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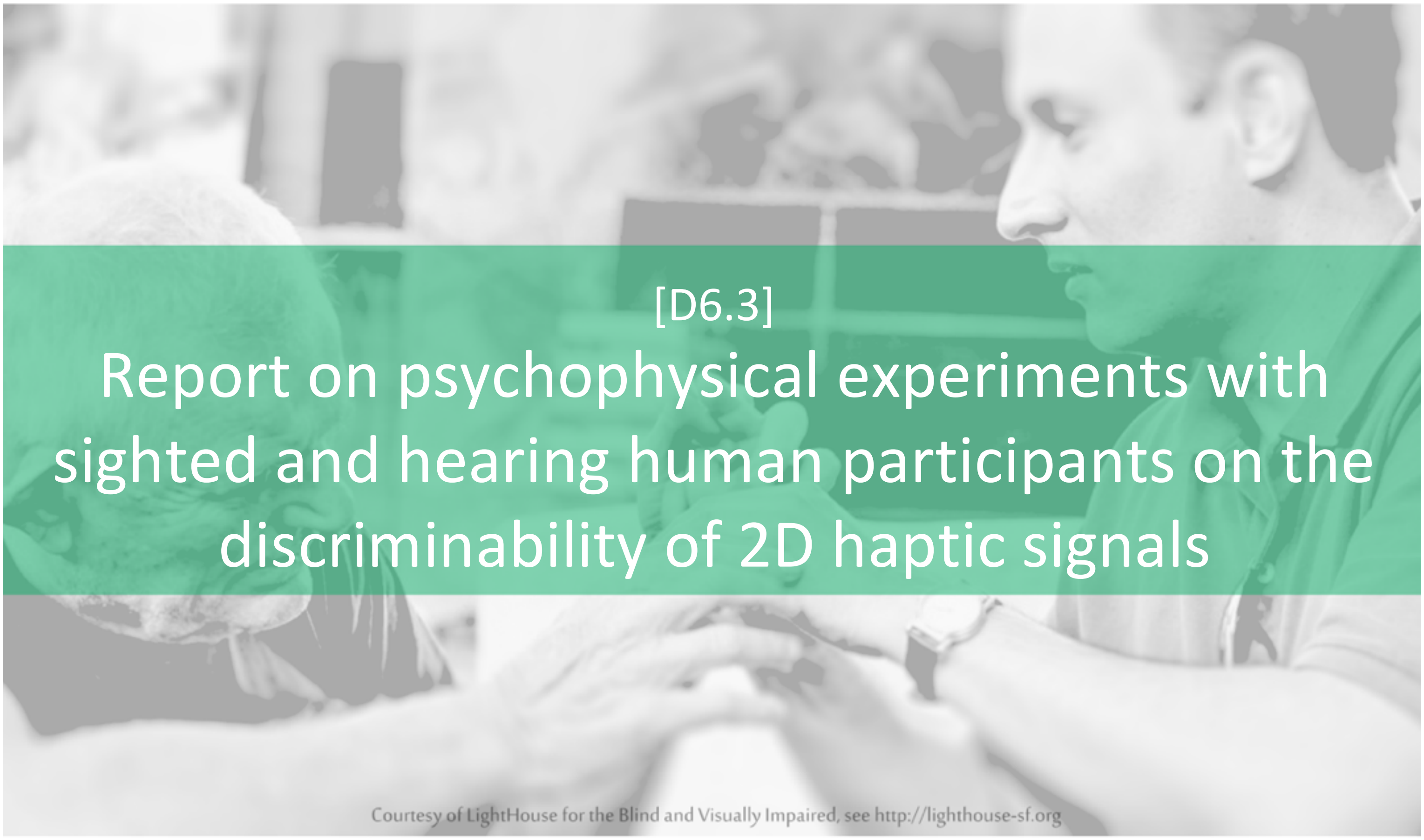
SUITCEYES

1 Jan 2018 - 31 Dec 2020

Smart, User-friendly, Interactive, Tactual, Cognition-Enhancer, that Yields Extended Sensosphere
Appropriating sensor technologies, machine learning, gamification and smart haptic interfaces



[D6.3]

Report on psychophysical experiments with sighted and hearing human participants on the discriminability of 2D haptic signals

Courtesy of LightHouse for the Blind and Visually Impaired, see http://lighthouse-sf.org

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Dissemination level		
PU	PUBLIC, fully open, e.g. web	X
CO	CONFIDENTIAL, restricted under conditions set out in Model Grant Agreement	
CI	CLASSIFIED, information as referred to in Commission Decision 2001/844/EC.	

Deliverable Type		
R	Document, report (excluding the periodic and final reports)	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

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HB	Checkerboard vest development	Nils-Krister Persson, Li Guo & Eva Lindell

Glossary	
Abbr./ Acronym	**Meaning**

Table of contents

Executive Summary

WP6 focuses on identifying the information needed for exemplar navigation tasks, and proposing and testing haptic signals to convey this. These serve as input for a larger scale psychophysical study on how well various stimulations can be discriminated by sighted and hearing human participants and what would be the best location for stimulation. In the second year we focussed on haptic stimuli in two dimensions: Temporal and spatial. Following the advice of the project reviewers we have no longer tested thermal stimulation and focussed on vibrotactile stimulation only. A prototype vest was designed in Borås specifically for psychophysical testing (WP5). This vest allows presenting arrays of vibration motors to the back of a participant while allowing for flexible placements of the motors. In this deliverable we have focussed on providing psychophysical input that is necessary for setting up tactile communication in the HIPI. To this end we have assembled a literature overview on tactual languages. We have investigated whether using tactile Morse code would be a suitable mode of communication. Furthermore, we have tested how performing a secondary distractor task influences perception of series of vibration pulses delivered to different body locations. We have also started experiments with the prototype vest developed in WP5 especially for psychophysical testing. We have measured propagation of vibration through this prototype vest in combination with a pilot test on how well participants can localise the vibrations on the back. This study will be followed-up in the next year with tests in which different types of damping materials (to be developed in Borås as part of WP5) will be added and evaluated. Finally, we have begun the process of translating social haptic signals, normally delivered by another person, into vibration patterns. This will be continued in the next year in collaboration with WP3 in which the ontology is designed. In the studies that are part of this deliverable we used a maximum of 9 vibration motors. The latest version of the controller can control up to 18 vibration motors and was developed in Leeds (WP5). With this new controller we can increase the number of motors used in the psychophysical tests in the next year.

Devices for Hands-free Tactual Communication

Background

One of the major goals of the SUITCEYES project is to develop a prototype device suitable for communication via touch. The purpose of such a so-called HIPI (haptic intelligent, personalised, interface) is, among others, to "extend and improve user's modes of communication via a haptic language". In the past, there have been many attempts at conveying speech and/or language by means of tactual stimulation with a device. It is therefore essential for all partners working towards this goal, to have a more or less complete overview of previous studies. As hands, fingers and face are the most sensitive body parts for tactual stimulation, many previous studies designed and tested devices meant for use with the hands or fingers. However, early in the SUITCEYES project, the decision was made to focus on hands-free applications, as individuals with deafblindness will often need their hands for other tasks. Therefore, the extensive literature overview that can be found in Annex 1, will only present hands-free devices for tactual communication.

The overview currently consists of a series of tables that focus on the tactual communication of phonemes (Annex 1- table 1), letters and digits (Annex 1- table 2), words (Annex 1- tables 3 and 4), and images and symbols (Annex 1- table 5).

Results

The studies presented in this overview are all published in peer-reviewed scientific journals or as paper in conference proceedings. All references of the included papers are checked for further relevant studies. In addition, papers that cite the included studies have also been checked for relevance. We only included papers that report on user studies, so that excludes papers that only present or analyse a device. Some papers report on several experiments, but we present here only the most relevant ones for the present purpose. We omitted, for example, experiments that studied the combination of a tactile device and lip reading or auditory information. Also devices specifically designed for navigation purposes are not included, as these focus on specific commands like "go to the right", "go straightforward", etc. However, it should be noted that there exists an extensive literature on haptic navigation devices using belts or vests.

A detailed analysis of these studies still has to be made, but the major findings are the following:

- Especially the earlier studies tested vocoders [1-6, 20-23]. These are devices that analyse the speech signal, usually by decomposing the speech signal into different frequency bands. Subsequently, this information is conveyed by means of a varying number of vibrators (ranging from 2 to up to 144) on usually the forearm of a participant. It seems that the success rates of these studies are rather limited, especially given the enormous number of hours needed for training and testing (see Annex 1- tables 1 and 3). One recent study, using only 2 vibrators, seems to be a successful exception [23].
- More recent attempts using somewhat arbitrary conversions from the speech signal to vibration patterns on the forearm seem promising [7, 27-28, 30-33] (see Annex 1- tables 1 and 4).

- There are several small studies that tested vibration patterns in the shape of letters or digits to the back or the wrist (see Annex 1- table 2). Even with a relatively small number of vibrators (around 9) and limited training durations, recognition rates of 70% and higher are reached [11, 16, 18, 19]. Especially the studies that base their patterns on handwriting seem quite successful.
- There are a few studies that tried to project visual images by means of a large number of vibrators (64-400) stimulating the back or the thigh [34, 36-37] (see Annex 1- table 5). Even with such high numbers of vibrators and many hours of training, success was limited.
- Several studies showed that dynamic patterns are easier to recognize than static patterns [9-10, 13, 17, 38, 42]
- Several studies show that vibration patterns can be learned or recognized [13, 38-40, 42-44] (see Annex 1- table 5). However, it should be noted that the number of different patterns was always very small (up to maximal 12).

Conclusions

Taking all these studies together, the conclusion seems justified that best successes were obtained with relatively small numbers of vibrators on the back, or with a sleeve with up to 64 vibrators on the forearm. It is clearly possible to recognize vibratory letters on the back, and even to recognize words composed of such letters. The advantage of using letters is that most participants were already familiar with the pattern (i.e. the letter) itself. Learning arbitrary patterns was also possible, but it still remains to be seen what the limits are in terms of set size (as mentioned above, 12 was the maximum tested in the literature).

Most of the studies tested blindfolded sighted persons. Only a few studies worked with blind or deaf individuals. Therefore, the relevance of these findings for the SUITCEYES target population, namely individuals with deafblindness, remains to be seen. However, it seems a safe hypothesis that their success rates will be similar or higher, especially for the individuals who are familiar with written letters. From the interviews performed in WP2 it became clear that these persons are interested to use devices that make their life easier, but also that even learning to use relatively simple devices will cost them a lot of energy. Therefore, it needs to be clear upfront that investing many hours of training to learn to use a new device or learn a new language, will be of great value for them. That is a challenge we have to keep in mind when developing the next generation of prototypes.

Output

The information in these tables has been made available to other partners in the SUITCEYES project (especially partners in WP3), but it will also be the basis for a survey paper.

Learning tactile Morse code

Background

There exist a multitude of tactual languages. Some of these are more commonly used by persons with deafblindness than others. However, the most commonly used ones like Braille, tactile sign language and fingerspelling are not hands-free. This makes these languages difficult to use in situations where the hands are occupied otherwise. In the literature overview discussed in the previous section, tactual languages that are not displayed on the hands are discussed. One of these is tactile Morse code. Tactile Morse code has as advantage that it is technically very easy to display as tactile Morse can be presented as a series of vibration pulses. Morse code is not a language that is currently commonly used by individuals with deafblindness. So this would require them to learn a new language. Therefore, we set out to get an insight into how difficult this would be.

From literature it is known that tactile Morse code can certainly be learned. However, most studies focus on the technical implementation of Morse code and not on learning Morse code. The studies that do focus on learning either had participants already familiar with auditory Morse code or gave participants a visual representation of the Morse code alphabet (Tan, Durlach, Rabinowitz, Reed, & Santos, 1997; Walker & Reed, 2018). Of course, this is not practical for persons with deafblindness. One case study with a deafblind user concluded that learning the tactile Morse code alphabet was the most difficult part of learning to use an interface they made for sending SMS messages (Arato, Markus, & Juhasz, 2014). In that study they gave the user an embossed representation of the Morse code with a Braille representation. The application, however, used the vibration motor in the phone to display Morse code. This was quite different from the embossed representation that was used for learning. It took a couple of weeks to be able to use the interface. But after a couple of weeks of familiarization the user indicated to really like the interface.

We conducted an experimental study to investigate how quickly the Morse code alphabet can be learned if participants are only presented with the tactile Morse code. We developed a protocol for learning the alphabet and tested how well participants could identify words after completing the learning protocol.

Psychophysical study

We performed an experimental study on learning tactile Morse code. Based on results known from literature we opted to presented dashes with a vibration motor on the left forearm and dots with a vibration motor on the right arm (Walker & Reed, 2018). None of the participants had prior experience with using Morse code and they were never shown a visual representation of the code.

They started by learning the Morse code alphabet tactually. They felt the first three letters of the haptic Morse code alphabet and the experimenter verbally indicated which letter it was. After having felt the first three letters, these letters were repeated 2 times in random order or until they had identified each letter correctly. After that they proceeded to learn the next 3 letters. After each 6 letters they performed a repetition block in which all letters they had learned up until that point were repeated in random order. For further details see Annex 2. This learning session always lasted 30 minutes and not all participants learned the same number of letters. All participants learned at least 18 letters. This indicates that they could learn the tactile Morse code quickly. After the learning session they were presented with words consisting of only the letters they had learned within the 30 minutes. Words varied in length (2, 3, 4, or 5 letters).

The results showed that participants were able to correctly recognize words, but that the correct rate decreased rapidly with word length (from 75% for 2 letter words to below 20% for 5 letter words). In previous studies, participants were sometimes allowed to write down the code as they received it (e.g. Tan et al., 1997), but that was not allowed here. So participants had to keep the whole sequence in memory. Moreover, there was no training session for words. They only trained letters. So word recognition can likely be improved with some more training.

A full description of the experimental setup and the results can be found in Annex 2.

Conclusion

Overall, these results are very promising. They show that tactile Morse code alphabet can be quickly learned without every being shown a visual representation of the alphabet. Even without any training in recognizing words, participants were able to correctly recognize short words.

Output

This study has been submitted to an international peer-reviewed journal. A draft is attached in Annex 2.

References

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The effect of performing a dual task on numerosity perception

Background

Vibration pulses are an easy way to convey information to the user. Vibration pulses were used in the previous section for displaying tactile Morse code. In previous Deliverable D6.2, we used vibration pulses to convey numerosity information. In both cases we found that vibration pulses can indeed be an effective way to communicate with the user. However, in both studies participants were completely focused on the task. Realistically, the user (or HIPI wearer) would possibly be doing some kind of activity while a message is being transferred. It is has been shown that performing a dual task can make it more difficult to perceive tactile input, for instance during navigation (Dim & Ren, 2017). Also, we aim to include multiple actuators at different body locations in the HIPI. The possibility that a message might be delivered to varying body locations might impact perceptual performance.

Previous studies have found effects of performing a dual task on haptic perception (Dim & Ren, 2017; Karuei et al., 2011; Wilson, Halvey, Brewster, & Hughes, 2011). In those studies, the dual task of the participants consisted of walking around. This is a quite demanding task and we wanted to test this for a task where the participant is sitting and the cognitive load is mild. Moreover, the performance measure in those studies was detection rate and/or response time while we would like to know how a dual task impacts the ability to perceive a number of vibration pulses.

To test if perception of the number of presented vibration pulses is significantly affected when a dual task is performed, we designed a psychophysical study. In this study varying numbers of vibration pulses could be delivered to one of 4 vibration motors. As a dual task we asked participants to sort beads by color. This task involved both moderate cognitive effort as well as motor skill.

Psychophysical experiment

Participants

Ten students (4 males, 6 females, age range: 21 -23) from Eindhoven University of Technology participated in the experiment. The data of two participants were excluded from the analysis because the experiment had to be terminated due to technical difficulties. The participants were compensated to participate in the experiment and signed an informed consent form. This study was approved by the ethical committee of the Human Technology Interaction group of Eindhoven University of Technology.

Experimental set-up and procedure

A vibration motor (Adafruit mini motor disk, 10mm diameter) was taped to the forearm and upper arm of the dominant hand, to the ankle and the lower back. Sequences of varying numbers of vibration pulses (4, 5, 6, 7 or 8) were presented to one of these body locations in a blocked randomized order meaning that each numerosity and each location was presented in randomised order. This ensured that all trial types were distributed evenly. Participants were asked to respond the number of vibration pulses they had felt. During a pulse a vibration motor was switched on for 80 ms, then a break followed by switching the motor off for 80 ms. They performed the two conditions in two experimental sessions: one with a dual task and one without. The order of the conditions was counter-balanced over participants. Each condition consisted of 60 trials.

In the block with a dual task participants were asked to sort beads by color as quickly as possible using their dominant hand.

Results

The absolute numerical error was calculated as the difference between the presented numerosity and the participants' responses. Figure 1A shows the results collapsed over numerosity and body location. It can be seen that the absolute error appears to be larger when participants were sorting beads compared to when they were not. This was confirmed with a paired samples t-test showing significant difference ($t(7)=-4,9$, $p=0.002$).

Figure 1B shows the absolute error by body location. No obvious differences are visible. A one-way ANOVA confirmed that there was no effect of body location ($F(3,28) = 0.6$, $p=0.6$).

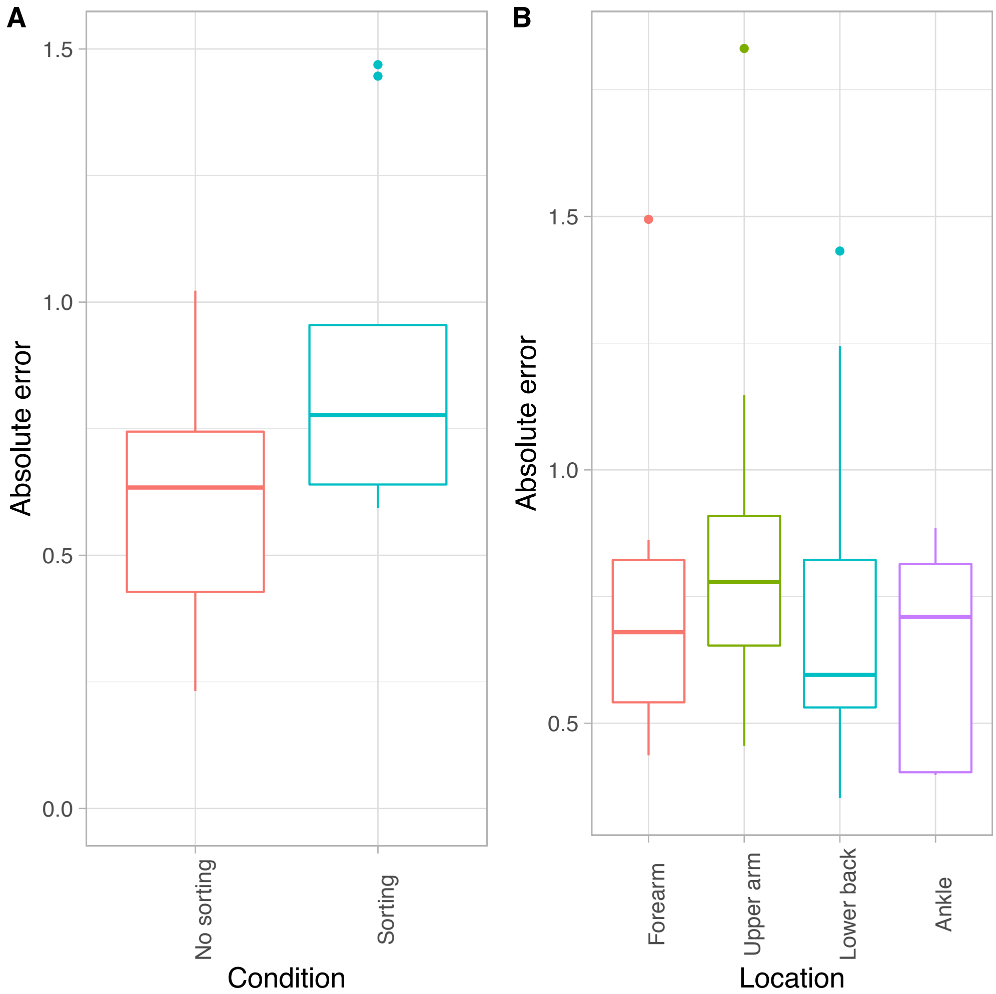

Figure 1: Boxplots of the results of numerosity judgment with a dual task. A) Numerical error with and without dual task. B) Numerical error per body location. The line indicates the median across participants, the boxes indicate the 25% to 75% intervals and whiskers indicate the 25% and 75% intervals minus or plus 1.5 times the inter-quartile range. The individual dots indicate extreme values.

Conclusions

Our results did not show an effect of body location. Possibly there is an effect of location that we failed to detect with this sample size, but such an effect would thus be rather small. Although there is quite some variation in tactile sensitivity over the body location we tested here, it is not surprising we didn't find an effect. The vibration pulses were strong enough to be clearly perceivable in all four locations.

There was, however, an effect of dual task. When participants were sorting beads the absolute error increased. This indicates that performing a dual task such as the one we used here has an impact on the ability to correctly detect the number of vibration pulses. The difference was, however, rather small and they never failed to detect the stimulus completely. This means that sequences of vibration pulses can also be used to convey information in a situation when the user is also attending to something else. It would, however, be advisable to first give a warning signal alerting the user to the fact that a sequence will be displayed.

Output

The results of this study will be communicated to other members of the consortium, especially those involved in WP 3 (tactual language). We plan to submit this study for publication in conference proceedings.

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Characterisation of vibration localisation in a textile prototype

Background

A more detailed description of this pilot can be found in Annex 3.

In WP5, a vest is created especially for doing psychophysical experiments. During the recent review meeting, but also earlier in various Skype meetings, a few questions came up. Among others, these were how well users are able to localise vibration stimuli on their back, and how local the vibration stimulation actually is. In order to provide answers to these questions, a pilot experiment was performed at Eindhoven University of Technology in collaboration with members from the University of Leeds. The already mentioned vest was made by Hoegskolan I Borås. The eventual goal of the experiments was to gain insights into how a full experiment should be designed.

Two types of experiments were performed: psychophysical localisation experiments and an experiment with accelerometer measurements. In both experiments, the same 5 non-naïve persons (2 were authors of this deliverable) participated while wearing the vest. In the localisation experiment, 9 vibration motors were placed in a 3 by 3 grid on their back. Participants had to indicate on a picture of the vest worn by a mannequin at which location they thought a vibrator was active. In the accelerometer experiments, the participants just had a passive role. While they were sitting and wearing the vest, one of the vibration motors was vibrating and at several horizontal and vertical distances the amplitude and frequency were measured by means of an accelerometer.

Results

The localisation experiment showed that overall the locations indicated by the participants were higher on the back than the location of the actual active motor. This was especially surprising and relevant since all the participants knew the lay-out of the grid. Less surprising was that stimulation from motors located on the spine were indeed localised as lying on the spine. Overall, the confidence ellipses fitted through the data points indicate that participants are quite consistent in their assessments of location.

The accelerometer experiments showed that although there is a gradual decline of intensity with distance from the active motor, vibration motor activity cannot be considered as very local. Moreover, the measured frequency differed substantially for the different measured locations. This could either be due to difference between the motors, differences between the tightness with which the motor was attached to the back, or differences due to body location.

Conclusions

These pilot experiments gave useful insights for the design of a full experiment. It will be essential to do these experiments with naïve observers. Of course, we knew that in advance, but for practical reasons that was not possible during these few days of piloting. It will also be necessary to make sure that the vest is fitted in a way that is consistent over all participants and also the means of responding the location should be improved.

Translating social haptic communication signals into vibration patterns

Background

A more detailed description of this pilot can be found in Annex 4.

As one of the outcomes from the interviews conducted in WP2, it became apparent that many of the interviewees would love to have better means of communication. Many of them commented also that even if they could hear what a speaker said (by means of cochlear implants or via an interpreter), they miss a lot of what is going on around them. There exists a form of communication that conveys exactly this type of environmental information, the so-called social haptic communication [1-3]. One aim of the current project is to try to convey such social haptic signals by means of vibratory patterns on the back. A grid of 3 x 3 vibration motors is placed in the checkerboard vest designed and created in WP5. Recently, we translated a set of 8 social haptic signals from the Dutch Handbook [3] into vibratory patterns. Below we present the first informal observations.

Results

After some piloting and optimising, we ourselves were able to recognize the 8 different vibratory patterns and link them to the original social haptic signals. Subsequently, we tested these patterns on three naïve colleagues, who were asked to draw the pattern the felt. The patterns they drew were mostly reasonably close to the actual patterns. Interestingly, there seem to be some systematic deviations. Two persons with deafblindness were also able to recognize the patterns.

Conclusions and future plans

Based on these informal pilot experiments, we conclude that it will be worthwhile to pursue this research direction in the near future. We aim at both fundamental psychophysical experiments, investigating the apparent deformations, and at developing a more extended set of vibration patterns relevant for social haptic communication. For this latter aim we sought collaboration with a Dutch workgroup that is trying to standardize the social haptic signals.

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Update on output of previous WP6 deliverables

Accepted for publication and published online:

A. M. L. Kappers and M. A. Plaisier, "Thermal Perception and Thermal Devices used on Body Parts other than Hand or Face," in IEEE Transactions on Haptics. doi: 10.1109/TOH.2019.2925339

Accepted for presentation as Work in Progress at World Haptics Conference 2019, July 2019, Tokyo, Japan, and finalist of the best Work in Progress Award:

Numerosity perception of temporally grouped vibration pulses

Myrthe Plaisier, Raymond John Holt, Astrid Kappers

Submitted for publication in International Journal:

Representing numerosity through vibration patterns

Myrthe A. Plaisier, Raymond J. Holt and Astrid M.L. Kappers

Annex 1

Devices for Hands-free Tactual Communication

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TABLE 1
Tactual phonemes

Reference	Location	Participants	Stimuli & Training	Task	Outcome
Clements et al. (1988) [1]	thigh	(1f, 1m)	- 144 vibrators (12 × 12) - 2 methods to represent phonemes based on speech signal - 20 hours training	discriminate syllables (2AFC)	percentage correct: - consonants (73), vowels (84) - spectral method (79), area function method (76)
Weisenberger et al. (1989) [2]	forearm, abdomen	17–23 (1f, 2m)	- array of 16 vibrators with input from different frequency channels - vibration patterns representing word pairs differing in 1 phoneme - more than 25 hours testing	discriminate (2AFC) or identify (8, 21AFC) vowels or consonants in word context	- no difference in accuracy between body sites or between articulatory features - 2AFC: above 50% correct - 8AFC of vowels: 61% correct - 21AFC of initial consonants: 52% correct
Weisenberger et al. (1991) [3]	forearm	20–27 (6f)	- 30 vibrators (6 × 5) with input from a PCA of the speech signal - 3 participants with almost a year of daily training	identify consonant	- trained participants: 38%, 39%, 23% correct with sets of 9, 10, 19 consonants - hardly trained participants: 24%, 23%, 12% correct with sets of 9, 10, 19 consonants
Weisenberger & Percy (1995) [4]	forearm	21–26 (6)	7 vibrators with input from different frequency channels together representing 1st and 2nd formants	discriminate or identify consonants and vowels in varying contexts	- vowel context has significant influence on performance - detailed confusion matrices for different contexts
Galvin et al. (1999) [5]	wrist (c1), sternum or abdomen (c2)	30–77 (8h)	- 2 (c1) or 7 (c2) vibrators conveying frequency and amplitude information from the speech signal - word pairs differing in 1 phoneme	identify stimulus (2AFC)	- performance slightly better with 2 vibrators (c1) - performance not the same for all phoneme contrasts
Wong et al. (2010) [6]	forearm	- 19–27 (2f, 6m) - 18–33 (2f, 2m)	- 5 or 10 equally spaced tactors - 6 equally spaced tactors representing articulation patterns	- identification (5AFC) - rate distance from elbow (scale 0–100) - discriminate 12 consonant pairs (12AFC)	- 81% correct location identification - linear relationship beteen physical and perceived distance - speech-to-touch method adequate for distinction of place of articulation - method works especially well for fricatives and affricates
Reed et al. (2019) [7]	forearm	19–32 (7f, 3m)	- 24 tactors (4 × 6) - 39 English phonemes represented by different activation patterns - 50–230 minutes training	identify phoneme	- mean recognition rate of 86% correct

For participants age range is given in years (if known) and between brackets the number of participants (f females, m males, h hearing-impaired). When not mentioned, participants were sighted. xAFC stands for alternatives–forced choice and the number x in front of it indicates the number of alternatives. PCA stands for principal components analysis. cy stand for condition y, where y is the number of the condition.

TABLE 2
Tactual letters and digits

Reference	Location	Participants	Stimuli & Training	Task	Outcome
Craig (1973) [8]	back	- (4) - (6) - (5)	- 100 vibrators (10 × 10) - 6 (9, 26) vibration patterns representing pictorial or abstract letters - 10 minutes warm-up - active pattern exploration	identify 6 (9, 26) letters	- hardly any decrement for abstract patterns - good transfer between pictorial and abstract modes - confusion matrices similar for the 2 modes
Loomis (1974) [9]	back	20–35 (2f, 5m; 3b, 4s)	- 400 tactors (20 × 20) embedded in chair - 26 block letters patterns - 5 modes of presentation: static/dynamic letter/slit vertical/diagonal slit - blind participants: 100 hours training	identify letter	- individual performances quite different - percentage correct: static letters (34), static vertical slit, moving letters (51)
Saida et al. (1982) [10]	abdomen	30–36 (4b, 4s)	- 100 vibrators (10 × 10) - 46 Katakana characters - 3 modes of presentation: static, moving, tracing	identify Katakana characters	- percentage correct: static (27), moving (39), tracing (95) - no difference between performance of blind and sighted participants
Yanagida et al. (2004) [11]	back	22–39 (2f, 8m)	- 9 tactors (3 × 3) embedded in chair - vibration patterns representing 26 letters & 10 digits	identify letter and/or digit	- percentage correct: digits (88), letters (87), mixed (86) - use of stroke-related information is promising
Kim et al. (2006) [12]	foot	26–31 (10m)	- 25 vibrators (5 × 5) - 2 modes of sequential stimulation: single motor or pair of motors	identify letter	percentage correct (without/with) training: - single motor (32, 60) - two simultaneous motors (68, 87)
Wu et al. (2012) [13]	back	25–30 (15)	- 48 vibrators (8 × 6) - 10 letters - 3 modes of presentation: scanning, handwriting, tracing	identify letter	percentage correct: - scanning (48) - handwriting (78) - tracing (82)
Arnold & Auvray (2014) [14]	belly, shin, thigh	18–47 (26f, 19m)	- 9 vibrators (3 × 3) - 8 vibration patterns representing drawing letters	identify letter (8AFC)	- significant improvement over sessions - training of one body site transfers to other sites
Cunha & Nohama (2015) [15]	abdomen	(13)	- patterns of gas jets representing 19 letters and 3 geometric figures - 30 minutes training	identify 11 letters	- accuracy depends on “plotting” speed (highest: 68% with 40 mm/s)
Liao et al. (2016) [16]	wrist	- 20–25 (8f, 4m) - 21–29 (13f, 11m)	- 4 (2 × 2) or 9 (3 × 3) tactors - vibration patterns representing 26 letters & 10 digits	identify alphanumeric characters	- identification accuracy (2 × 2): 79%, (3 × 3): 71% - accuracy: letters: 71%, digits: 78.5%
Schätzle et al. (2017) [17]	wrist	- 22–34 (1f, 3m) - 16–48 (7f, 11m)	- 6 vibrators in linear array representing Braille characters - 8 or 3 mapping methods - few trials training	- draw Braille character	- better performance with sequential methods - better performance with 2-dot than with more than 2 dots Braille characters - best performance if unraised dots are also represented (97% correct)
Janidarmian et al. (2018, 2019) [18], [19]	back	18–46 (5f, 5m)	- 9 vibrators (3 × 3) - vibration patterns representing 26 letters & 10 digits - standard or personalized - training: 108 trials	identify alphanumeric characters	percentage correct: - standard pattern (71), - personalized pattern (87)

For participants age range is given in years (if known) and between brackets the number of participants (f females, m males, b blind, s sighted). When not mentioned, participants were sighted and hearing. 8AFC stands for 8 alternatives–forced choice.

TABLE 3
Tactual words - stimulation based on speech signal characteristics

Reference	Location	Participants	Stimuli & Training	Task	Outcome
Brooks & Frost (1983) [20]	forearm	(2f)	- tactile vocoder - 16 spectral filter channels activating 16 solenoids coding spoken language - 40–55 hours training in sessions of 20 minutes	learn words	- participant 1: 70 words in 81 sessions - participant 2: 150 words in 110 sessions - rapid transfer to words spoken by other person
Brooks & Frost (1985) [21]	forearm	(1f) participant 2 of [20]	- tactile vocoder - 16 spectral filter channels activating 16 solenoids coding spoken language - 26 hours training in sessions of 20 minutes	learn additional 100 words	- 26 hours needed to learn the 100 additional words - learning rate 3.9 words/hour
Lynch et al. (1988) [22]	abdomen	20, 32 (1fd, 1md)	- array of 16 electrodes representing different frequency bands - more than 41 hours training on 50 words	recognize word	overall 42% correct of 11,324 trials
Fontana-de-Vargas et al. (2019) [23]	forearm	22–43 (6f, 8m)	- 2 vibrators - patterns resembling 24 English phonemes - 100 minutes training	- recognize words - multiple choice (50 words)/open test	accuracy: - multiple choice: words 94.4% - open test: words 45%; phonemes 68%

For participants age range is given in years and between brackets the number of participants (f females, m males); d indicates deaf participants.

TABLE 4
Tactual words - arbitrary conversion from speech to language

Reference	Location	Participants	Stimuli & Training	Task	Outcome
Velásquez et al. (2011) [24]	foot	19–23 (6m, 14m)	- 4 (1–2–1) vibrators - 5 temporal patterns representing words	recognize word (5AFC)	overall 75% correct
Velásquez & Pissaloux (2014, 2018) [25], [26]	foot	18–24 (4f, 16m)	- 4 (1–2–1) vibrators - 4 temporal patterns representing words	- recognize word (4AFC) or 2,3,4-word sequence	average recognition performance of sequences: 1 word 84%, 2 words 77%, 3 words 77%, 4 words 66%
Dunkelberger et al. (2018) [27]	upper arm	19–30 (6f, 4m)	- vibrotactor band, radial squeeze band, haptic rocker - patterns representing 23 English phonemes - 100 minutes training	- recognize words - multiple choice (50 words)	accuracy: word recognition 86.6%
Zhao et al. (2018) [28]	forearm	20–50 (4f, 5m)	- 6 voice-coil actuators - layout similar to Braille - various training protocols	- learn 9 phonemes - learn 20 2- and 3-phoneme words	- in 26 minutes 9 phonemes and 20 words can be learned - recognition faster if trained on words instead of phonemes
Walker & Reed (2018) [29]	forearm	20–30 (2f, 6m)	- 12 unimanual/bimanual morse vibration patterns - dash duration equal/ unequal to dot duration	identify sets of 3 morse characters	- fewer errors with bimanual presentation - no significant influence of dash duration
Turcott et al. (2018) [30]	forearm(s), upper arm(s)	- 24–54 (2f, 8m) - 22-44 (4f, 12m)	- 2 or 4 displays of 8 vibrators (8 in a row, or 4 × 2) - 4 algorithms to convert language to vibration patterns representing 18 pairs of words	- decide whether words were same or different - play a word learning game	- discrimination sensitivity was better for algorithms using Frequency Decomposition and Dominant Spectral Peaks (DSP) than for Autoencoder - in game learning the Phonemic algorithm yielded better scores than DSP
Chen et al. (2018) [31]	arm	21–43 (6f, 13m)	- 3 displays of 8 (4 × 2) vibrators - patterns representing 13 phonemes used to form 100 1–3-phoneme words - 2 learning methods - 65 minutes training	type the word	- performance better with guided learning than with self-guided learning - percentage correct: guided learning 86, self-guided learning 72
Jung et al. (2019) [32]	forearm	20–30 (4)	- 24 tactors (4 × 6) - patterns representing 10 phonemes used to form 51 2–3-phoneme words - 60 minutes training/testing	- identify phoneme and/or word	near perfect performance for phonemes and words
Jiao et al. (2018) [33]	forearm	- 18–26 (6f, 6m) - 19–39 (6f, 6m)	- 24 tactors (4 × 6) - patterns representing 39 phonemes used to form 100 1–3-phoneme words - 2 learning methods - 100 minutes training/testing	identify phoneme and/or word	- learning method: phoneme-based gives better results than word-based - large differences between participants - 8 of 24 participants learned 80 words in 100 minutes
Janidarmian et al. (2019) [19]	back	(10)	- 9 vibrators (3 × 3) - vibration patterns representing 20 2–4 letter verbs - no training	recognize word	percentage correct: 91

For participants age range is given in years and between brackets the number of participants (f females, m males). xAFC stands for x alternatives–forced choice, where x is the number of alternatives.

TABLE 5
Tactual images and symbols

Reference	Location	Participants	Stimuli	Task	Outcome
Bach-y-Rita et al. (1969) [34]	back	(6) blind	- 20 × 20 solenoids - image projection - over 20 hours training	discriminate or recognize objects, letters, persons, locations	- accurate description of objects on table - sensory input seems to come from the front instead of from the back
Geldard (1965) [35]	arms, legs, abdomen, thighs	(6)	- 10 vibrators distributed over the body - patterns of 1–9 vibrators - 500 equal & 500 unequal pairs - several hours of training	decide whether patterns were equal or unequal	- error rate increases with number of vibrators - error rate increases with degree of communality - communality is major cause for errors - no dependence on body location
Gottheil et al. (1978) [36]	thigh	(10)	- 64 vibrators (8 × 8) - pairs of static patterns of 16 or 32 vibrators	decide whether patterns were equal or unequal	- error rate increases with degree of communality - for higher communalities, error rates increase faster with number of vibrators
Cholewiak & Collins (1995) [37]	thigh	(7f, 5m)	- 64 vibrators (8 × 8) - pairs of static patterns of 32 vibrators	decide whether patterns were equal or unequal	error rate increases with degree of communality
Piateski & Jones (2005) [38]	arm, torso	21–32 (5f, 5m)	- arm: 9 vibrators (3 × 3) - torso: 16 vibrators (4 × 4) - 8 vibration patterns	identify vibration pattern	- patterns moving across the arm easier than along the arm - most patterns on torso 100% correct
Jones et al. (2009) [39]	torso	18–38 (5f, 5m)	- 16 vibrators (4 × 4) - 7 patterns representing military arm-and-hand signals - 20 minutes training	identify vibration pattern	- for experiment 1, see [38] - 98% correct if choices are visibly shown - 75% correct if choices are only pictures of represented signals
Jones & Ray (2008) [40]	back	19–22 (4f, 5m)	- 16 vibrators (4 × 4) - 12 patterns representing possible navigation cues	identify vibration pattern (12AFC)	- 95% correct identification
Israr et al. (2011) [41]	back	mean 29 (4f, 8m)	- 12 vibrators (4 × 3) - 3 patterns - different algorithms	decide whether it were 1, 2 or more strokes	- most participants perceived patterns generated with the Tactile Brush algorithm as one continuous movement
Wu et al. (2011, 20012) [13], [42]	back	- (10) - (2f, 8m)	- 48 vibrators (8 × 6) - 5 (4) patterns of sequentially stimulated vibrators	identify shape (5(4)AFC)	- dynamic stimulation gives better performance than static pattern - about 90% correct for dynamic patterns - distinctive vertex vibration improves recognition
Ion et al. (2015) [43]	forearm	mean 22 (3f, 5m)	shapes drawn on skin by - skin stretch - vibrators (4 × 4)	recognize pattern (12AFC)	- error rate lower for skin strech (24%) than for vibratory stimuli (43%)
Alvina et al. (2015) [44]	palm, arm, thigh, waist	- exp 2: 20–27 (3f, 9m) - exp 3: 18–27 (5f, 7m) - exp 4: 19–24 (4f, 2m)	- exp 2: 9 vibrators (3 × 3) - exp 3: 4 vibrators (2 × 2)	- exp 2: recognize 6 patterns of 2 vibrators - exp 3: recognize 8 patterns of 1, 2 or 3 vibrators - exp 4: recognize 5 preferred patterns while watching movie	exp 2: - overall recognition rate 60% - performance worse than with palm exp 3: - overall recognition rate 86% - performance on arm better than on thigh or waist - significant influence of pattern exp 4: - overall success rate 88%
Velásquez et al. (2012) [45]	foot	13–32 (10fs, 10ms, 1fb, 4mb)	- 16 vibrators (4 × 4) - 6 shape patterns	- recognize shape (6AFC)	- average percentage correct: 33% - adult blind had best performance (44%), young blind worst (22%)

For participants age range is given in years and between brackets the number of participants (f females, m males, b blind, s sighted). exp stands for experiment. xAFC stands for alternatives–forced choice and the number x in front of it indicates the number of alternatives.

Annex 2
Learning the Tactile Morse code alphabet

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Tactile Morse code provides a way to convey words using the sense of touch. This can be useful in applications for users with a visual and/or auditory impairment. The advantage of using Morse code is that it is technically easy to accomplish. The usefulness of tactile Morse code also depends on how easy it is to learn to use. In this study we focussed on the time that is needed to learn tactile Morse code. Two vibration motors were used: one was attached to the left arm (dots) and the other to the right arm (dashes). We gave the participants a learning session of 30 minutes and determined how many letters they had learned. All participants managed to learn at least 15 letters in this time. Directly afterward they were presented with 2-, 3-, 4-, or 5-letter words consisting of only the letters they had learned. Participants were able to identify words, but correct rates decreased rapidly with word length. We can conclude that it is possible to learn tactile Morse code using only a tactile representation (15 to 24 letters in 30 minutes). After the learning session it was possible to recognise words, but to increase the recognition rates extra training would be beneficial.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**.

Additional Key Words and Phrases: Haptic communication, Vibration, Morse code

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1 INTRODUCTION

Vibration is an easy way to transfer tactile messages to a user. A very common use in mobile phones is to alert the user that there is an incoming message. However, it can be necessary to convey more complex messages. For instance, in assistive technology for individuals with a visual and/or auditory impairment. There exist many tactile languages. The most well-known is probably Braille, but there are others such as tactile sign language, Moon or finger spelling. Although tactile sign language relies in practice mainly on an interpreter, for some of

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the others digital displays have been developed. There are numerous commercially available Braille displays and recently displays to deliver finger spelling have been designed such as the Hapticomm [5] and the Lorm glove [7].

What these aforementioned languages have in common is that they are not hands-free. So the user cannot receive a message if the hands are otherwise occupied. Also some, such as Braille, can be difficult to learn. Some forms of deafblindness (i.e. a combination of auditory and visual impairment) are acquired over time and it can be difficult to start using Braille at a later age, see for instance [10]. Tactile Morse code provides a possible alternative. Morse code is international and it is very easy to display as it can be done with even just one vibration motor. Given these advantages there have been several initiatives to develop apps or other platforms to incorporate tactile Morse code technical applications [1, 2, 9, 13]. Often these were designed especially for individuals with deafblindness. However, if tactile Morse code proofs difficult to learn it might not have much of an advantage over Braille in that respect. Also, the pace at which tactile Morse code can be reliably perceived is slower than auditory Morse code [11]. Although the pace might increased with training, it makes tactile Morse code most suitable for shorter messages. Despite the interest in developing technological means for displaying tactile Morse code, very little is known about learning tactile Morse code.

A few studies have focussed on the learning of tactile Morse code. Tan and colleagues compared novices and experienced auditory Morse code users in learning to use tactile Morse code [11]. They showed that tactile Morse code can be learned, but participants were shown a visual representation of the Morse code alphabet and were allowed to write down the code. This is not practical for individual with a visual impairment. Also, it is not a demonstration of learning tactile Morse using the sense of touch only.

Another study on learning tactile Morse code focussed on finding the best way of presenting the code [12]. The authors compared using a single vibration motor, two motors on the same arm or two motors distributed over both arms to indicate dashes and dots. They found that presenting tactile Morse code by using a vibration motor on each arm was perceived the best. In that study, however, they focussed on comparing different vibration motor configurations and not on learning the whole alphabet.

In the current study we set out to test how many letters of the tactile Morse code alphabet can be learned in 30 minutes. Here we focussed on individuals with no prior experience using Morse code. We never showed them a visual representation of the code and they were not allowed to write it down. After learning the letters we tested their performance on recognising words containing the letters they had learned.

2 METHODS

2.1 Participants

Ten participants (4 male and 6 female, age range 20-26) were recruited from the student population of Eindhoven University of Technology. All students were Dutch native speakers and had experience with learning foreign languages. None of the participants had prior experience with using Morse code. All participants signed informed consent prior to participating in the experiment. The experiment was approved by the ethical committee of the Human Technology Interaction group at Eindhoven University of Technology.

2.2 Set-up and Stimuli

Morse code was provided using two coin-style vibration motors (Adafruit mini motor disc, diameter 10 mm, thickness 2.7 mm) controlled with a micro controller (Arduino Nano). One vibration motor was taped near the wrist on the volar side of the left forearm and the other one on the same location on the right forearm. The motor on the left arm was used to represent dots and the one on the right to represent dashes. This means a dot was represented by a vibration pulse of 103 ms and a dash by a vibration pulse of roughly 3 dots lengths (307 ms). A break of roughly 7 dot lengths (730 ms) was used between letters. This timing is consistent with the timing of International Morse Code.

Letters were not learned in alphabetical order, but in an order that was chosen such that Dutch words could be made even after learning only 5 letters. The order in which the letters were learned was: A, F, K, M, O, T, I, S, B, C, D, E, G, H, J, L, N, P, Q, R, T, U, V, W, X, Y, Z.

2.3 Experimental Procedure

Participants first performed a 30 minute session in which letters were learned (Letter session). During this session letters were learned in blocks of 3 letters at the time. This means in the first block A, F and K were learned. First each letter was presented using tactile Morse code while the experimenter announced which letter was being presented. This means that only a tactile representation of Morse code was provided and they were never shown a visual representation of the Morse code alphabet. Then each of the three letters was presented two times in random order (practice phase). The participant was asked to respond which letter was presented and the experimenter provided feedback on what the presented letter was. If their answer was incorrect the experimenter informed them of what the correct answer was. This was directly followed by a test phase in which each letter was presented in random order. If they answered with a correct rate of 100%, they continued to learning the next block of three letters. If they made a mistake, the test phase continued with the block of three letter being presented again in random order until a 100% correct rate was achieved in one block of three letters before continuing to the next block. Each time two blocks of letters were learned a repetition phase occurred. During a repetition phase all letters that had been learned up until that point were presented a number of times in semi-random order. The number of repetitions depended on the total number of letters learned. After learning the first 6 letters, they were all repeated 2 times, during the next repetition phase each of the letters was repeated 4 times, then 6 times etc. Also during repetition phases and test phases participants were asked to respond which letter was presented and the experimenter gave feedback on what the presented letter was. The letter session continued until all letters had been learned, or until 30 minutes had passed.

After a short break the Word session was started. The Word session lasted 20 minutes. During this session words (2, 3, 4 or 5 letters) were presented that consisted of the letters that were learned by the participant. All letters up to the last test phase they had passed were considered learned. So they did not necessarily have to finish the whole repetition phase that followed the last test phase. The set of words therefore differed between participants. Also the number of words presented in the 20 minutes session differed because some participants answered quicker than others. Participants were asked to answer which word was presented and again feedback was given on what the presented word was.

3 RESULTS

3.1 Letter session

For two out of the 10 participants the data files of the letter learning session were corrupted. Therefore, these participants' data were left out of the analysis of the letter session, but included in the analysis of the word session. For the remaining eight participants the correct rates of the repetition phases are shown for each letter individually as a function of the number of times this letter was presented (Figure 1). The panels are ordered in the same way as the order in which the letters were learned. It can be seen that towards the end of the sequence of letters, the number of times these letters were presented was smaller than in the beginning of the sequence. Not every participant learned the same number of letters and therefore the number of participants included in each data point can vary. One participant reached the repetition phase with up to letter 'x', while the other 7 reached the repetition phase up to the letter 'p'. It can be seen that overall the correct rate during the repetition phases was quite high.

To analyse which confusions between letters occurred most often, a confusion matrix was calculated. This was done by calculating the percentage of confusions that occurred between each possible letter combination

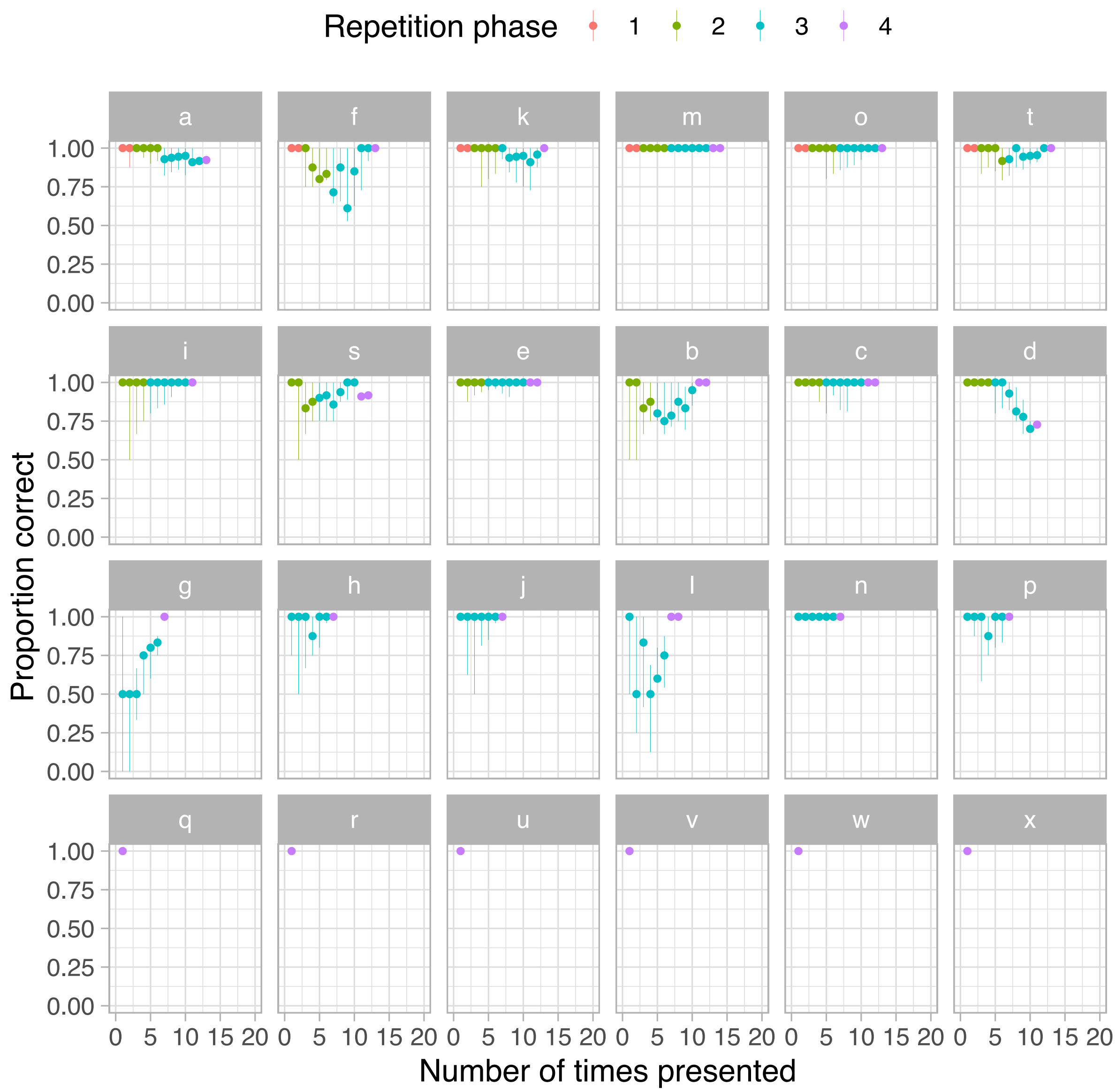

Fig. 1. Percentage correct as a function for the number of times the letter was presented in the repetition phase. Each panel shows a letter and the the panels are presented in the order in which the letters were learned. Dots indicate the median over participants and the error bars indicate the 25% to 75% intervals. The colours indicate the number of the repetition phase.

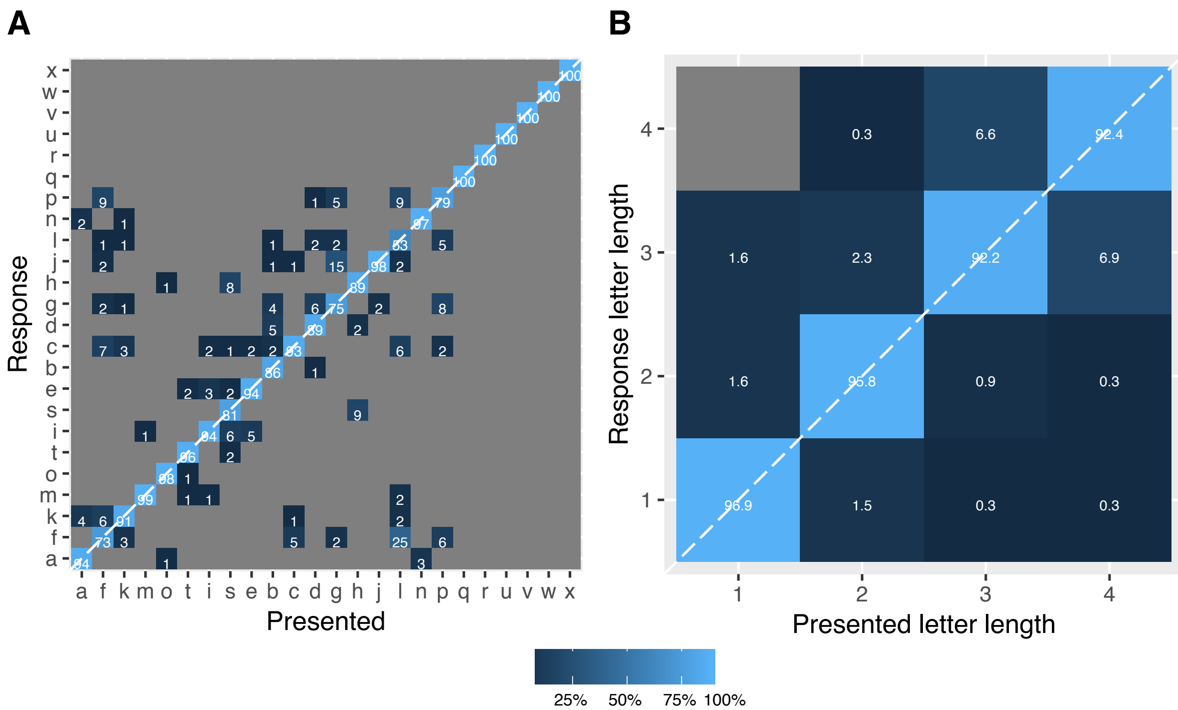

Fig. 2. Confusion matrices for the letter session with the percentage of confusions averaged over participants. A) Confusions between the different letters. B) Confusions between letters depending on letter length.

for each participant individually. The individual confusion matrices were then averaged over participants. The result is shown in Figure 2A. It can be seen that most answers fell on the diagonal indicating that the answer was correct. The only two letter combinations that occurred above 10% that were not on the diagonal were l – f, and g–j. The first letter combination makes sense because l and f are very similar in terms of pattern (· – ·· vs · · –·). They are both 4 characters long and the only difference is that a dash and a dot in the center are swapped. The g and j are more dissimilar because they differ in length (3 vs 4 characters). To see if mistakes between letters of different numbers of characters occurred often, we calculated a second confusion matrix. Here the percentage of confusions between presented letter lengths and responded letter length are shown (Figure 2B). It can be seen that confusions between letters with different numbers of characters were actually quite rare.

3.2 Word session

The word session always lasted 20 minutes per participant. For each participants a set of words that contained only letters they had learned was presented. A letter was considered learned if they had entered the test phase in which that letter was learned. Four participants learned up to the letter X, one learned only up to the J and the others somewhere in between. So the minimum number of letters learned was 15. The number of words that was presented during this session varied between participants because some took much longer to answer than others. The minimum number of words presented was 14 and the maximum was 72. For each participant the proportion of correctly identified words was calculated per word length. The median and 25% to 75% interval

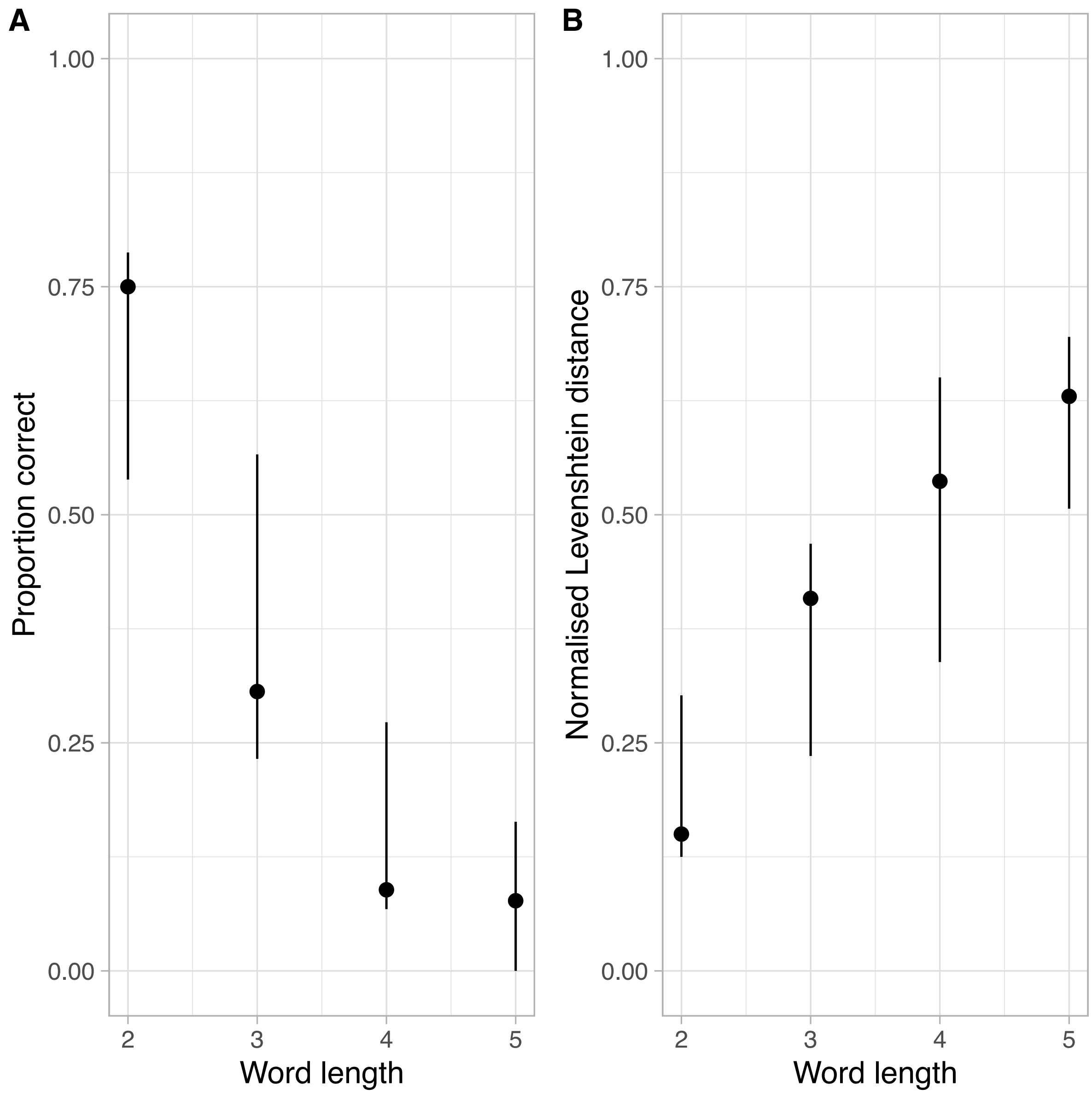

Fig. 3. Results of the word session. A) Proportion of correct answers as a function of word length. B) The normalised Levenshtein distance between the presented word and the participant's response as a function of word length. Dots indicate the median over participants and the error bars indicate the 25% to 75% intervals.

over participants are shown in Figure 3A. It can be seen that the correct rate rapidly decreased with word length and it was difficult to correctly recognise 4 and 5 letter words. However, a word was only counted as correct if all letters were identified correctly. So a word with only 1 letter mistaken was counted as incorrect.

To analyse how dissimilar the answers of the participants were from the presented words, we calculated the Levenshtein distance. This is a measure for the minimum number of actions needed to transform one word (or sentence) into another. The minimum value is 0 (all letters correct) and maximum value is the number of letters in the word. The actions available are deletion, substitution or addition. Here we normalised the Levenshtein distance by dividing by the word length. This means that the maximum Levenshtein distance was 1 for all word lengths. For each participant the average Levenshtein distance per word length was calculated. The median and 25% to 75% intervals over participants are shown in Figure 3B. It can be seen that the normalised Levenshtein distance seems to increase with word length. To test whether this increase was statistically significant, linear regression was performed on the individual participants' data. This yielded a slope of 0.88 ± 0.06 ($mean \pm se$). A t–test on the values of these slopes showed that these were significantly larger than zero ($t = 15$, $p < 0.001$). This indicates that the answered words became more dissimilar to the presented words with increasing word length, despite normalising for word length.

4 DISCUSSION AND CONCLUSION

Our results show that it is possible to learn a substantial part (at least 18 letters) of the tactile Morse code alphabet in only one session of 30 minutes. This was without any prior experience with using Morse code (tactile or otherwise) and the Morse code was learned in a haptic way. So, participants were never given a visual representation of the Morse code and only experienced the tactile Morse code. In previous studies on tactile Morse code participants were always given a visual representation of the Morse code alphabet and/or were allowed to write down the code they received [11, 12]. This can be highly impractical for individuals with perceptual and/or motor disabilities. One study that involved a user with deafblindness resorted to an embossed representation of Morse code to learn the code [2]. One of the difficulties was that this knowledge of the embossed representation of the code had to be transferred to recognising Morse code that was displayed using vibration pulses. The current study shows that it is possible to quickly learn the tactile Morse code alphabet without writing the code down.

After the 30 minutes learning session they could recognise words using tactile Morse code, but the number of errors did increase rapidly with word length. Also, the normalised Levenshtein distance increased with word length. This indicates that their answers became more dissimilar from the presented word with increasing word length. One reason for this could be that they had to keep a longer sequence in memory before answering. This could give rise to errors.

In addition to tactile Morse code being easy to display, we here show that it is also relatively easy to learn. Here we opted to optimise the presentation of tactile Morse code. Based on the study of Walker and Reed we presented dashes and dots to the left and right arms, respectively [12]. Also the speed at which the vibration pulses were presented was chosen based on a previous study indicating that this presentation speed works well. Both of these factors probably influence how fast the Morse code can be learned. The correct rates for 4- or 5-letter words were quite low and to be able to reliably use tactile Morse code in an application these should increase. Note, however, that in this study participants only received 30 minutes of training and this was just learning the alphabet. There was no training with words. The correct rates for words will likely increase with training.

There is also a way to communicate via touch without the need for learning a new language. This is done with tactile vocoders [3, 4, 8]. A vocoder analyses the speech signal and presents it via vibration. Varying numbers of vibration motors can be used for this. This might seem an easy solution: just display a tactile version of the speech signal and the user does not have to learn a language. However, there are many hours of training associated with learning to recognise speech through a tactile vocoder. For instance, in a study by Lynch and colleagues it took 41 hours of training to learn 50 words [8]. Even after this many hours of training the correct rate still was only 42 %. A recent study in which the speech signal was decomposed into phonemes seems to be more promising [6]. After 100 minutes of training a correct rate of 45% percent for recognising words was achieved. Overall it can be concluded that this approach does involve a long training process, and based on the results in the current study learning tactile Morse code does seem easier to learn. For displaying longer messages, however, vocoders might have an advantage, as displaying tactile Morse code is relatively slow. Even trained auditory Morse code users need tactile Morse code to be displayed at a much slower pace to be able to use it [11].

In addition to Morse code being universal and technically easy to present, we show here that it can be learned very quickly. This makes it a good option as a way of communication to implement in assistive technology. This is especially the case when displaying shorter messages and while doing activities that do not leave the hands available to receive communication.

ACKNOWLEDGMENTS

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Annex 3

Characterisation of vibration localisation in a textile prototype

Abstract

This text reports on pilot experiments performed at Eindhoven University of Technology together with members of the University of Leeds, using the vest created by the partners at Borås. Both localisation and accelerometer experiments are presented and discussed. This pilot leads to recommendations for the design of a full experiment.

1 Introduction

Before using a vest with many vibrators for conveying information to users, it is important to have answers to three questions: 1) How well are users able to localise the stimuli? In other words, how good is the spatial acuity for vibrotactile stimulation on the back. 2) How local is the actual stimulation of the vibrator? 3) How suitable is the vest created in WP5 for doing such experiments? Especially the second question was also posed by the reviewers during the review meeting in Borås. To get a preliminary answer to these three questions, a pilot study was performed. The results of this study will be used to design a more extensive study. The first question will be answered by doing localisation experiments with participants wearing the vest. For the second experiment, accelerometer measurements will be done, while the same participants are wearing the vest. The third question will be answered based on the results of the two experiments.

1.1 Vibrotactile localisation

There are only few studies that reported on vibrotactile localisation performance (e.g., arm: [1, 2], abdomen: [3], back: [2, 4]). As vibrotactile thresholds depend strongly on body location [5], only the results obtained on the back are relevant for our work with the vest. Lindeman and Yanagida [4] used a 3 × 3 grid of vibrators fixed to a chair. The spacing between neighbouring vibrators was 6 cm. This distance is well above the spatial acuity threshold for vibrotactile stimuli of 11 mm [6]. The task for the participants was to identify the relative location of the stimulated vibrator, such as "upper-left" or "lower-center". Their participants reached an overall successful identification rate of 84%. Note that this experimental design does not say anything about the accuracy of the absolute localisation performance, that is, the response of the participant does not give information of the exact location where the participant felt the vibration. Jones and Ray [2] performed a similar experiment with a grid of 4 × 4 vibrators attached via a waist band to the back. The vertical spacing of neighbouring vibrators was 40 mm and the horizontal spacing was 60 mm. Also in their experiment, the task was to identify the relative location of the stimulated vibrator. They report an average correct identification rate of 59%, which ranged from 40% to 82%

for the various vibrators. Both these experiments tested relative localisation, which does not provide information on where the participants exactly felt the vibration. In our experiment, we are more interested in absolute localisation, so we used a slightly different design for this pilot experiment.

1.1.1 Participants

None of the five participants in this pilot study were naïve with respect to the design and the purpose of the study, but for practical reasons this was the only way to obtain these pilot data (this was a project from a visiting student from Leeds, which had to be finished within a week; moreover, pilot experiments are usually done with ourselves and our students). Three participants acted also as experimenter and the other two were students who used the same set-up (vest plus vibration motors) for other experiments. All participants signed for informed consent. This study was approved by the ethical committee of the Human Technology Interaction group of Eindhoven University of Technology in The Netherlands.

1.1.2 Procedure and set-up

Participants wore the vest designed and made in WP5 (see Figure 1a). Nine vibration motors (Adafruit mini motor discs) were placed in small pockets attached with velcro to the vest in a 3×3 grid. The spacing of the vibrators was 65 mm, so well above the spatial acuity threshold for vibration. Horizontal (a–l) and vertical (1–14) scales were indicated on a photo of the vest worn by a mannequin in such a way that the locations of all black and white squares could be uniquely marked (see Figure 1b). Task of the participants was to name the location of where they thought the vibrating motor was placed. All 9 motors were vibrating 5 times in pseudorandom order (that is, there were 5 blocks in which all 9 motors were stimulated once). The participants performed this task while seated.

As can be seen by comparing Figures 1a and b, the exact placement of the vest and thus also the vibration motors differed between the participant and the mannequin. Looking at Figure 2, that this also differs between participants. As all participants had to use the same photo for indicating the location they had felt, afterwards corrections were made to account for these differences.

1.1.3 Results, discussion and conclusions

In Figure 3 the mean responses of all five participants are shown. A first observation is that most of the indicated locations are higher on the back than the actual locations. As mentioned above, these responses are corrected as well as possible for the mismatch between the placement of the vest on the back of the participant and that on the photo. Debriefing with the participants suggests that this upward shift is indeed real and not due to an incorrect correction of the mismatch. This is an interesting observation that is worthwhile investigating in more detail in a follow-up experiment. The earlier studies [2, 4] measured relative locations, so in these experiments such an absolute mislocalisation could not have been found.

Another observation is that for most participants vibrators on the spine were indeed indicated as located on the spine. There exists literature that shows that localisation on the body midline is more accurate than just off this line (e.g., [7]). Our results seem to be in agreement with this finding, but we should be careful in our case as all of our participants knew that three of the vibrators were placed on the spine. Although they all did their best to ignore all the knowledge about the locations of the vibrators, it cannot be excluded that they used this knowledge either consciously or unconsciously.

In Figure 4 the spread of the data points is indicated by means of confidence ellipses fitted to the raw data points. Apart from some obvious outliers, most ellipses are quite small, indicating that participants are reasonably consistent in their answers. Moreover, the majority of the data points still lie closest to the vibrator location to which they belong. This is in agreement with the localisation performance reported in previous studies [2, 4].

1.2 Accelerometer measurements

To get an indication of how local the stimulation of a particular vibration motor actually is, we performed accelerometer measurements at various horizontal and vertical distances from the motor while a participant was wearing the vest. We did this for all participants after the localisation experiments. For these measurements we used a triple-axis Adafruit accelerometer, type ADXL345. Acceleration readings were taken at a rate of 667 Hz, and acclerations were measured in all 3 axes (x, y, and z). Frequencies were extracted using a Fast Fourier Transform, and the dominant frequency in each axis is the value extracted. For the subsequent analysis, we averaged over the 3 axes and over participants.

1.2.1 Results, discussion and conclusions

The mean rms values averaged over participants and x-, y, and z-directions are shown in Figure 5. It can be seen that the intensity of the stimulation is indeed highest at the location of the active vibration motor (i.e., the red dot). It can also be seen that the intensity only gradually declines with distance, both in horizontal and in vertical directions. However, the spacing of these measurements was smaller than the distance between neighbouring vibrators, so in most cases, the intensity was substantially reduced at the location of the neighbouring vibrator.

The mean frequencies averaged over participants and x-, y, and z-directions are shown in Figure 6. The variation over distance seems limited and not quite systematic. The major difference can be seen by comparing the right and left graphs, which show the frequencies caused by two different active vibration motors. The frequency ranges due to these two vibration motors do not even overlap. This is something we should look into in more detail when performing the full experiment. It would be relevant to find out whether one of these two motors is a clear outlier with respect to frequency or whether the whole set of motors shows a wide range of frequencies. Alternatively, it could also be the case that the major frequencies measured depend substantially on the location where the motor is placed or how tight the motor is attached to the back.

2 General conclusions and recommendations

The results of the localisation experiment seem interesting enough to warrant a full experiment. There are several major issues that need to be improved. The first is that it is essential to test naïve observers who are not familiar with the research questions and the number and locations of the vibration motors. It would be very interesting to investigate whether they also show this upward shift. The systematic upward shift in the absolute location perception seem interesting both from a fundamental and a more applied perspective. This shift is especially surprising as none of our participants was naïve and debriefing showed that this shift seems indeed real. Thus, it is reasonable to expect a similar shift for naïve participants.

A second major issue is the placement of the vibration motors and more in particular how the vest is worn by the participant. There are regular brainstorm Skype meetings with the partners working in WP5 on how we could improve on this issue. We are also discussing whether placing the vibration motors on a chair instead of in a vest would create a workable solution.

Another issue that should be reconsidered is the way the participants provide their answer. The axes shown on the vest worn by a mannequin were not ideal. We are currently thinking of other ways to convey the axes. Although a picture of the individual participant wearing the vest would provide a solution, this is not possible as this would give information about the number and the locations of the vibration motors, which have to be placed into the vest before it is put on.

Furthermore, all participants mentioned that not all vibrators were equally clear to feel. Indeed, we did not in advance equalize the perceived intensity at the various locations (that would not have been possible with the vibration motors and controller we used). We informally tested whether perception would improve if participants were to sit on a chair leaning to the back. The difference was enormous and all vibrators were easily perceived. So in the full experiment, we will use a configuration like that. It is, however, uncertain how that will influence the accelerometer measurements.

The accelerometer measurements showed that intensity only gradually declined over distance. However, the confidence ellipses measured in the localisation experiments were reasonably small, suggesting that participants were still able to determine the location with highest activity. It will be an interesting question to investigate that if the decline were steeper due to using a damping textile, localisation performance would further improve. This is a plan we are currently considering with the Borås partner.

A final issue that needs attention is that the frequency ranges measured were quite different for the two vibration motors in the accelerometer experiment. It should be made clear whether this was due to variability in the vibration motors, due to the location to which the motors were attached or, due to the tightness of the attachement.

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Figure 1: a) The vest worn by the participants. The locations of the 9 (3 x 3) vibration motors can be seen by following the wires. b) Photo of the vest with marked axes. Participants used this photo to indicate where on their back they felt a vibrating motor.

Figure 2: Vest as worn by the participants during the measurements.

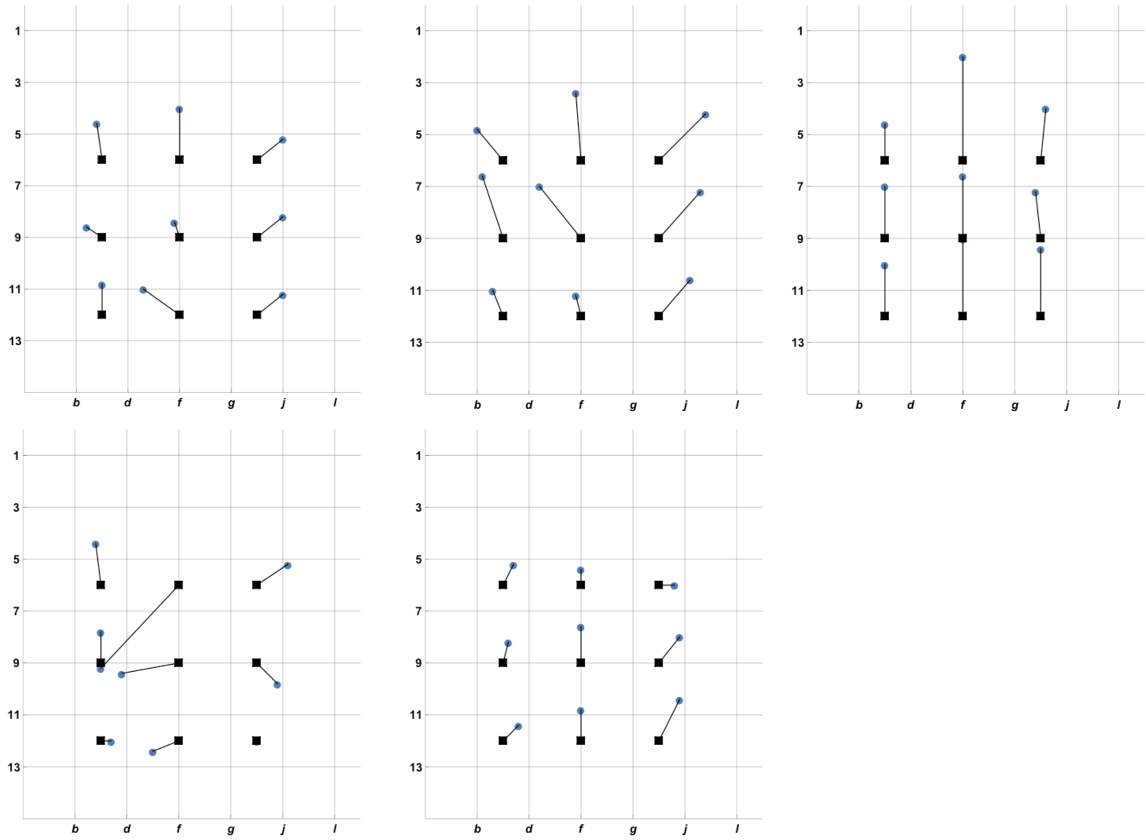

Figure 3: Mean localisation results for all participants. Black squares indicate the actual locations of the vibration motors and blue dots the average location indicated by the participant. The lines connect actual and indicated locations.

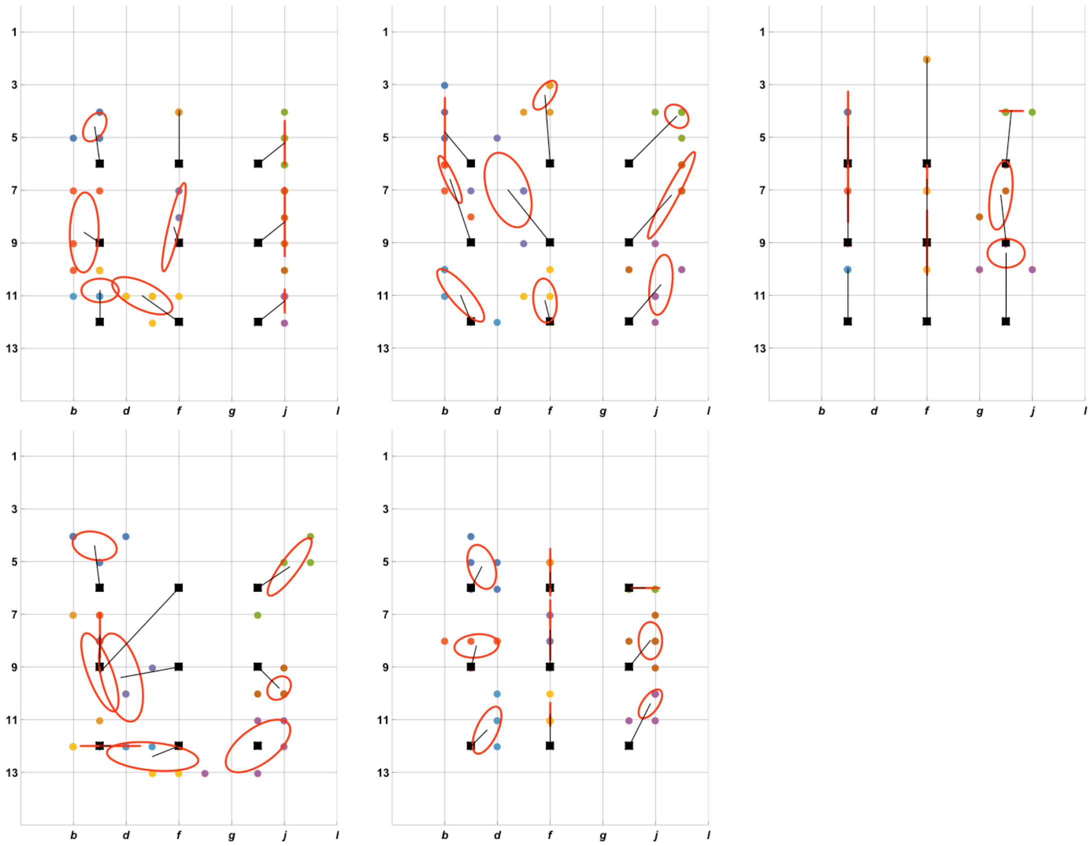

Figure 4: Localisation results with raw data points and confidence ellipses for all five participants. Each confidence ellipse is based on 5 trials. The differently coloured dots belong to different locations. Note that often not five but fewer dots of a certain colour can be seen. This is due to overlap of responses and the coarseness of the response grid.

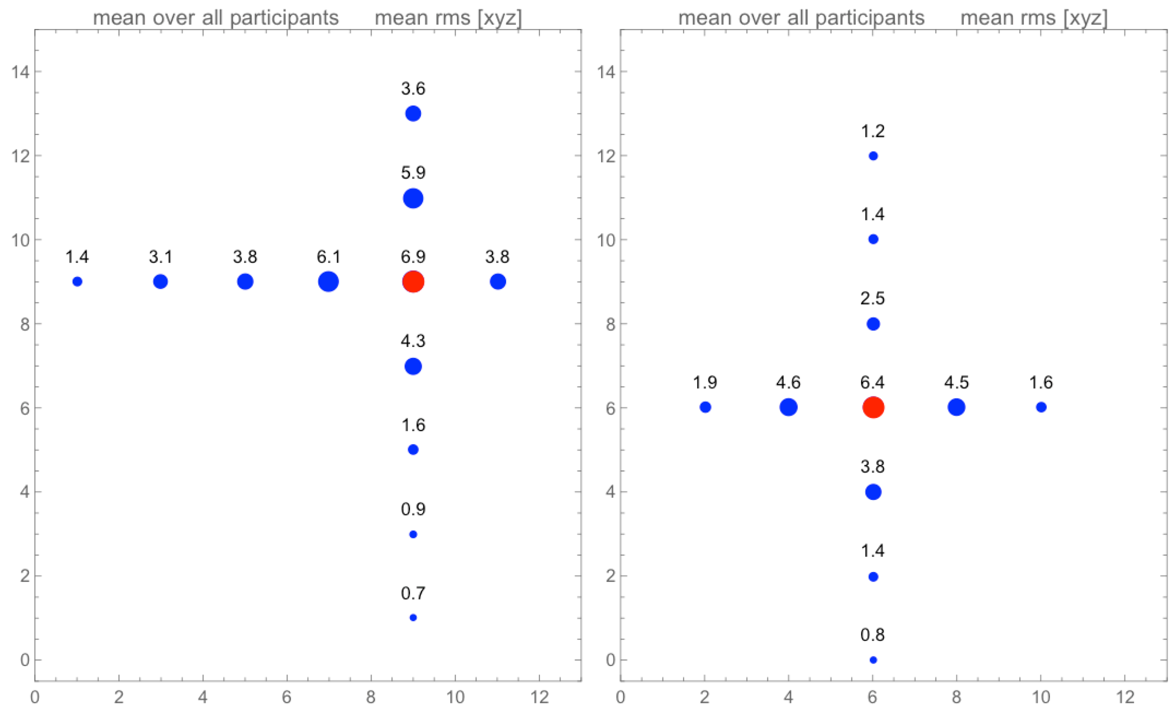

Figure 5: Amplitude (rms) averaged over the three directions and over the five participants. The red dot indicates the location of the active vibration motor and the blue dots indicate the locations of various measurements. The sizes of the dots are scaled, and the number above the dots gives the average rms for that location. The left and right graphs are for two different active vibration motors. For reasons not relevant to explain here, the scales on the axes are slightly different from those shown in Figures 3 and 4; on the vertical axis 1–14 should be read as 14–1, and on the horizontal axis, 1–12 should be read as a–l.

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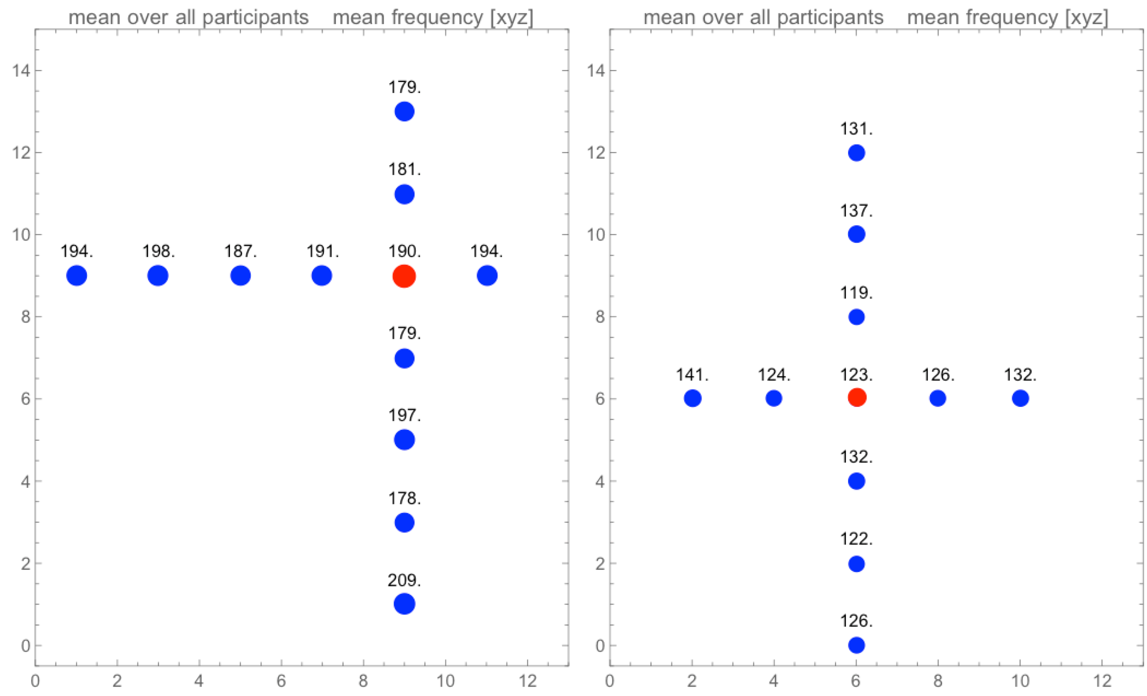

Figure 6: Frequency averaged over the three directions and over the five participants. The red dot indicates the location of the active vibration motor and the blue dots indicate the locations of various measurements. The sizes of the dots are scaled, and the number above the dots gives the average frequency for that location. The left and right graphs are for two different active vibration motors. See the note on the scales in the caption of Figure 5.

Annex 4

Translating social haptic communication signals into vibration patterns

Abstract

1 Introduction

In the project proposal, it is mentioned that the possibility to convey social haptic signals by means of a HIPI will be investigated. These are signals, usually given by another person, that do not give literal information of what is said (the information an interpreter would give), but information about the environment. Such information can be very advanced, as is shown in the thesis by Lahtinen [1]. However, this requires a regular and very intensive collaboration between the individual with deafblindness and the social haptic communicator, resulting in a kind of personal language. In several countries (e.g., Denmark and The Netherlands), attempts are made to standardize the signals. This resulted in, among others, "103 Haptic Signals – a reference book" of the Danish Association of the Deafblind [2]. In the Netherlands a similar project is ongoing, but their reference book is not yet publicly available [3].

During a recent brainstorm session with people from Bartiméus, an expertise centre in the Netherlands, the idea came up that a prototype HIPI would be very attractive in situations where several individuals with deafblindness attend a meeting. Usually they either bring their own interpreter, or they can hear the speaker via their cochlear implants. In this way, they can follow what is being said, but they still miss what else is going on around them, such as applause, noise, laughter, etc. For these environmental happenings already exist social haptic signals, but in realistic situations, there will not be social haptic communicators for every person with deafblindness in the room. However, if such signals could be conveyed through vibration patterns on a HIPI, every person needing such information could get access to this information. If all the HIPIs were connected to the same interface, only one person would be needed to decide what kind of information needs to be given. Moreover, this person does not even need to be familiar with social haptic communication. With a good computer interface, almost everyone could easily make this information available. An illustration of this idea is shown in Figure 1. This text describes the first steps into the design of such a network of connected HIPIs.

2 Social haptic signals

In the situation described above, we have chosen (for a start) a number of more or less standard signals that could be of use in this context, such as applause, question, etc. The symbols were taken from the Dutch handbook (not yet publicly available), but these are very similar to the Danish signals. The signals we have chosen are shown in Figure 2.

For our experiments, participants were wearing the checkerboard vest that was designed and created in WP5. We started with using a 3 × 3 grid of vibrators, but this will probably

Figure 1: Illustration of the idea how several persons wearing a HIPI could simultaneously receive social haptic signals (i.e. vibration patterns) on their back.

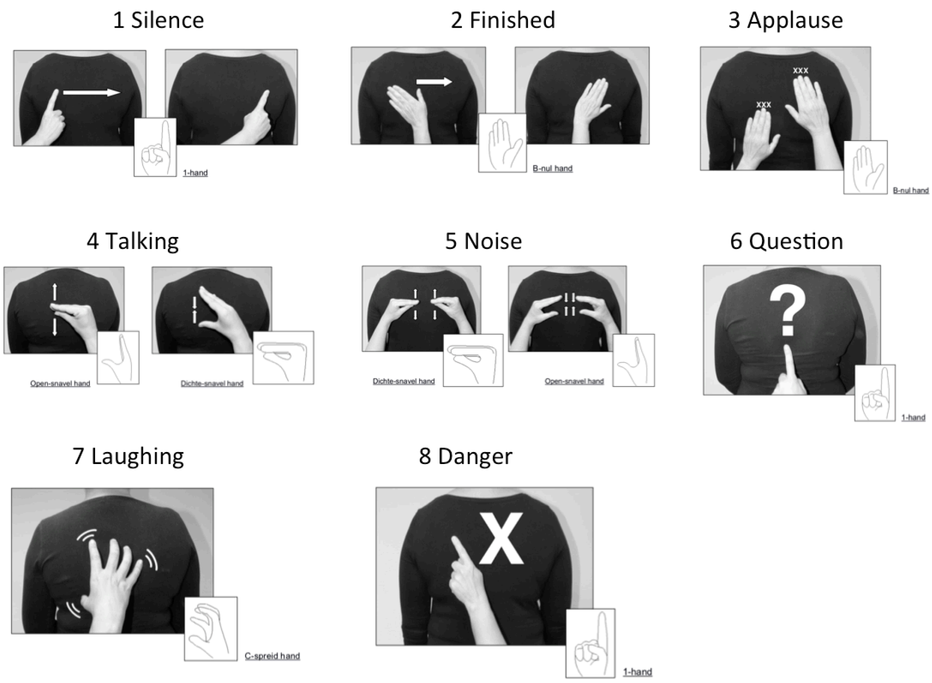

Figure 2: Examples of common haptic communication signals. Note that these pictures were taken **without explicitly asking for permission** from "Handboek Social Haptic Communication (SHC)" of the Dutch Projectgroep Social Haptic Communication.

be extended to a 4 × 4 grid in the near future. The challenge is to translate these signals into vibration patterns that can be discriminated and preferably also recognized as the signals they are based on. In the following figures we present how we performed this translation. Each black square stands for fixed duration of 200 ms. The red dots indicate which vibration motor(s) is/are active during that period. Time goes from left to right. The rightmost picture shows all the vibration motors that have been active during that signal. During a few informal pilot tests on ourselves and colleagues, we did some optimalisation of the timing and durations.

2.0.1 Silence

The social haptic signal for silence is a movement of one finger from left to right, high on the back. In Figure 3 it is shown that this is translated into sequential vibrations of the three motors on top of the grid.

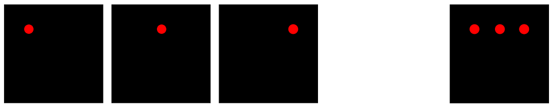

Figure 3: Silence. Series of frames indicating active vibrators (red dots). Each frame lasts for 200 ms and is directly followed by the next frame. Time goes from left to right. The vibration pattern forms a straight line. The rightmost frame shows all vibration motors that were active during (part of) the pattern.

2.0.2 Finished

The social haptic signal for finished is a curved movement from left to right with the whole hand over the upper part of the back (see Figure 2). This signal cannot be translated to a curved pattern on a 3 × 3 grid of vibrators. After some piloting on ourselves we came to a kind a rectangular pattern of sequential vibrations as is shown in Figure 4.

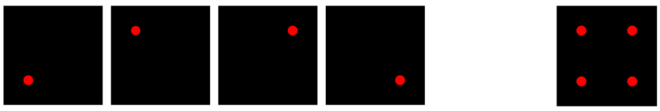

Figure 4: Finished. See Figure 3 for further explanation.

2.0.3 Applause

Applause is a repetitive alternating placement of the two hands on the back, the right hand placed slightly higher than the left hand. The vibratory pattern that seems to simulate this signal best is an alternating pattern of the three left vibration motors and the three right vibration motors as shown in Figure 5. As hand taps are much stronger than finger taps, we have chosen for three instead of two simultaneously vibrating motors.

Figure 5: Applause. See Figure 3 for further explanation.

2.0.4 Talking

The social haptic symbol for talking is moving index finger and thumb toward and away from one another, vertically centred on the back, as shown in Figure 2. The vibration pattern to simulate this signal is shown in Figure 6.

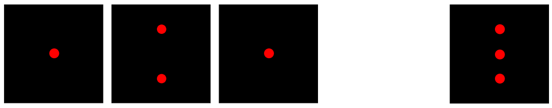

Figure 6: Talking. See Figure 3 for further explanation.

2.0.5 Noise

The social haptic symbol for noise is similar to that of talking, exept that it is made with both index fingers and thumbs, as shown in Figure 2. The vibration pattern created to simulate this is to use the left- and right most vibration motors instead of the central ones (see Figure 7).

Figure 7: Noise. See Figure 3 for further explanation.

2.0.6 Question

The social haptic signal for question is a movement that traces the shape of a questionmark, as shown in Figure 2. The final dot is marked by a longer duration (as long as the questioning goes on). Due to the 3×3 grid, the vibration pattern is a bit more stylised (see Figure 8).

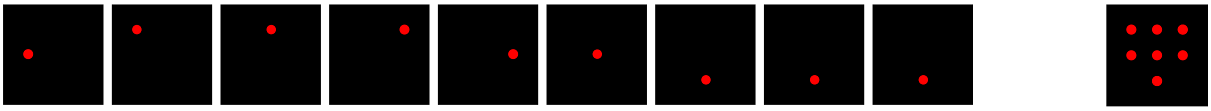

Figure 8: Question. See Figure 3 for further explanation.

2.0.7 Laughing

The social haptic signal for laughing is to make small movements with several fingers (see Figure 2). We simulate that by sequentially putting all nine vibrators on and off for a few times, as shown in Figure 9.

Figure 9: Laughing. See Figure 3 for further explanation.

2.0.8 Danger

Finally, the social haptic symbol for danger is the well-known symbol in traffic for warnings: a cross (see Figure 2. The vibration pattern consists also of a cross. At first, the two legs of the cross followed each other directly, but that made it hard to perceive the pattern. A break between the two legs made perception much easier (see Figure 10).

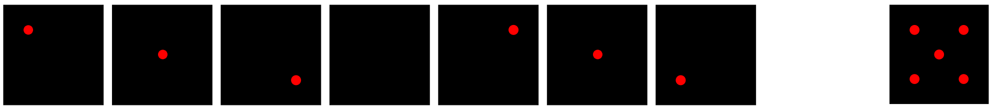

Figure 10: Danger. See Figure 3 for further explanation. The black square in the middle indicates a break in the signal.

3 First observations

These vibration patterns simulating social haptic signals were designed based on our own introspective perceptions with the intention to mimick the original signals as well as possible. We were able to recognize all 8 patterns at a 100% recognition rate. However, we were, of course, not naïve. To get a more useful first impression on how well these patterns can be recognized, we asked three colleagues to wear the vest and experience the vibration patterns. These colleagues were unfamiliar with social haptic communication and we just told them that they would be presented with vibration patterns that they subsequently had to draw. The results are shown in Figure 11.

Although participants sometimes remarked that they found it hard to draw these patterns, it can be seen that most drawn patterns reasonably well resemble the actual patterns.

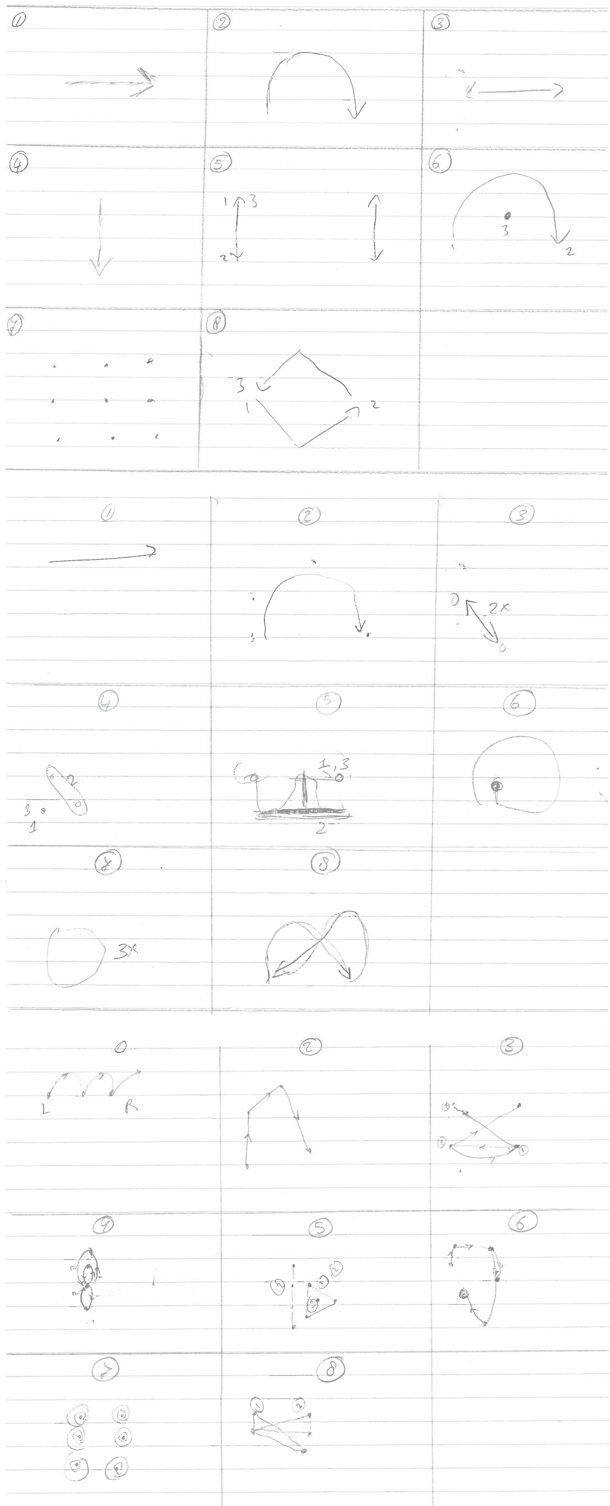

Figure 11: Drawings made by three volunteer colleagues while experiencing the social haptic vibration patterns. 1) Silence, 2) Finished, 3) Applause, 4) Talking, 5) Noise, 6) Question, 7) Laughing, 8) Danger.

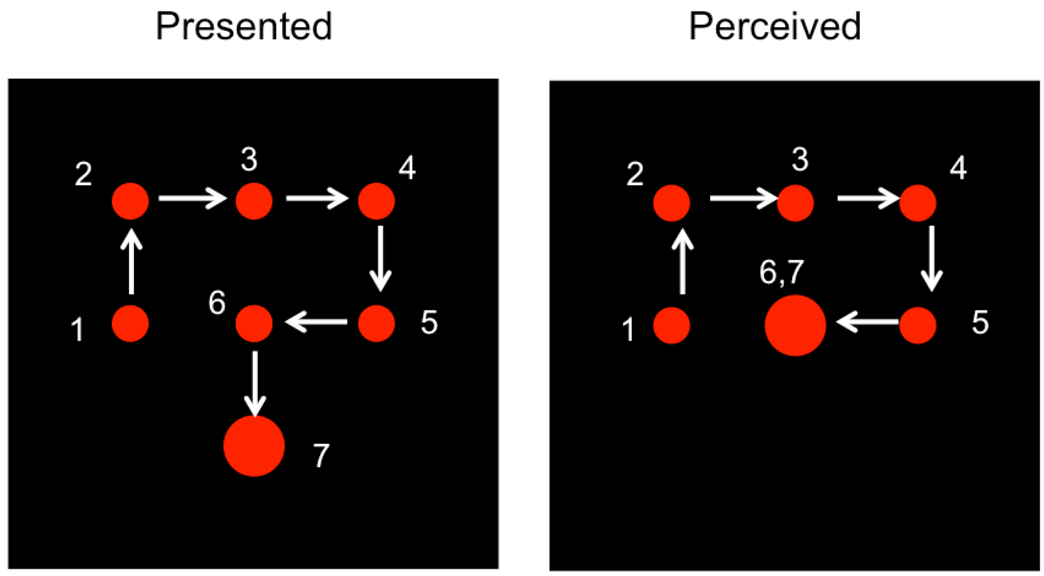

Figure 12: Actual vibratory pattern of the questionmark (left) and the way our three volunteer participants drew the pattern (right)

It is of interest to see that often the vibration patterns are drawn more circular than they actually were, but thereby better resemble the original social haptic signals. See, for example, the drawings for finished (pattern 2) and questionmark (pattern 6). It is also intriguing that all three participants drew the final dot of the questionmark somewhere in the middle of their drawing and not below all the other stimulated locations. This is illustrated in Figure 12. Possibly, this is related to the finding by Hoffmann et al. [4], who showed that low intensity stimulation followed by high intensity stimulation results in an illusory upward movement. Although in our case of the questionmark the intensities of the stimulation were kept the same, the duration of the stimulation was different. So possibly, an extended stimulation is perceived as a stimulus of higher intensity, and subsequently, localisation is misjudged.

At a workshop organised before the recent review meeting in Borås, two persons with deafblindness (also members of our advisory board) tried the vest and they were able to describe the symbols correctly.

4 Conclusions and future plans

It is clear that at this stage it is way too early to come to any conclusions concerning the value of vibration patterns as a substitute for social haptic signals conveyed by another person. However, we find this a promising start, and therefore we will pursue this research direction in the coming months. We have established contacts with the workgroup in the Netherlands that is working on standardizing the set of signals. In this workgroup, both persons working at expertise centres and giving courses on social haptic communication, as well as persons with deafblindness participate. In addition, we will continue with more fundamental psychophysical studies via student projects, to investigate how the perception of vibrations patterns is deformed (or not).

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