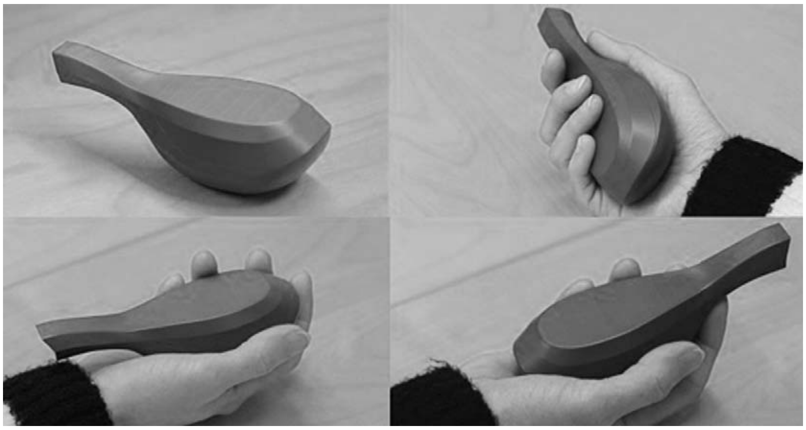

Fig. 1. The hand-held mock-up and some of the various ways users held it during the first experiment.

Repeated measures analysis of variance (ANOVA) was used for statistical analysis of the subjective ratings for easiness, understandability and reasonability. 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.

4.2. Results

To draw up the findings, the different gesture types and their frequencies in the first study are presented in Table 2. The most common gestures in each scenario are marked with a bold font. The number of gestures varied between scenarios. Participants presented often more than one possible gesture and these are all listed. The amount of visual and auditory modalities that was requested is also listed. Finally, the number of individual gestures which did not fit into any of the gesture types listed is shown.

The width of various gestures and strokes the participants made up were remarkable. Smoothing the surface, tapping the device or with it, shaking, drawing and touching certain parts of the device or certain part of the body with the device were the most often used gestures. In addition, throwing, pointing with, warming, squeezing and modifying the device's shape were also observed to be ways to express oneself through the haptic modality.

In scenarios 5, 7 and 8 *gentle and soft smoothing* was used to express longing, comforting, cheering up and supporting emotional information. Conveying the *feeling of presence* was more important than precise communication. The gestures were done by smoothing the device itself or making a smoothing gesture in the air or on one's body (e.g., smoothing one's arm with the device). It was noted that the sender's device should be able to detect and the receiver's device to reproduce the level of softness or intensity of touch. Also hugging, smoothing, kissing, drawing hearts and holding the device close to the participant's chest (i.e., close to heart) came up. In scenario 6 a few users also squeezed the device and explained that it was a metaphor for *holding the receivers hand*. Additional information was desired to complement the haptic feedback and *to aid in the interpretation*: images, colors, flashing lights, sounds effects and speech were mentioned. Three participants considered the situation in scenario 8 *too sensitive* for haptic communication.

The first three scenarios with happiness, excitement and agreeing evoked similar gestures. In the first two, the most used gesture was fast shaking with a moderate to large trajectory, often while squeezing the device. In the second scenario, the fast shaking was often moving upwards or above the chest level with both hands at the same time. Some participants noted that showing enthusiasm and happiness is often *random and subconscious* movement instead of clear and predefined gestures. A different shaking gesture was used in scenario three. Over half of our participants suggested a calm vertical nodding gesture for agreeing, a metaphor for *nodding one's head when agreeing*. Disagreeing could be conveyed by shaking the device horizontally as opposite to the nodding. The *amount of squeezes* would also signal agreement or disagreement, but this would require agreements between people. Some participants pointed out, that additional information was needed to distinguish the shaking from aggressiveness. However, the agreeing and disagreeing were felt to be well conveyed through unimodal haptic stimuli.

Tapping was most prevalent gesture in scenarios 6 "Encouraging and cheering a friend before important job interview" and 10 "Privately reminding your noisy friend to stay quiet during interesting lecture". Around half of the participants suggested tapping, e.g., *encouraging by tapping on the back or shoulder* but the individual gestures varied largely in scenario 6. Some participants used the device to tap on the palm of their hand while some others tapped on the device with fingers or hand. It was also mentioned that without context, tapping gestures could also be interpreted as aggressive gestures. In scenario 10,

Table 2
Summary of the main gesture types and the number of suggestions from different participants in the free-form study.

Information content and Scenarios:	**Emotional**							**Factual**		
Gesture type	***1***	**2**	**5**	**6**	**7**	**8**	**10**	**4**	**3**	**9**
Shake	**6**	**10**		5			2	1	**13**	3
Wave	3	1		1			3	3		1
Hands up in the air	1	5								
Toss	1	1		2						
Random movement	4	2					1			1
Circular movement		2		1			1	2		1
Hug			7		3	2				
Touching a part of the device or body	2		3						3	**8**
Tap	2	3		**11**	2	3	**9**	1	6	6
Smooth	1		**11**	1	**11**	**12**	1			1
Squeeze	5	8	6	2	5	7	5	1	4	4
Kiss			6							
Drawing and writing	1	1	2		2			**9**		
Text, audio and images	3	3	5	4	6	6	4	8	1	5
Other	2	3	1	5	1	1	7	2	2	

forceful tapping was used to draw the receiver's attention and to express dislike. However, the gestures varied a lot and also squeezing was mentioned few times. In this scenario, it was more important to *catch the receiver's attention* and get him/her to stop and think.

In scenario 9 with the task of signaling to intention to call soon, *spatial location* of the device was the most common way to inform the receiver. Nine participants picked up the device and held it like a phone *next to their ear*. Here, it was seen important that the device detects where it is held in relation to one's body. Some of them also added tapping or squeezing in addition to the movement. A couple of the participants requested a *symbol of a clock*. Many of the participants wished to add text to the message to ease the interpretation and three were not able to send this message through the haptic modality.

The most difficult scenario for the participants was scenario 4 "Agreeing to a meeting with friends, but postponing it by one hour", which required participants to agree and express numeral information. This led to *many wanting to use text*, *voice or images* instead of haptics. Also, drawing and describing the time using characters or using a scale repeated many times. Again, the gestures varied much. Some participants used the same agreeing gestures as in scenario 3 and then combined it with another gesture to tell the temporal information. Various kinds of *forwards rotating gestures* were used. Some moved the device in a circular path in place while others moved the device away from them at the same time.

4.2.1. Motivations and backgrounds behind the participants' gestures

Mimicking intuitive and often subconscious gestures used in face-to-face conversations was the most often mentioned background behind the gestures. These gestures were considered to be easy to understand as the gestures and their contexts are familiar to people. Abstract and metaphorically unrelated gestures would require agreements or universal "codes", which stress users' memory like one participant noted. Eventually, these gestures may also evolve but the learning process might be too difficult if there are lots of different gestures that must be memorized.

In most cases, the participants held on to the first gesture idea that came naturally and intuitively to their mind. This was especially valid with gestures that were easy and spontaneous to create for the participant, which suggests that haptic messaging is fast and spontaneous. In the more difficult scenarios (varied between participants) users had to actively think about the gestures and the first gesture idea was not so permanent.

The prototype device was held in many ways – almost every participant quickly adopted an individual way to hold and use it. The prototype served in various functions as part of the gestures and interaction, varying between users and scenarios: (1) The device representing the receiver, e.g., smoothing or tapping the device like the participant was doing the same thing directly to the receiver (*metaphorical strategy*), (2) The prototype being an extension of the participant's hand, e.g., poking, pointing, using it as a tool, such as a phone (*tool strategy*), (3) The participant representing the receiver, and the device being an extension of one's hand, e.g., smoothing oneself with the device to communicate a hug (*extensional strategy*). These can be seen as *strategies* of using the new modality.

In most scenarios one gesture was considered enough to convey the intended message when properly understood. In scenario 4, the conveyed message had evidently two parts. Participants often created two separate gestures one after the other or wanted to use text, images or voice to convey the exact temporal information. This suggests that gestures could be joined together to form simple multi-element haptic messages.

Similar gestures were used in different scenarios and to convey very different meanings. Thus, misinterpretations were predicted to happen easily. The speed, length of the trajectory, direction, number of repetitions and softness/hardness of the touch or squeeze were common attributes to customize the basic categories for specific purposes.

4.2.2. Opportunities and drawbacks of haptic communication

Participants identified both good use cases and features for the haptic communication as well as problem areas. The comforting in scenario 5 was seen to be more concrete with haptic feedback and able to bring people closer. It was also noted that such emotions can be difficult to convey with speech or text. Haptic modality can also mediate the intensity and depth of the feeling. The more intimate the people that are communicating, the easier it would be to interpret the haptic feedback participants commented. The haptic modality would be mainly used between the few closest people only. Understandability was seen to be affected by the amount of use. The more one has used the haptic modality, the easier it was seen to become. However, few participants did not want to use touch-based communication at all. They were afraid it might alienate people from each other or they were not comfortable with touch in communication. Nevertheless, creating haptic information by gestures in Experiment 1 was mentioned mostly to be easy, simple and fun.

The most difficult aspect of the haptic communication was providing information about the context of communication. To be interpretable, both parties must be aware of the context of communication. Similar gestures were used in different scenarios and without the contextual information interpretation becomes difficult. This, with the comments about the lack of precise information, often led to suggestions of multimodal interaction. Other modalities, such as speech, text, images or colors were desired to be able to communicate the context. Haptics was mostly seen as a way to add new information to multimodal communication. Some participants said that the doubt whether the message was received or not is greater in haptic communication.

4.3. Discussion of experiment 1

The presented findings provide new insight on users' expectations and ideas about haptic communication with conversational gestures. Participants used some emblematic (e.g., "thumb up" and "shush" gestures) and beat gestures (number of taps as a predefined message). With these gestures the multimodality was not requested as often as with others. However, most gestures were propositional (e.g., smoothing) or deictic (e.g., waving), which required additional information to complement the haptic modality to be interpretable by the recipient.

Three different use styles for the mock-up were found: metaphorical, extensional and tool strategy. These strategies illustrate possible future research topics and design space for haptic applications. Tool strategy hints that such device could be used for providing additional information to conversations by manipulating environment. The other two strategies, metaphorical and extensional, apply especially to communication applications. These strategies define the nature of the communication applications for haptic communication. What comes to differences between nationalities, the only observable difference (not statistically significant) was found to be the scale and energy of the gestures. However, as the gestures were often highly related to communicating by touch in real-life situations, and the communication is, again, very dependent on culture, it can be assumed that further differences between nationalities could be found with larger sets of users.

The most distinctive gestures were smoothing, shaking (often fast or randomly), tapping and touching a certain part of the device or body part with the device. Clearly, participants used mainly existing and familiar gestures like they discussed during the interviews. However, the development of new gestures and meanings could happen when such communication modality is used during a longer period of time. Development of this symbolism (for example "haptic emoticons") is both essential for the future acceptability of haptic communication and an interesting research topic. Overall, participants saw the haptic communication as free-form and continuous interplay instead of discrete messages, even though both styles were wanted. A vast majority wanted manipulative gestures instead of semaphoric. This type of gestural interaction and the resulting spatial haptic feedback is technically and application wise demanding and not fully understood.

Overall, Experiment 1 revealed information about the gestural creation of spatial haptic messages. It showed that users want to freely select the modalities they use. Multimodality was often requested with haptic feedback and it was seen as a tool to improve visual and auditory modalities. Also, similar gestures were used in various scenarios, which further show the need for other modalities in describing the reason and context for haptic communication. Experiment 1 did not limit the ways the users interacted, but it was not directly linked to the present state of the art haptic communication technology. This is why a second experiment was needed.

5. Experiment 2: haptic gesturing with a functional prototype

The goal of Experiment 2 was to enable the participants to physically create haptic messages in the same situations as in Experiment 1 and to compare how this affects the communication. In Experiment 2 the participants produced and felt the haptic feedback at the same time. We wanted to investigate how users compose haptic messages when they can simultaneously feel the feedback they are creating. We used an identical device mock-up in both experiments to keep testing setups as similar as possible. A separate functional feedback prototype was used for sensing the haptic feedback.

There are several unaddressed research questions in using multiple haptic actuators simultaneously for presenting messages created with gestures. Chang et al. [5] complemented voice communication in their study with vibrotactile feedback based on touch input created by the other user. In their work fingers had to be placed in specific locations on a pad to send and receive tactile information. We were interested in investigating how movements with relatively simple physical gestures, such as tilting and shaking, could be transferred to multiple spatially arranged haptic actuators.

5.1. Methods

The methodology used in Experiment 2 is described below.

5.1.1. Participants

A total of 10 volunteers participated in Experiment 2. All of the participants were Finnish. Nine of the participants were male and one female. The mean age was 27.6 years ranging from 20 to 49 (st. dev. 10.2). All of the participants had experience in using mobile devices for over 2 years. Two of the participants were left-handed and eight right-handed by their own report. None of the participants of Experiment 2 had taken part in Experiment 1.

5.1.2. Technical settings

We used two devices that separated the functions for creating and receiving haptic information. The mock-up device from Experiment 1 was used for gesturing and a separate feedback prototype was used for sensing the haptic feedback (Fig. 2). Sensor data from the gesture mock-up had to be transferred in real time to dynamic haptic output. For this purpose we needed haptic actuators and sensing technology that could meet the requirements of low-latency communication and dynamic input–output mapping. An external Motion Band sensor pack [36] was attached on top of the device to gather sensor data. The sensor pack used 40 Hz frequency in data transmission and it was thus suitable to be used in our study as the delay between gesture input and haptic output could be kept low. We measured movements using several sensors, i.e., accelerometer, magnetometer and gyroscope. Sensor readings were sent wirelessly to a host

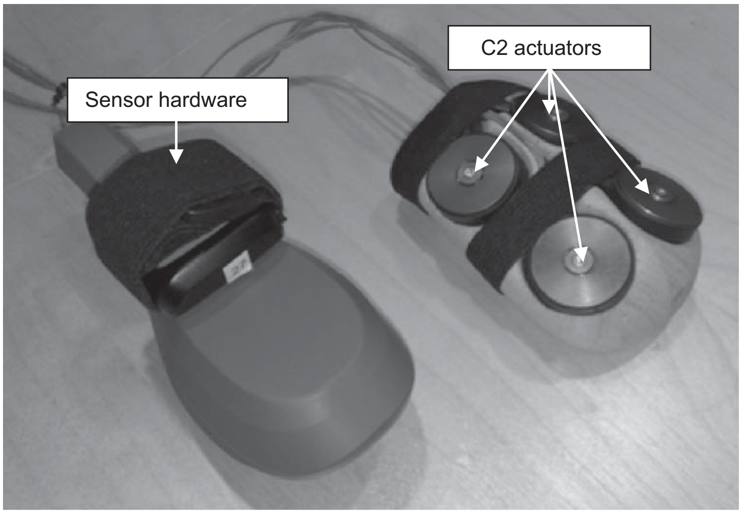

Fig. 2. The mock-up with external motion sensor hardware for gesturing (on the left) and the functional prototype with C2 actuators for sensing haptic feedback (on the right, upside down).

unit using wireless Bluetooth connection. Wireless motion sensor hardware was an ideal solution for reading gesture data as it did not require any data or power cables between the device and its host. This enabled users to manipulate the mock-up and create different gestures without any restraining physical connections.

The functional feedback prototype that was used for receiving haptic messages was carved out of wood so that haptic actuators could easily be attached (Fig. 2). The shape and the size of the prototype resembled a computer mouse with dimensions of $10.0 \times 6.5 \times 3.8$ cm (length × width × height). We used vibrotactile C2 actuators from Engineering Acoustics Inc. (http://www.eaiinfo.com) on the prototype for presenting haptic feedback. The C2 actuators are miniature voice-coil speakers that are designed to vibrate at frequencies up to 300 Hz. These actuators are capable of producing fairly strong and versatile haptic feedback suitable for presenting distinguishable haptic sensations. When an electrical signal is applied, a moving contactor oscillates perpendicular to the skin. We drove the actuators using an audio signal. Because of this, we were able to easily modify the feedback using audio synthesizer software which made the feedback more dynamic compared to standard vibration (e.g., motors with eccentric rotating weights). Four actuators were attached in a 2×2 matrix using two elastic bands. The size of an individual actuator (3.05 cm in diameter) allowed us to place several actuators on the prototype so that they were in contact with the skin of the palm area. The distances between outer edges of the four actuators were 0.7 cm for horizontally and 1.1 cm for vertically aligned actuators. The prototype device was held so that the C2 actuators faced downwards towards the palm (contrary to Fig. 2, which shows the actuator configuration).

Although the sensor hardware provided accelerometer, gyroscope, and magnetometer data, we utilized only the accelerometer data for feedback synthesis. We wanted to present dynamic movements using the four spatially arranged C2 actuators so that haptic sensations could be dynamically composed to move between actuators. For this purpose the accelerometer data were sufficient as we could detect both tilting and linear movements of the device. The range of the accelerometer was ± 6 G. These values were scaled down by a factor of 24 so that the final values were in the range of -250 to 250. The scaling was done in order to make the accelerometer values fit for use in frequency modulation with the actuators. The recommended audio signal for the C2 actuators is a 250 Hz sine wave. Based on this, we used sine wave in the feedback synthesis and set the maximum frequency to 250 Hz.

In the first phase, the accelerometer readings for X (left–right) and Y (forward–backward) axes were used for calculating four separate acceleration values that represented the movement of the device. The sensor readings were zero for both X and Y axes when the mock-up was held still as depicted in the bottom right corner of Fig. 1. When being tilted, the accelerometer sensor gave negative readings for leftwards and backwards accelerations and positive for rightwards and forwards accelerations. We used the following equations to calculate accelerations for separate directions: $V_{left} = (-X-c)^d$, $V_{right} = (X-c)^d$, $V_{forward} = (Y-c)^\theta$, $V_{backward} = (-Y-c)^\theta$, where $c = 15$, $d = 1.12$, and $e = 1.2$. The constant c was hand tuned to allow some movement near the still state of the mock-up device where both X and Y values were zero. That is, there was no haptic feedback for small unintentional hand movements. The exponents d and e were added to the formulas after we noticed that by increasing the frequency linearly based on the accelerometer values the frequency of the feedback did not correlate with fast movements or tilting. Thus, by increasing the frequency more rapidly high intensity feedback could be created with less gesturing. The exponent was set to be greater in forward and backward movements to compensate the limited wrist mobility in vertical direction. The sensor values for Z-axis (V_z) were 250 when the device was in still state. This data were used to modify the feedback only when

$|V_z| \geq 500$. In practice, high energy linear movements such as shaking the device up and down could be used to create strong feedback to all four actuators simultaneously.

In the second phase of the feedback synthesis the separate acceleration values for each gesturing direction (V_{left}, V_{right}, $V_{forward}$, $V_{backward}$, V_z) were summed up to get audio frequencies for the four actuators. These frequencies were determined using Eqs. (1)–(4) for the four actuators,

$$Freq_{frontleft} = V_{left} + V_{forward} + V_z - c, \tag{1}$$

$$Freq_{frontright} = V_{right} + V_{forward} + V_z - c, \tag{2}$$

$$Freq_{backleft} = V_{left} + V_{backward} + V_z - c, \tag{3}$$

$$Freq_{backright} = V_{right} + V_{backward} + V_z - c, \tag{4}$$

where $c = 100$. The constant c was used to adjust the sum of combined frequencies suitable for C2 actuators. For example, by tilting or moving the device leftwards the front left and back left actuators would provide feedback. In principle, fast movements and thus high acceleration values created high-frequency tactile feedback. Using the feedback mapping described, a simultaneous 45° tilt to leftwards and forwards (where $V_z = 0$) would be synthesized as a 172 Hz sine wave on the front left actuator, 59 Hz on the front right actuator, and 13 Hz on the back left actuator.

The gesture data were read from the Motion Band using a Java application run on a PC laptop (Toshiba Portege R500). This application both saved the sensor data for later analysis and forwarded it to Pure Data audio synthesizer software (PD, http://puredata.info) via a socket connection. The sensor signal was processed on PD and corresponding tactile feedback was created in real time. An external Audiotrak MAYA EX5 CE USB sound card and a Behringer Mini Amp AMP800 amplifier were used for feeding individual audio signals to each actuator.

5.1.3. Procedure

In the beginning of each test session the participants filled in a background questionnaire. In addition, the participant was verbally introduced to the concept of haptic communication, gestures, and bimanual use of the two devices for experimental purposes. After this, the two devices were given to the participant with verbal instructions on how to hold the devices. Lastly, the possible gesture types were introduced so that the participant knew what kind of gestures could be detected and transferred to the functional prototype for feedback. As in Experiment 1, a written explanation was used to ensure that each participant was given similar introduction to the experiment and experimental tasks.

A training block followed when the participant was ready to start the experiment. In this training the participant was verbally presented with an example communication scenario. The participant's task was to ideate ways to communicate the given task. The participant could try out different gestures and haptic feedback with the two devices without a time limit before deciding which message to use. Then, the participant was asked to reproduce the chosen gesture three times using the mock-up device so that gesture data could be recorded for later analysis. The mock-up device was held still (i.e., as shown in the bottom right corner of Fig. 1) in the beginning of each recording. The experimenter gave a verbal signal when the participant could start reproducing the gesture. After the gesturing was completed the mock-up device was moved back to the initial position. The experimenter stopped the logging when the mock-up device was again in still state. This procedure was performed three times in each scenario to get multiple samples of each gesture and thus decrease the effect of accidental movements in gesturing.

The actual experiment with the 10 scenarios proceeded similarly to the training block. The order of the scenarios was balanced between participants so that each participant was presented with the scenarios in a different order. After each scenario the experimenter interviewed the participant by asking subjective ratings using the same scales (i.e., easiness, understandability, and reasonability) as in Experiment 1. In addition, at the end of the experiment general questions were asked for example on how feasible the concept of haptic communication was and how well the feedback prototype responded to gestures.

5.1.4. Data analysis

Statistical analysis methods for subjective ratings were identical to those used in Experiment 1.

We used the recorded accelerometer and gyroscope data in calculating mean gesture dynamics and energy levels for each of the ten scenarios. In the first phase we calculated total acceleration for each logged data sample. We used the accelerometer data from all three axes to detect data samples where the mock-up was held still. These samples were detected using Eq. (5),

$$Totacc = \sqrt{\left(\frac{X}{X_{\max}}\right)^2 + \left(\frac{Y}{X_{\max}}\right)^2 + \left(\frac{Z}{Z_{\max}}\right)^2}, \tag{5}$$

where X, Y, and Z are values of a data sample and $X_{\max}$, $Y_{\max}$, and $Z_{\max}$ are the maximum values (6000). The result of Eq. (5) was 1 for those data samples where only gravitation was detected (i.e., no linear acceleration). In the second phase we cut off irrelevant data from the beginning and end of each gesture using a relatively common single-threshold method based on comparing the sensor signal with a fixed threshold [37]. The *Totacc* values from the first 500 ms of each gesture signal were used for calculating a baseline standard deviation (SD) representing the still state of the mock-up device. A multiplication factor of 8 was set for detecting onset of actual gesturing. That is, the first sample from the beginning of each gesture where the *Totacc* value was 8 times greater than the baseline SD was detected to be the sample where the still state of the mock-up ended and actual gesturing began. The same was applied to data in the end of each gesture to detect the end of gesturing.

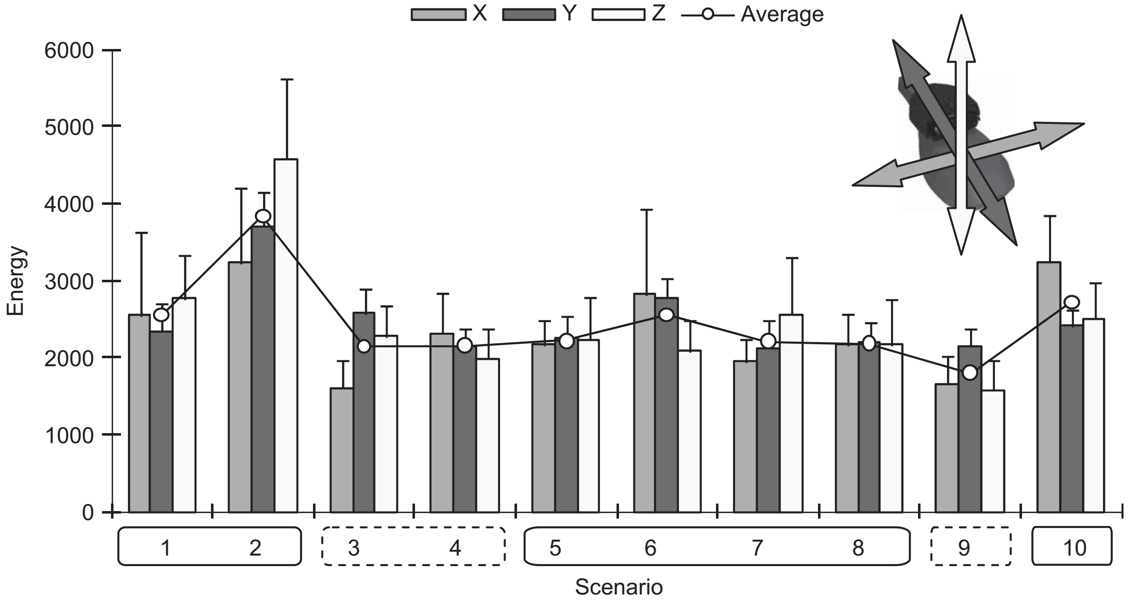

Fig. 3. Mean energy values for accelerometer data. Scenarios 1, 2, 5–8, and 10 contain emotional information (solid rectangles) and scenarios 3, 4, and 9 factual information (broken rectangles).

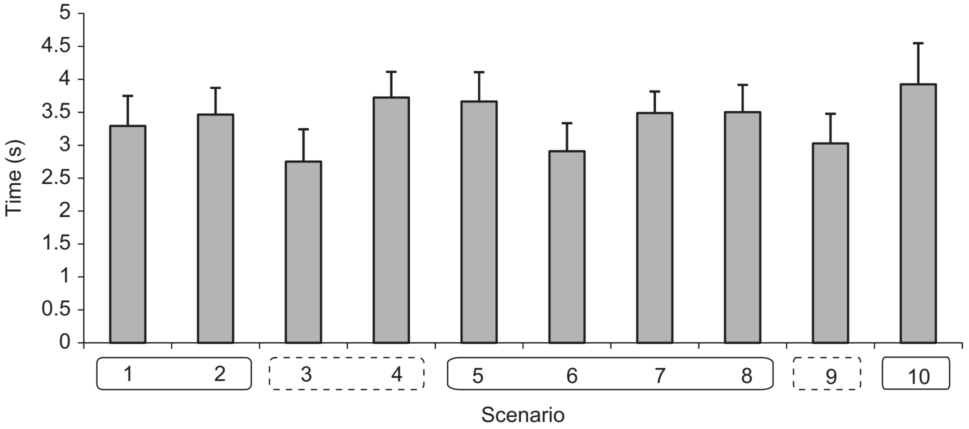

Fig. 4. Mean gesture durations. Scenarios 1, 2, 5–8, and 10 contain emotional information (solid rectangles) and scenarios 3, 4, and 9 factual information (broken rectangles).

5.2. Results

The mean energy values for accelerometer data are shown in Fig. 3. The *X*-axis represents left and right, the *Y*-axis backward and forward, and the *Z*-axis up and down movement. The mean energy values were the highest in the second scenario where the participants were asked to communicate happiness. Also the first (excitement), the sixth (cheering up) and the tenth (displeasure) scenario evoked somewhat energetic gestures. On the other hand, the ninth scenario (call notice) was observed to induce the least energetic gestures. When considering the energy results in terms of individual axis, we can see the left and right direction (*X*-axis) to be dominant in scenario 10 (displeasure). The forward and backward (*Y*-axis) movement is dominant in scenarios 3 (agreeing) and 9 (call notice). Lastly, the up and down direction of movement (*Z*-axis) is dominant in scenarios 2 (happiness) and 7 (comforting).

The figure distinguishes scenarios by their information content (emotional or factual, Table 1). The average energy level in scenarios 3, 4 (telling time), and 9 containing factual information was lower (2028) compared to the other seven scenarios with emotional information (2606). It should be noted, though, that the difference was relatively modest. Furthermore, the average energy measurements especially for scenarios 3, 4, 5 (longing), 7, and 8 (empathy) were almost identical although the scenarios differed in information type.

Only accelerometer energy measures are reported at this point as the analysis on gyroscope data energies correlated strongly with the accelerometer data and thus provided no additional insight.

Mean gesture durations for the 10 scenarios are shown in Fig. 4. The differences between scenarios are fairly small as the longest mean duration measured was 3.9 s (scenario 10) and the shortest 2.6 s (scenario 3). The mean gesture duration of all 10 scenarios was 3.4 s. The mean gesture duration for emotional scenarios was 3.5 and 3.2 s for informational scenarios.

5.3. Discussion of Experiment 2

The findings of the data analysis suggest that the participants were able to at least to some extent accommodate their gesturing and haptic messages to suit the given scenario. This was particularly noticeable in scenario 2 where the participants were asked to express happiness haptically. Fast shaking of the device to create powerful feedback was the most common gesture. Furthermore, we got results suggesting that the participants were able to use the spatial feedback aspect of the prototype for creating messages that utilized multiple actuators. In scenario 3 the participants were asked to communicate agreeing and in scenario 9 at least partial agreeing (signaling intention to call a friend soon without disturbing others). In these two scenarios the dominant direction of gesturing was forward and backward which could be considered as a metaphor for nodding. On the contrary, in scenario 10 where the participants were given the task to communicate displeasure the dominant directions of movement were left and right (i.e., shaking one's head to disagree). Additionally, there was some evidence that the energy used for gesturing was lower and the gesture durations shorter when expressing factual information. This suggests that binary information (i.e., yes or no) was fast to communicate and did not require as much gesturing as expressing emotional information.

In general, the feedback mapping from gestures to haptic feedback received acceptance from the participants. They commented that the idea of haptic communication was intriguing and something that could very well be utilized in real interpersonal communication. All of the participants comprehend the concept of composing haptic messages with physical movements as every participant figured out and created haptic messages in each scenario. Furthermore, the participants ideated various haptic messages that utilized the spatial aspect of the haptic actuators. The most common gestures were the metaphors for nodding and shaking for agreement and disagreement. These were accompanied with different intensity levels for example by making a short shaking movement to say that although the answer was negative, it was not definite (scenario 4). Another approach was to create three nodding gestures in a sequence to express definite agreement or happiness (scenario 2). The same gestures used for agreement and disagreement were created also in emotional scenarios. For example, the shaking movement from left to right was found to be fit also in scenario 7 for mimicking a smoothing movement from side to side to comfort the receiver. In addition, spatial gestures were used for example to signal the concept of time by creating a haptic sensation travelling clockwise between the four actuators. One participant also used the same circular movement to express agreement and a counter-clockwise movement to signal disagreement. The spatiality of the actuators was also used several times for communicating uncertainty by creating a haptic message containing a nodding (forward–backward) movement followed by a head shaking (left–right) movement. There were also attempts to draw figures (e.g., letter "x" or shape of a heart) using tilting gestures but the current resolution of the spatially aligned actuators was discovered to be insufficient for this purpose.

On the other hand, several participants noted that it would be challenging to create complex and yet understandable messages using the given prototype devices. The possibilities to compose versatile messages for expressing fine-grained emotions were limited due to the current feedback mapping. The participants desired more control of the feedback synthesis. For example, there was a need to control whether the haptic feedback created while gesturing was felt in the receiver's end. In the present feedback synthesis each movement was automatically felt on the feedback prototype but this could be easily changed using a button or key on the sending device to toggle the feedback synthesis on and off when necessary. Moreover, the range of different sensations that could be produced using the actuators was found to be relatively narrow. Some of the participants mentioned that they would have preferred more variety and sharpness to the feedback so that all the fine details in gestures could be felt more vividly. This might be partly due to the fact that we used frequency modulation to transfer different gesture intensities to haptic feedback. Whereas this is an intuitive approach to start with when representing physical movements using spatial haptics, it can also become restricting when the users get familiar with the concept. Different approaches to synthesize physical movements to the sense of touch should be investigated as the mapping used in this study may not necessarily be optimal (e.g., modulate amplitude instead of frequency or utilize also gyroscope data). However, because of the lack of previous work on this topic, we believe that relatively simple feedback synthesis was a reasonable choice when starting to explore how to combine sensor input and spatial haptic actuation for communication purposes.

6. Results: subjective ratings

In this section we present the subjective results of both experiments and comparison of the results between the experiments.

6.1. Experiment 1

Figs. 5–7 show the mean responses and standard error of the means (S.E.M.s) for the ratings of easiness, understandability, and reasonability.

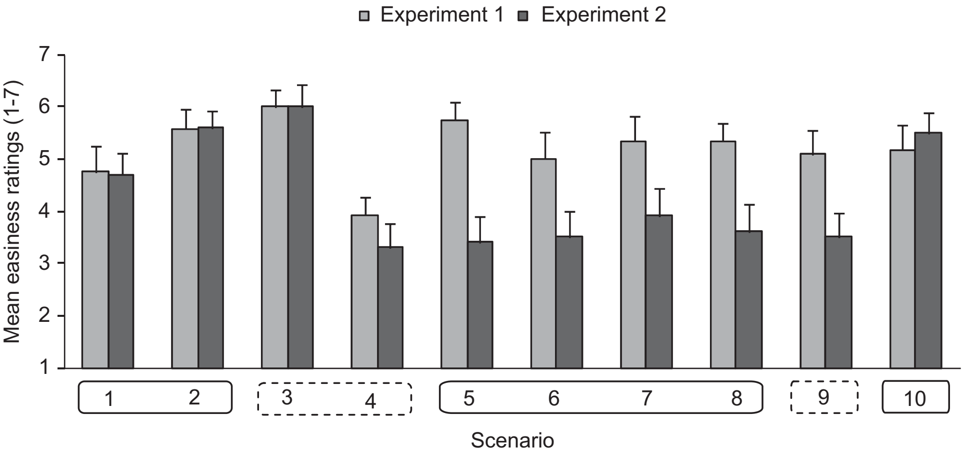

Fig. 5. Mean ratings and S.E.M.s for the easiness of the scenarios in Experiments 1 and 2. Scenarios 1, 2, 5–8, and 10 contain emotional information (solid rectangles) and scenarios 3, 4, and 9 factual information (broken rectangles).

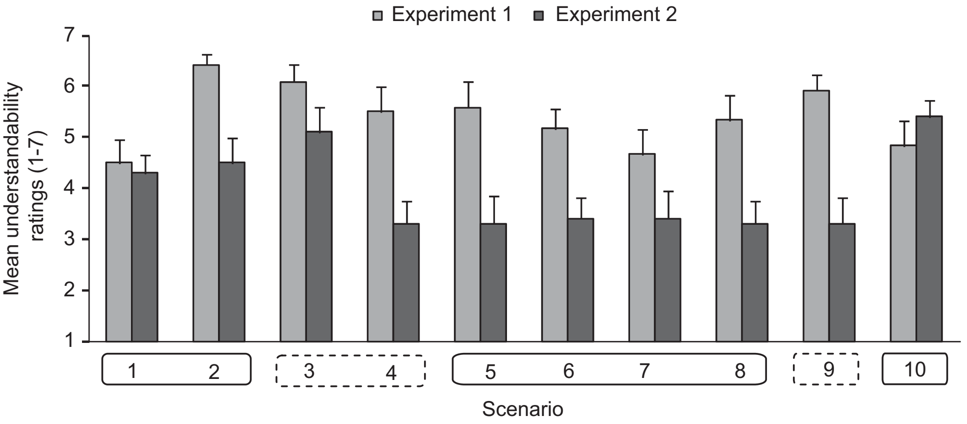

Fig. 6. Mean ratings and S.E.M.s for the understandability of the scenarios in Experiments 1 and 2. Scenarios 1, 2, 5–8, and 10 contain emotional information (solid rectangles) and scenarios 3, 4, and 9 factual information (broken rectangles).

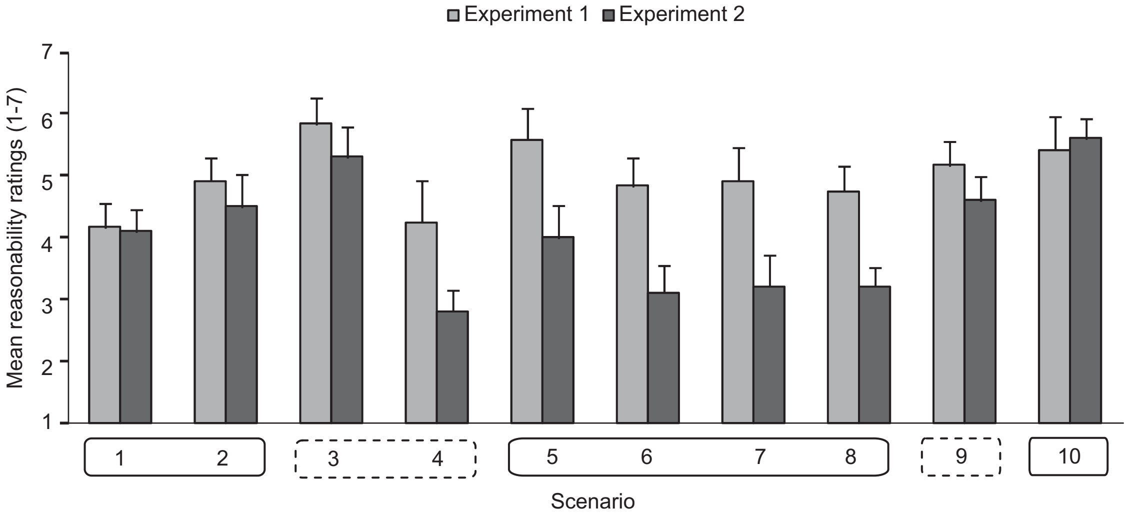

Fig. 7. Mean ratings and S.E.M.s for the reasonability of the scenarios in Experiments 1 and 2. Scenarios 1, 2, 5–8, and 10 contain emotional information (solid rectangles) and scenarios 3, 4, and 9 factual information (broken rectangles).

6.1.1. Easiness

For the ratings of easiness (Fig. 5), a one-way ANOVA showed a statistically significant effect of the scenarios $F(9,\ 99) = 2.1$, $p < 0.05$. Post hoc pairwise comparisons showed that the participants evaluated the scenario 3: "Agreeing to a friend's suggestion of a place for a casual meeting" as significantly easier than the scenario 4: "Agreeing to a meeting with friends, but postponing it by one hour" $MD = 2.1$, $p \leq 0.05$. Also the scenario 5: "Expressing longing to loved one over a distance" was evaluated as significantly easier when compared to the scenario 4 $MD = 1.8$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

6.1.2. Understandability

For the ratings of understandability (Fig. 6), a one-way ANOVA showed a statistically significant effect of the scenarios $F(9,\ 99) = 2.4$, $p < 0.05$. Post hoc pairwise comparisons showed that the participants evaluated the scenario 2: "Showing happiness to a friend after winning a surprise prize" as significantly more understandable than the scenario 7: "Comforting a friend whose old and beloved pet has passed away recently" $MD = 1.8$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

6.1.3. Reasonability

For the ratings of reasonability (Fig. 7), a one-way ANOVA did not reveal statistically significant effect of the scenario $F(9,\ 99) = 1.6$, $p = 0.17$. Post hoc pairwise comparisons did not show statistically significant differences between the scenarios either.

6.2. Experiment 2

Figs. 5–7 show the mean responses and S.E.M.s for the ratings of easiness, understandability, and reasonability.

6.2.1. Easiness

For the ratings of easiness (Fig. 5), a one-way ANOVA showed a statistically significant effect of the scenario $F(9,\ 81) = 5.0$, $p \leq 0.01$. Post hoc pairwise comparisons showed that the participants evaluated the scenario 2 as significantly easier than the scenario 4 $MD = 2.3$, $p \leq 0.001$. Also the scenario 3 was evaluated as significantly easier when compared to the scenario 4 $MD = 2.7$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

6.2.2. Understandability

For the ratings of understandability (Fig. 6), a one-way ANOVA showed a statistically significant effect of the scenario $F(9,\ 81) = 3.9$, $p < 0.05$. Post hoc pairwise comparisons showed that the participants evaluated the scenario 10: "Privately reminding your noisy friend to stay quiet during interesting lecture" as significantly more understandable than the scenario 6: "Encouraging and cheering a friend before important job interview"$MD = 2.0$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

6.2.3. Reasonability

For the ratings of reasonability (Fig. 7), a one-way ANOVA showed a statistically significant effect of the scenario $F(9,\ 81) = 5.3$, $p < 0.001$. Post hoc pairwise comparisons showed that the participants evaluated the scenario 3 as significantly more reasonable than the scenario 6 $MD = 2.2$, $p < 0.05$. In addition, the scenario 10 was evaluated as significantly more reasonable than the scenario 4 $MD = 2.8$, $p < 0.05$. The other pairwise comparisons were not statistically significant.

6.3. Between-group analysis

Nonparametric Mann–Whitney tests were used for statistical analysis between Experiments 1 and 2.

6.3.1. Easiness

Regarding the ratings of easiness (Fig. 5), a few statistical significances were found. Mann–Whitney tests showed that the participants of Experiment 1 evaluated scenarios 5, 6, 8, and 9 as significantly easier than the participants of Experiment 2 $Z = -3.04$, $p \leq 0.01$; $Z = -2.01$, $p < 0.05$; $Z = -2.35$, $p < 0.05$; and $Z = -2.04$, $p < 0.05$, respectively. Easiness ratings of the other scenarios did not differ statistically significantly between the experiments.

6.3.2. Understandability

For the ratings of understandability (Fig. 6), Mann–Whitney tests showed that the participants of Experiment 1 evaluated the scenarios 2, 4, 5, 6, 8, and 9 as significantly more understandable than the participants of Experiment 2 $Z = -3.29$, $p \leq 0.001$; $Z = -3.05$, $p < 0.01$; $Z = -2.67$, $p < 0.01$; $Z = -2.55$, $p < 0.05$; $Z = -2.97$, $p < 0.01$; and $Z = -3.30$, $p \leq 0.001$, respectively. Differences between the experiments in regard to the other scenarios were not statistically significant.

6.3.3. Reasonability

For the ratings of reasonability (Fig. 7), Mann–Whitney tests showed that the participants of Experiment 1 evaluated the scenarios 5, 6, 7, and 8 as significantly more understandable than the participants of Experiment 2 $Z = -2.03$, $p < 0.05$; $Z = -2.42$, $p < 0.05$; $Z = -2.18$, $p < 0.05$; and $Z = -2.56$, $p \leq 0.01$, respectively. Reasonability of the other scenarios did not differ statistically significantly between Experiments 1 and 2.

6.4. Discussion of the subjective ratings

When considering the easiness ratings from Experiment 1, scenarios 3 (agreeing) and 5 (longing) were the most positively rated (Fig. 5). The easiness ratings were relatively high also in scenario 2 (happiness). These three scenarios were quite straight-forward in a sense that their information content is common in everyday life and gestures are often used in face-to-face communication. The most difficult was scenario 4. The same results could be seen in easiness ratings of Experiment 2 where scenario 2 received significantly higher ratings than scenario 4. This was partly expected as the sense of touch is not customarily mapped to discrete symbolic information. Thus, the information content in scenario 4 was not straight-forward to communicate through the haptic modality. The fact that the between-group analysis of easiness ratings showed scenarios 5, 6 (cheering up), 8 (empathy), and 9 (call notice) to be significantly easier in Experiment 1 is an interesting finding. The prototype devices used in Experiment 2 were restricted in a sense that the mock-up did not recognize gestures such as smoothing or squeezing that could be used in Experiment 1 to compose more emotionally loaded messages. These results suggest that there should be alternative ways to give gesture input so that haptic messages could be formed differently depending on the informational content.

The understandability ratings in Experiment 1 were significantly higher in scenario 2 (happiness) compared to scenario 7 (comforting). This can be partly due to the fact that the gestures in scenario 2 were well noticeable because of the participant's enthusiasm and large movements. However, there might be a risk that fast movements can get confused with aggressive gestures in cases where there is no additional information available on the context of the message. In general, in the first experiment without a working prototype the participants were confident that their gestures will be easily understandable. The understandability ratings in Experiment 2 showed that scenario 10 (displeasure) was rated as significantly more understandable than scenario 6 (cheering up). Based on this, the current feedback prototype device seemed to be suitable for presenting very noticeable but yet understandable feedback. However, scenario 6 as well as scenarios 2, 4 (telling time), 5 (longing), and 9 (call notice) were rated significantly higher in terms of understandability in Experiment 1. On the basis of these results we can question whether gestures could always be detected and translated to haptic output as the participants would have desired. However, the high understandability ratings in Experiment 1 are encouraging in a sense that the participants saw the spatial haptic communication as a potential method for communicating assuming that suitable technology can be implemented.

Reasonability ratings of the different scenarios in Experiment 1 were generally lower than the easiness and understandability ratings (Fig. 6). The fact that there were no statistically significant differences in the ratings implies that the reason to use haptics as a communication modality was not dominantly dependent on the message to be conveyed. Instead, the ratings showed that participants did not overall consider the haptic modality as the best medium of communication. In the reasonability ratings of Experiment 2, scenarios 3 (agreeing) and 10 (displeasure) were considered to be significantly more reasonable contexts for haptic communication than scenarios 4 (telling time) and 6 (cheering up). The two most positively rated scenarios were scenarios where agreement and disagreement/negative information were central. These results show that the devices used in Experiment 2 were most suitable to be used in communicating binary information with explicit content. On the contrary, the messages in scenarios 4 and 6 were more abstract and emotional. Although the reasonability ratings in Experiment 1 were low compared to the other two scales, between-group analysis for reasonability showed a common trend; scenarios 5–8 were rated more significantly more reasonable in Experiment 1 than in Experiment 2. This is convergent with the other between-group analysis where ratings in Experiment 2 were generally lower than in Experiment 1. The tenth scenario (displeasure) was an exception as the ratings were higher in Experiment 2 regardless of the scale. Thus, the current functional prototype and the feedback mapping used can be considered to be a good fit for mediating attention grabbing information.

One could argue that the overall lower subjective ratings of Experiment 2 are partially due to the differences between the experiments; in Experiment 2 the output of the created message was simultaneously presented to the participants. In addition, only one type of feedback synthesis was used. On the contrary, in Experiment 1 the output was only imagined and could be mapped to other modalities as well. These overall differences suggest that the expectations the participants had for haptic communication in Experiment 1 were higher than the realized experience with the feedback prototype in Experiment 2. Furthermore, even though both experiments used the same mock-up, the device was equipped with motion sensors in Experiment 2. This changed the appearance and form of the device and thus might have had an effect on the gestures. The participants were also required to use both hands in Experiment 2 – one hand reserved for creating and the other hand for receiving gestures – while in Experiment 1 the participants were able to use one or both hands freely.

In the light of the insight gained through the analysis of the subjective ratings we can state that the idea about spatial haptic communication is promising, but not all of the scenarios were suitable or realistic for communication solely with haptics. Several participants would have liked to use other modalities such as audio and visual as well in the communication. Few participants would have preferred to use only alternative modalities. The main reason for the need of multimodal communication was that the non-haptic information could provide additional information on the communication context. We acknowledge that pure haptic communication is not suitable for all communication situations. However, on the basis of the subjective ratings we were able to identify communication tasks that were especially appropriate for spatial haptic communication (i.e., binary information) and tasks that may need supplementation in the future to make the communication more fluent (i.e., abstract information). The binary information task consisted of yes/no answer, which was liked because of the fast and easy response method haptic communication enables. However, this may also apply to other similar situations, where user has a limited number of options to choose from with a simple gesture based on direction, for example.

7. Conclusions and future research

The two experiments reported in this paper open new views on the ways we could communicate through spatial haptics. It can be expected that this additional method of communication would in most cases support the auditory and visual communication channels in selected communication acts. Overall, the first experiment showed that the best scenarios for haptic communication were those with comforting or affection – situations in which finding the right words can be hard or not necessary at all. Touching is also often present in such situations in real life. The results of the second experiment differed from those of Experiment 2 as transmitting binary information with limited reply choices, such as agreeing and disagreeing, was found to be especially suitable for remote haptic communication.

The scenarios were the same in both experiments, but the testing setups differed, providing information from two different angles to the same problem. While the first experiment did not set any particular restrictions for the gestures and interaction, the second experiment was limited by the current technological restrictions. No actual haptic feedback or interpretation experiments were present in the first study. This may lead to differing conceptions about the capabilities of present haptic technologies and the understandability of the messages, which were based on subjective evaluations. However, this approach was selected on purpose as it was believed to bring more ideas during the interviews and we did not want to restrict participants' innovation with the present technological constraints.

The subjective ratings in scenarios 4–9 were noticeably lower in Experiment 2. This implies that the functional prototype did not meet the users' expectations in the given scenarios in an optimal way. In these scenarios participants in Experiment 1 used mostly tapping, squeezing and smoothing, which were not available in Experiment 2. Also, the setup in second experiment offered only the tool strategy type of use. Ratings were similar in scenarios 1, 3 and 10 between the experiments. The haptic prototype, the interaction and feedback it provides more or less met users' expectations in these scenarios. The results suggest these are more suitable for haptic communication and could have potential for further development and research in the sense that they were rated coherently regardless of the contexts.

Many research questions remain open in spatial haptics and gestural interaction. Our future research concentrates on creating a more refined prototype with multiple actuators for communication purposes. Studies with communication between pair of users will be conducted in the future. Furthermore, we are interested in the user experience of the haptically enriched prototype and applications. Evaluating the overall experience is essential to understand how the design corresponds to the potential users' expectations and how the actual use of such an underutilized modality as part of communication will evolve. For example, how can the strategies, found in Experiment 1, be used with more advanced functional prototypes? In time the users will most probably learn the motor skills required for this new way of communication, and using it becomes more automatic – in a similar way as the playing skills of a musician. People might learn to create various nuances to the messages, as well as learn to understand them. After that, totally new research questions become relevant: e.g., how are attributes, such as speed, extent of trajectory, directions, number of repetitions and softness of touch used to vary the message? How much certain fundamental characteristics of gestures can be found in the messages created by various users? How do people create haptic messages consisting of multiple parts, i.e., gestures? Also, further research on users' interpretation of unimodal and multimodal messages is central for understanding the process of haptic communication.

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