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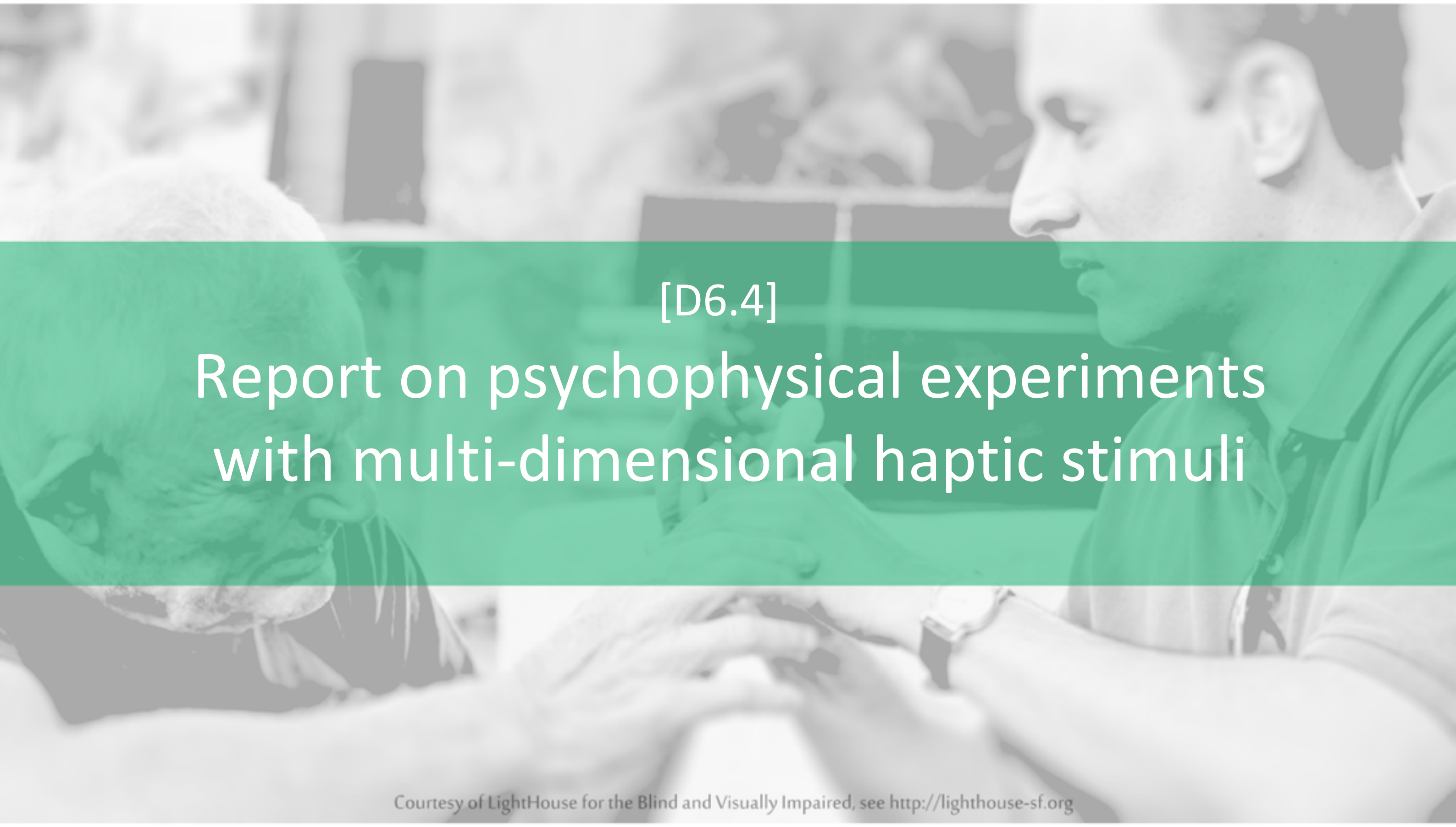

[D6.4]

Report on psychophysical experiments with multi-dimensional haptic stimuli

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

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Dissemination level		
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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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Partner	**Contribution type**	**Name**
TU/e	Author & experimenter	Myrthe Plaisier & Astrid Kappers
HB	Checkerboard vest & chairable development	Nils-Krister Persson, Li Guo, Eva Lindell, Amelie Olesen
UNIVLEEDS	Controller for vibration motors	Raymond Holt
TU/e	Experimenter	Jordie Kolkman

Glossary	
Abbr./ Acronym	**Meaning**
SHC	Social Haptic Communication

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Executive Summary

WP6 focuses on identifying the information needed for exemplar navigation tasks, and proposing and testing haptic signals to convey this. In this third year of the project, we have focussed on vibrotactile stimulation using multiple vibration motors distributed across the back. In concurrence with the tasks of WP 6 in the proposal we have performed formal psychophysical studies on perception of direction and distance with sighted and hearing participants in a laboratory setting. The results from these experiments together with results presented in earlier WP 6 deliverables, including a literature review on tactual language, have served as a basis for the formulation of a set of design recommendations for vibrotactile patterns on the back. Additionally, we have performed user tests with Social Haptic Communication (SHC) users with deafblindness and SHC instructors. These were not psychophysical tests, but rather a proof of principle to show that vibrotactile patterns can be used to mimic SHC and to get user input to improve the recognizability of the vibrotactile patterns. This can only be assessed by SHC users and we collaborated with members of the SHC The Netherlands group in order to do so.

Perception of vibrotactile distance on the back

Background

In the current study we focus on vibrotactile stimulation on the back. Vibrotactile stimulation is often chosen over other types of stimulation because it is easy and cheap to implement using vibration motors. Previous studies have shown that such displays have been used to, for instance, convey shapes and letters, but also military hand signals. Vibrotactile patterns can be displayed statically where a number of vibration motors is switched on and off at the same time or dynamically where motors are switched on and off sequentially. The second case is most similar to tracing a shape on the back. It has been shown that for shapes and letters dynamic patterns are easier to recognise than static ones. So, the recognisability of vibrotactile patterns is determined by both spatial and temporal aspects.

We set out to systematically investigate distance perception on the back using vibrotactile stimulation. We use horizontal distances displayed on one side of the spine as our baseline condition. We compare this to distances presented in the vertical direction to test if indeed distances are systematically perceived differently between the two orientations. To test how the spine influences distance perception we compared the horizontal baseline condition to a horizontal distance presented with a vibration motor on the left and right sides of the spine. In all these conditions two vibration motors were switched on sequentially and thus distances were presented dynamically. To compare distance perception between dynamic and static distance presentation we added also a condition that was identical to the horizontal baseline condition except that both vibration motors were turned on simultaneously. The perceived distance was measured using the method of free magnitude estimation and participants were asked to rate the size of the distance on an arbitrary scale that they were free to choose.

Summary

This study has already been published. The full text can be found in Annex 1, a summary follows here:

Vibrotactile displays worn on the back can be used as sensory substitution device. Often vibrotactile stimulation is chosen because vibration motors are easy to incorporate and relatively cheap. When designing such displays knowledge about vibrotactile perception on the back is crucial. In the current study we investigated distance perception. Biases in distance perception can explain spatial distortions that occur when, for instance, tracing a shape using vibration. We investigated the effect of orientation (horizontal vs vertical), the effect of positioning with respect to the spine and the effect of switching vibration motors on sequentially versus simultaneously. Our study includes four conditions. The condition which had a horizontal orientation with both vibration motors switching on sequentially on the same side of the spine was chosen as the baseline condition. The other three conditions were compared to this baseline condition. We found that distances felt longer in the vertical direction than in the horizontal direction. Furthermore, distances were perceived to be longer when vibration motors were distributed on both sides of the spine compared to when they were on the same side. Finally, distances felt shorter when vibration motors were switched on

simultaneously compared to sequentially. In the simultaneous case a distance of 4 cm was not clearly perceived differently than a distance of 12 cm. When designing vibrotactile displays these anisotropies in perceived distance need to be taken into account because otherwise the intended shape will not match the perceived shape. Also, dynamically presented distances are more clearly perceived than static distances. This finding supports recommendations made in previous studies that dynamic patterns are easier to perceive than static patterns.

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Perception of vibrotactile direction on the back

Background

Vibrotactile displays provide ways to convey information in circumstances where vision or audition are occupied with different tasks or are not available at all. For persons with deafness, blindness or even deafblindness such devices might be helpful in daily tasks such as navigation and communication. In many situations a hands- and head-free device is preferred, and then the back is an obvious choice. Although there certainly has been done some research on the perception of vibrotactile stimulation on the back, the fundamental knowledge at this stage is far from sufficient to design an optimal device. Therefore, the current study focuses on vibrotactile stimulation on the back, and more in particular, on the perception of direction.

Part 1

The first part of this study has already been published. The full text can be found in Annex 2, a summary follows here:

In this study, we investigated the accuracy and precision by which vibrotactile directions on the back can be perceived. All direction stimuli consisted of two successive vibrations, the first one always on a centre point on the spine, the second in one of 12 directions equally distributed over a circle. Twelve participants were presented with 12 times 12 vibrotactile directions. They were required to match the perceived direction with an arrow they could see and feel on a frontoparallel plane. The results show a clear oblique effect: performance in terms of both precision and accuracy was better with the cardinal directions than with the oblique ones. The results partly reproduce an anisotropy in perceived vertical and horizontal distances observed in other studies.

Published as:

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Part 2

A follow-up study is currently being prepared for submission. The draft of the manuscript can be found in Annex 3. A summary follows here:

Vibration motors on the back of a person can be used to convey direction by switching two motors on sequentially. In the first study (part 1) we found that participants' responses were more accurate and more precise for cardinal directions than oblique directions. In that study, however, the first motor to vibrate was always spaced centrally on the spine. The spine has been shown to influence perception as it is used as an anchor point. Here we investigated the effect of the positioning of vibration motors with respect to the spine on the oblique effect. In the first condition all vibration motors were placed in a circle around the spine ('Circle' condition) and direction was conveyed by switching on vibration motors on opposite sides of the circle. In the second condition the motors were placed in two semi-circles of which the centers were on the left and right sides of the back ('Semi-circle' condition). In this condition first one of the motors in the center of one of the semi-circles was switched on followed by a vibration motor on the semi-circle. We found that participants made larger errors and showed a larger spread for oblique angles than for cardinal angles in both conditions. This indicates that the oblique effect occurred. This shows that centering the vibrations around the spine is no prerequisite for the oblique effect to occur. Furthermore, we found that both errors and spread were larger in the 'Semi-circle' condition than in the 'Circle' condition. This suggests that centering the vibration motors in a circle centered around the spine improved task performance, although this result could also have been influenced by the distance between vibration motors.

User study with Social Haptic Communication users

Background

By switching vibration motors on and off it is possible to display a spatiotemporal pattern. This makes it possible to, for instance, trace a shape on the back of another person. In that case motors are switched on and off sequentially with a bit of overlap between two motors. This means that the second motor is switched on before the first motor is switched off. This type of interpolation leads to a smoother perceived trace. There have been examples in the literature of haptic shape perception, but also letters being displayed this way (Kim et al., 2006; Wu et al., 2012). Besides interpolation of which an example is the tactile brush algorithm (Israr & Poupyrev, 2011), also emphasizing corners of a shape (Wu et al., 2012) can be used to facilitate perception of the shapes.

Social haptic communication (SHC) is a haptic language which involves tracing shapes or other types of patterns on the back and other body parts of another person. Often this is used to give information about the environment such as the lay-out of a room, but also about emotions, whether there is applause or that there are loud noises etc. This form of communication was first developed by Palmer and Lahtinen (Palmer & Lahtinen, 2013; Lahtinen, 2008) and is mostly used in the Nordic European countries. The current study investigated whether vibrotactile patterns can mimic SHC and whether SHC users would be able to readily recognize what was being communicated with the vibrotactile patterns. Also, it was discussed with users how to adapt vibrotactile patterns to increase recognizability and whether they thought that they could easily learn to recognize the vibrotactile patterns. This study was done with the help of the SHC The Netherlands group. Members of this group provide training on SHC. They do this in co-teacher couples. One of the co-teachers is always a group member with deafblindness.

Participants

All participants were members of Social Haptic Communication the Netherlands (part of DB Connect). The participants were distributed over three sessions. In each session a couple of one person with deafblindness and their co-teacher participated. These couples provide training sessions on Social Haptic Communication and are used to working together. At two of the sessions there was also an additional member of the SHC group present. Some participants were also employees of Dutch expertise centers Bartiméus or Kentalis. All participants were familiar with the Dutch handbook SHC (2017) and we used that book as a basis for the vibrotactile patterns.

Description of the sessions

The goal of these sessions was two-fold. First, we set out to determine whether the vibrotactile patterns were perceived clearly. The second goal was to investigate whether persons familiar with SHC would recognize which SHC sign, referred to as haptice, was emulated with the vibrotactile pattern.

For these test sessions we used the chairable which was developed in WP5. The chairable is a textile cover that can be pulled over the back of a chair. Vibration motors are embedded in the textile cover. The advantage of using the chairable instead of a vest for these test sessions was that participants can easily take turns sitting on the chair instead of having to put on a vest. We used a set of 9 vibration motors (coin-style ERM motors) and these motors were placed in a 3x3 grid[1]. The grid had a horizontal spacing of 4 cm between the motors and a vertical spacing of 6 cm. The vertical spacing was larger because pilot testing showed that spatial patterns felt compressed in the vertical direction. This was solved by placing motors further apart in the vertical direction. Where appropriate we used interpolation, i.e. a second motor was turned on before the first one switched off so that there was an overlap in time. This makes the path that is being traced to be perceived more smoothly and more like a continuous path instead of discrete sequential vibrations. In sessions 2 and 3 we also switched on the first motor of a traced shape for slightly longer than the other motors as results from WP 7 suggest that this increases recognizability of the patterns. The set of vibration motors used here were controlled with an Arduino Nano which only has 3 pulse width modulation pins. This means that we couldn't control the vibration strength as we could only switch motors on or off. Perceived vibration strength was for some vibrotactile patterns varied by varying the number of motors that was switched on simultaneously.

For each session we took a selection of SHC haptices from the Dutch Handbook Social Haptic Communication. We tried to mimic the haptices using vibrotactile patterns as closely as possible. For some haptices this is not possible and we would have to deviate quite far from the regular haptices. For the first session we chose a subset of 6 haptices that we could closely mimic with vibrotactile patterns. As the results from that session were encouraging, we expanded the set of vibrotactile patterns for the other two sessions.

[1] The final HIPI will incorporate a 4x4 grid of motors following the design recommendations presented in this Deliverable. However, at the time of these tests we did not have access to a 4x4 grid due to COVID-19 measures restricting lab access.

In each session the participant with deafblindness tried the vibrotactile patterns first. They described what they felt like and what they thought which haptice we were trying to mimic. The vibrotactile patterns were repeated as often as they liked. After all participants had tried the vibrotactile patterns, we discussed their impressions and improvements were implemented. Sometimes also new vibrotactile patterns were designed together during the session. The results reported here focus on the feedback we received from the user with deafblindness in each of the sessions in particular. The other participants tried the vibrotactile patterns after the participant with deafblindness and had already heard the feedback from the first participant.

Session 1 – First exploration

This session was performed in March 2020. Participants were a co-teacher couple who are part of the SHC group The Netherlands. One participant has deafblindness. This was the very first time we presented the vibrotactile patterns to a user with deafblindness (apart from a pilot demo at one of our consortium meetings). We selected 6 haptices for this initial test session (Figure 1).

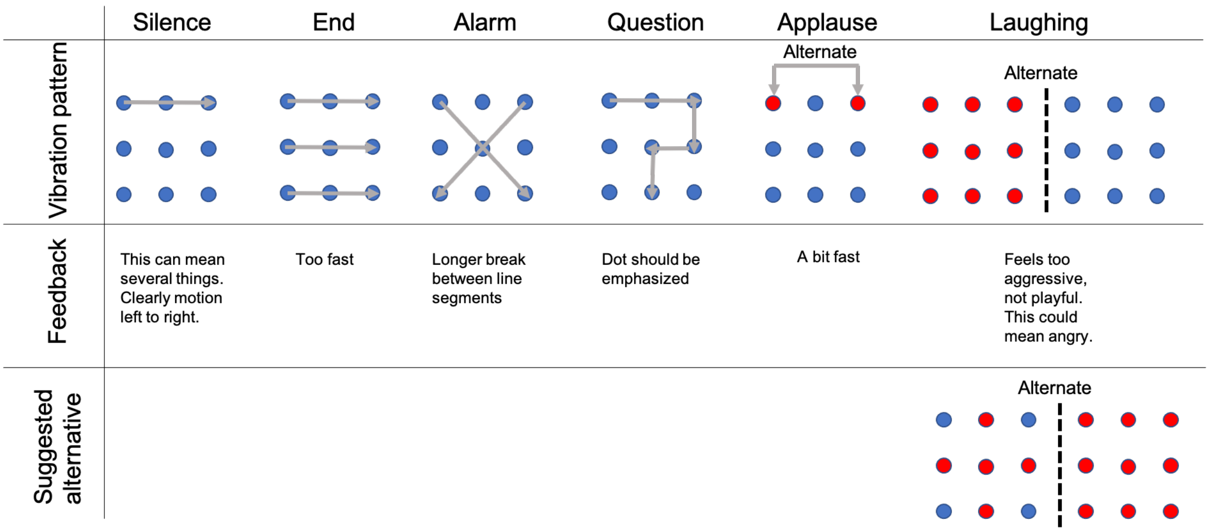

Figure 1 Set of vibrotactile patterns that were designed to mimic social haptic communication haptices in test session 1. The gray arrows indicate that motors were sequentially switched on and off with an overlap between subsequent motors to induce the sensation of a shape being traced. Blue dots indicate the position of a vibration motor. For patterns in which no shape was traced the motors that were switched on are indicated with red dots. The shown feedback from the participants is paraphrased. For 'laughing' an alternative vibrotactile pattern was suggested by the participants. For the other patterns only changes in the duration of motor activation and breaks between motor activation were implemented.

The main feedback from both of the participants in session 1 was that often the pattern was displayed too fast. Especially in the case of 'silence' a motion from left to right can indicate different meanings and the speed plays a role in differentiating the meaning. Another important observation was that in the case of 'alarm' for one of the participants the time between the end of the first line segment and the start of the second was too short. This meant that this shape was perceived to be one continuous trace instead of two separate line segments. The vibrotactile pattern for laughing was perceived as rather aggressive and that laughing should feel more happy and playful. It was suggested that the pattern that was originally designed for laughing would be better to indicate 'angry'. During the session we designed a new pattern for 'laughing'. The main difference is that the new patterns feels like a gradual increase and decrease in intensity. This makes it come across less aggressive.

General feedback from the participants at the end of the session indicated that they felt that it would be important to be able to communicate emotions and also the intensity of the emotions (i.e. haptemes). It was clear from the explorative sessions that indeed users familiar with SHC were able to recognize the vibrotactile patterns with only a little effort. Also, their feedback was very useful for improving recognizability of the patterns. Due to the Corona virus pandemic we had to wait almost a full year before the opportunity for follow-up sessions occurred. These sessions were done with other members of the SHC The Netherlands group.

Session 2 – Emotions

The second session was done in February 2021. During this session three members of the SHC The Netherlands group were present. One of them had deafblindness. The participants were told that all vibrotactile patterns in this session were intended to mimic haptices from the Emotions chapter in the Dutch SHC handbook.

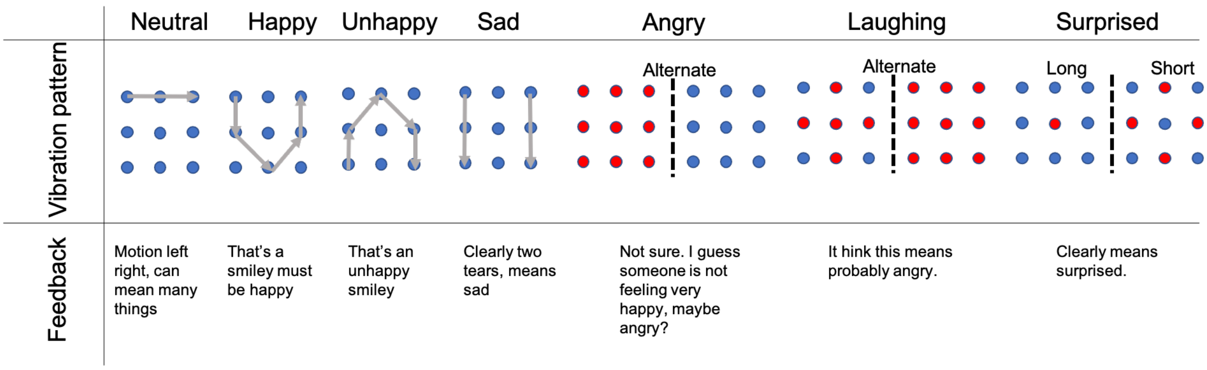

Figure 2 Test session 2 focussed on emotions. A set of 7 vibrotactile patterns was designed to mimic haptices indicating emotions. The shown feedback from the participants is paraphrased.

Notably the vibrotactile patterns for "Happy", "Unhappy", "Sad" and "Surprised" were recognized immediately by the participant with deafblindness. Similar to the feedback in the first session, this participant indicated that the pattern for "Neutral" was difficult because it is similar to the haptice for "Silence'. The vibrotactile pattern for "Laughing" was confused with "Angry" initially. After a few repetitions the participant with deafblindness was able to tell these patterns apart.

The fact that so many of the vibrotactile patterns were immediately recognized is very encouraging. Also the participants indicated that they thought that it would take only little practice to learn to recognize patterns that were less similar to the normal SHC haptices. They also indicated that repeating the vibrotactile patterns a couple of times could be used as a way to indicate the strength of an emotion. This would be very simple to implement in the HIPI. After all participants had felt the vibrotactile patterns we discussed how we could translate other haptices to vibrotactile patterns. We decided on the haptice for "Uninterested/Looking away". The participants suggested a snake-like trace through the vibration motor grid. This new vibrotactile patterns was tried by the participants to make sure it felt like they thought it should feel and whether the speed was correct. This co-designed vibro-tactile pattern in shown in Figure 3.

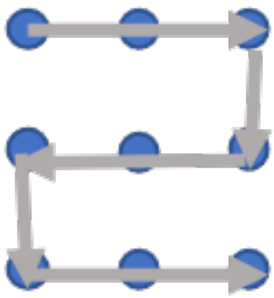

Figure 3 Vibrotactile pattern to indicate "Uninterested" that was designed with the participants during Session 2.

One difference between the feedback from the participants without deafblindness and the participant with deafblindness that was particularly notable pertained to the desired speed of the vibrotactile patterns. The participant with deafblindness expressed a clear priority for vibrotactile patterns to be displayed fast over increasing recognizability by displaying them more slowly. He indicated that he thought he would get used to the higher pace of the vibrotactile patterns and it was important to him that he wouldn't miss out on information especially during fast paced conversations.

Session 3 – General information

This session was also performed in February 2021. The participants were three members of the SHC The Netherlands group. None of them had participated in any of the other two sessions. One participant has deafblindness. The participants were told that in this session all vibrotactile patterns were meant to mimic haptices from the General chapter of the Dutch SHC handbook. Recognition of haptices for Emotions such as used in Session 2 might be highly intuitive. Therefore, we chose haptices from the General chapter because we wanted to test how easily these would be recognized.

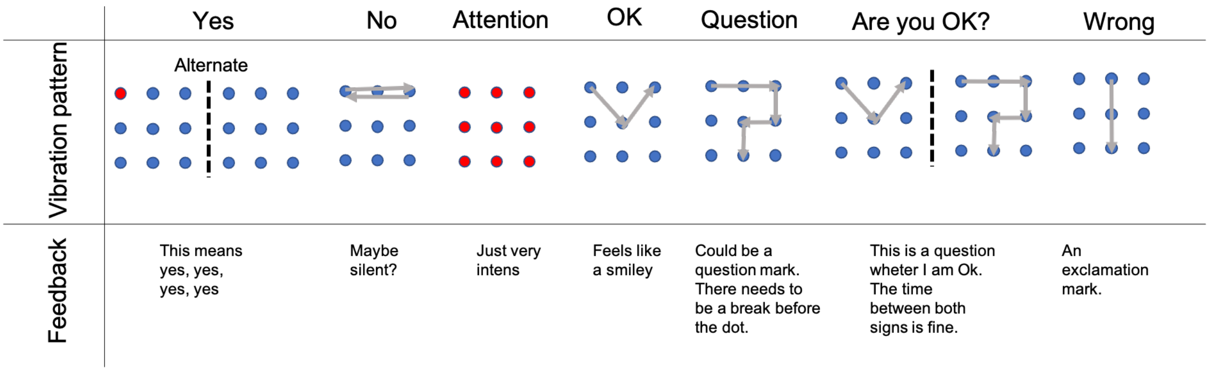

Figure 4 Test session 3 focussed on general information. A set of 7 vibrotactile patterns was designed to mimic haptices. The shown feedback from the participants is paraphrased.

The haptices for "Yes" and "Question" were immediately recognized by the participant with deafblindness. The haptice for "No" was difficult to recognize. This was due to the fact that we had emphasized the starting point like in other patterns of sessions 2 and 3, but in this case also the point where the motion reversed by switching the motors at those points on for longer. In this specific case this resulted in a perceived rhythm that was not associated with the haptice for "No". The haptice to ask for attention was effective for getting the attention of the participant, but it was too intense for the participant to relate this vibrotactile pattern to the haptice for asking attention. The vibrotactile pattern for "OK" was first recognized as a smiley by the participant with deafblindness. After this participant felt both the patterns for "OK" and the pattern for "Happy" that was used in session 2, she indicated the difference between the two was quite clear and that the pattern for "Happy" more strongly resembled a smiley. The vibrotactile pattern to ask "Are you OK?" was correctly recognized, but it should be noted that the participant with deafblindness was first familiarized with the patterns for "OK" and "Question". The pattern for "Wrong" was initially recognized as an exclamation mark. After discussing we concluded that the vibrotactile patterns more closely mimicked the haptice for "Wrong" than an exclamation mark because no dot was indicated. This led to the conclusion that in the vibrotactile pattern for "Question" the dot should be more clearly indicated. In the initial pattern the dot was indicated by leaving the last motor on for longer. The participants indicated that it would be better to introduce a short break before displaying the dot by switching the last motor on.

Discussion

The results of the test sessions clearly show that vibrotactile patterns can effectively mimic haptices and can thus be used to mimic SHC. The users indicated that they felt like they could easily learn to recognize vibrotactile patterns that were not immediately recognized. This serves as a proof of principle for the use of vibrotactile patterns in SHC. It was also clear that when designing the vibrotactile patterns it has to be kept in mind that, for instance, patterns that feel very intense will not be easily associated with mild emotions. This underscores the importance of using a process of co-creation when designing vibrotactile patterns for haptic communication. The outcomes of these user tests were provided as input for the haptograms that are designed in WP3.

Design recommendations from WP 6 for vibrotactile pattern design

Background

Below we present a series of design recommendations for the design of vibrotactile patterns. These recommendations are based on results from WP 6. For each recommendation it is indicated on what type of result it is based, i.e. published papers or unpublished observations from WP6 or existing literature reviewed in WP6. We distinguish between spatial and temporal design aspects. All recommendations are aimed at maximizing recognizability of the vibrotactile patterns and based on psychophysical studies as well as observations made during demonstrations of vibrotactile patterns to users including users with deafblindness.

Spatial lay-out of Vibration motors

1) The human back provides a large surface area for displaying vibration patterns. This is an advantage over other body parts and can compensate for the fact that the back generally has a lower tactile spatial resolution. (For a literature overview on this and related topics see Kappers & Plaisier, 2021)

2) Vibration motors placed directly on, or very near the spine are difficult to perceive and it is recommended that vibration motors are not placed on the spine. (based on unpublished observations, and it has been reported that sensitivity is reduced on top of the spine (Hoffmann et al., 2018))
3) Following point #2 it is recommended that an even number of columns is used in case motors are positioned in a rectangular grid.
4) We have found that the distance between motors on the back is perceived differently in the horizontal direction than in vertical direction and depends on whether both motors are on the same or different sides of the spine (Plaisier et al., 2020a). It is recommended that spacing between motors in the vertical direction should be larger than in the horizontal direction. If not, the spatial pattern will be perceived as compressed in the vertical direction. (based on unpublished observations and Kappers et al., 2020)
5) If the exact location of vibration is important it must be kept in mind that spatial accuracy on the back is low. Vibrations that are on the left and right side of the spine are much easier to distinguish than vibrations presented on the same side of the spine. Therefore, it is recommended that vibration patterns that are only distinguishable for the location at which they are presented are distinguishable by the fact that they are presented on the left or right side of the spine. (based on Plaisier et al., 2020a)
6) From point 5 it follows that the spatial lay-out of static patterns is very difficult to recognize. It is recommended that dynamic patterns are used.
7) The two-point threshold for vibration on the back can be as large as 52 mm depending on the time between the two vibrations (Stronks et al., 2016). This low spatial acuity indicates that four columns of vibration motors in a grid of the back is desirable. For larger numbers of columns the distance between vibration will be near or smaller than the two-point threshold. Instead of using more vibration motors it is recommended to use a smoothing method such as the Tactile brush algorithm. (Israr & Poupyrev, 2001)

Temporal aspects of vibration patterns

1) It is recommended to make a distinction between patterns that are meant to convey a shape and those that are not. In the case of patterns that convey a shape it should be avoided to switch multiple motors on at the same time as this will make it very difficult or even impossible for the user to perceive the shape. A possible reason for this is that is difficult to perceive the distance between two simultaneous vibration sources (Plaisier et al., 2020a). To convey a shape an outline should be traced by switching vibration motors on and off subsequently. An exception to this rule is when adjacent motors are switched simultaneously on in order to achieve a smoother trace such as when using the tactile brush algorithm. (based on unpublished observations and literature reviewed in Kappers & Plaisier, 2021)
2) Switching on a varying number of motors at the same time can be used to convey differences in overall intensity. For instance, switching on half of the available motors compared to all motors will result in a perceived vibration intensity difference. (based on unpublished observations)
3) When tracing a shape that consists of multiple line segments such as a cross, a significant break should be introduced between ending one segment and starting the next. In WP 6 good results have been achieved by introducing a break of about twice the length of the break between motors during tracing of a segment. For instance, we have used 0.12 s between subsequent motors when tracing a segment and introducing a break of 0.24 s between the first and the

second segment. It is expected that the optimal temporal characteristics will vary between users and is advisable to keep this customizable. (based on unpublished observations)

4) Recognizability of traced shapes can be increased by emphasizing corners. This can be, for instance, done by increasing the vibration duration of motors at the corners of a shape. (see literature reviewed in Kappers & Plaisier, 2021)
5) Vibration patterns can consist of a number of vibration pulses. This means a single vibration motor is switched on and off subsequently to produce a series of vibration pulses. In this case it is recommended that the different pulses are temporally grouped to increase recognizability. Six vibration pulses temporally presented in two groups of three pulses are easier to recognize than six pulses presented equally spaced in time. (based on Plaisier et al., 2020a)

Update on output of previous WP6 deliverables

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Kappers, A.M.L. & Plaisier, M.A. (2021). Hands-free devices for displaying speech and language in the tactile modality - Methods and approaches, IEEE Transactions on Haptics. DOI: 10.1109/TOH.2021.3051737

Plaisier, M.A., Holt, R. & Kappers, A.M.L., (2020) Representing numerosity through vibration patterns, IEEE Transactions on Haptics, Vol. 3 (4), 691-698. DOI: 10.1109/TOH.2020.2988211

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Perception of vibrotactile distance on the back

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Vibrotactile displays worn on the back can be used as sensory substitution device. Often vibrotactile stimulation is chosen because vibration motors are easy to incorporate and relatively cheap. When designing such displays knowledge about vibrotactile perception on the back is crucial. In the current study we investigated distance perception. Biases in distance perception can explain spatial distortions that occur when, for instance, tracing a shape using vibration. We investigated the effect of orientation (horizontal vs vertical), the effect of positioning with respect to the spine and the effect of switching vibration motors on sequentially versus simultaneously. Our study includes four conditions. The condition which had a horizontal orientation with both vibration motors switching on sequentially on the same side of the spine was chosen is the baseline condition. The other three conditions were compared to this baseline condition. We found that distances felt longer in the vertical direction than in the horizontal direction. Furthermore, distances were perceived to be longer when vibration motors were distributed on both sides of the spine compared to when they were on the same side. Finally, distances felt shorter when vibration motors were switched on simultaneously compared to sequentially. In the simultaneous case a distance of 4 cm was not clearly perceived differently than a distance of 12 cm. When designing vibrotactile displays these anisotropies in perceived distance need to be taken into account because otherwise the intended shape will not match the perceived shape. Also, dynamically presented distances are more clearly perceived than static distances. This finding supports recommendations made in previous studies that dynamic patterns are easier to perceive than static patterns.

Sensory substitution devices are often designed to help compensate for vision or hearing loss. Especially when there is a combination of vision and hearing loss the tactile modality is used to compensate. Braille displays are a well known example using the tactile modality to compensate the loss of vision. In that case tactile information is displayed to the finger tips. This is an obvious choice since the finger tips have a very high spatial acuity compared to other body parts. Despite their high spatial acuity, the finger tips are not in all cases the best choice. The hands can be occupied with a different task and are therefore not always available for communication. Another consideration is the available surface area. For instance, when the information that needs to be conveyed is represented by a shape that is traced, a body part with a larger surface area can be more desirable. Available surface area is one of the main reasons that devices have been designed to display information to the back of a person. The back has a relatively low spatial acuity[1], but it can still be a desirable location for sensory subsitution. For instance, it provides a large surface area which can be preferable despite low spatial acuity. Kristjánsson and colleagues have also argued that passive body parts might be preferable for sensory substitution as it enables devices to be, for instance, hands-free[2]. In addition, it has been shown that pattern recognition is actually better on the torso than on the forearm[3].

In the current study we will focus on vibrotactile stimulation on the back. Vibrotactile stimulation is often chosen over other types of stimulation because it is easy and cheap to implement using vibration motors. Previous studies have shown that such displays have been used to, for instance, convey shapes and letters[4–6], but also military hand signals[7]. Vibration patterns can be displayed statically where a number of vibration motors is switched on and off at the same time or dynamically where motors are switched on and off sequentially. The second case is most similar to tracing a shape on the back. It has been shown that for shapes and letters dynamic patterns are easier to recognise than static ones[4–6,8]. So, the recognisability of vibrotactile patterns is determined by both spatial and temporal aspects.

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Spatial distortions of, for instance, a perceived shape might be related to variations in spatial acuity. It has been shown that there are anisotropies in terms of discrimination threshold and localisation accuracy on the trunk. Vibrotactile stimulation has been shown to be more accurately localised near the spine and navel than at other positions around the torso[9,10], although reduced sensitivity has been found directly on the spine[11]. Furthermore, Hoffmann and colleagues have shown that vibrations on the back were more accurately localised with respect to one another in the horizontal direction than in the vertical direction[11]. In the same study it was also found that tactile sensitivity near the spine was higher than further towards the side, but only in the horizontal direction.

Anisotropy in spatial acuity does not necessarily have to lead to traced shapes being perceived as distorted. For pressure stimulation there are, however, many examples of distortions in distance perception which would lead to distorted shape perception. Longo and Haggard showed that when presenting a line on the hand of a participant by pressing two rods onto the skin, the length of this line was perceived to be different depending on whether it was presented along or across the hand[12]. This effect of distance being perceived as longer when presented across body width compared to along body length has been found for other body parts as well such as the forearm, thigh, shin and face[13–15]. There are variations across body locations in the size of this effect. For instance, this effect is larger for the hairy skin on the dorsal side of the hand than on the palm[16], and it was not found for the belly[17].

These biases in distance perception have been linked to variations in spatial acuity. Distances on body parts with high spatial acuity tend to be perceived as longer than on body parts with lower spatial acuity. This is known as Weber's illusion[18]. Longo and Haggard have introduced a model based on receptive fields[12]. They argued that to estimate the distance between two locations that are stimulated, the number of unstimulated receptive fields in between is used. The receptive field density is higher for areas with higher spatial acuity and there will be many unstimulated receptive fields in between two stimulation points. Also, receptive fields are often oval shaped and elongated along the distal axis. This can explain the perceived difference between distances across the body width compared to along the body length for pressure stimulation. It has been argued though that differences in receptive field density cannot be the whole explanation. Taylor-Clarke et al. have argued that based on differences in spatial acuity the differences in perceived length would be expected to be much larger than observed[19]. Also, they found that tactile distance perception was altered after viewing the hand via size-enhanced video.

Another reason for biases in distance perception to occur is the presence of anchor points[20]. Anchor points are usually joints. Spatial localisation can be better near such reference points than further away. For instance, localisation of a vibrotactile stimulus on the forearm has been shown to be best near the wrist or elbow[21]. The spine might also be considered to be an anchor point even though it does not move in the way that joints do. Tactile localisation has been shown to be better near the spine compared to other locations on the back[9,11]. The spine is on the body mid-line and its bilateral cortical representation might also play a role[9].

There is some evidence that anisotropy in terms of distance perception also exists on the back for vibrotactile stimulation. Kappers and colleagues recently found that perception of directionality is anisotropic across the back[22]. Furthermore, Novich and Eagleman found that a line traced using vibration motors along the diagonal was relatively often confused with a horizontal line[8]. Gaining understanding of perceptual biases in distance perception on the back will make it possible to anticipate distortions of shapes or letters drawn on the back.

In the current study we set out to systematically investigate distance perception on the back using vibrotactile stimulation. We use horizontal distances displayed on one side of the spine as our baseline condition. We compare this to distances presented in the vertical direction to test if indeed distances are systematically perceived differently between the two orientations. To test how the spine influences distance perception we compared the horizontal baseline condition to a horizontal distance presented with a vibration motor on the left and right sides of the spine. In all these conditions two vibration motors were switched on sequentially and thus distances were presented dynamically. To compare distance perception between dynamic and static distance presentation we added also a condition that was identical to the horizontal baseline condition except that both vibration motors were turned on simultaneously. The perceived distance was measured using the method of free magnitude estimation[23] and participants were asked to rate the size of the distance on an arbitrary scale that they were free to choose.

Results

The perceptual ratings were converted to Z scores to be able to compare across participants. For each distance the average perceptual rating was calculated for each condition (Fig. 1A). It can be seen that for most conditions the slope appears to be positive which is consistent with participants using larger ratings for larger distances. To investigate this further we performed linear regression on these data from each participant individually. The R^2 values averaged over participants were 0.8, 0.7, 0.8, and 0.6 for the "Horizontal", "Vertical", "Around spine", and "Simultaneous" conditions, respectively. A boxplot of the resulting slopes is shown in Fig. 1B. For each condition we used a t test on the individual participants' slopes to test whether they differed from zero and report Bonferroni corrected values to control the type I error. The slopes were significantly larger than zero for the "Around spine" ($t(11) = 6.0, p = 0.0004, d = 1.7$) and "Vertical" ($t(11) = 5.4, p = 0.0009, d = 1.5$) conditions. For the "Horizontal" condition the slope was marginally significant ($t(11) = 3.0, p = 0.051, d = 0.9$). The slope for the "Simultaneous" condition was not significantly different from zero ($t(11) = 1.9, p = 0.3, d = 0.6$). This indicates that in the "Simultaneous" condition the differences in distance were hardly perceived even though the largest distance was three times larger than the smallest distance.

To investigate the perceived distance further we calculated the average rating a participant gave in each condition. In Fig. 1C it can be clearly be seen that most participants rated distances to be smaller in the "Simultaneous" condition than in the other conditions. To compare between the four conditions we performed a Friedman test. We used a non-parametric test because a Shapiro–Wilks test showed a violation of the normality assumption.

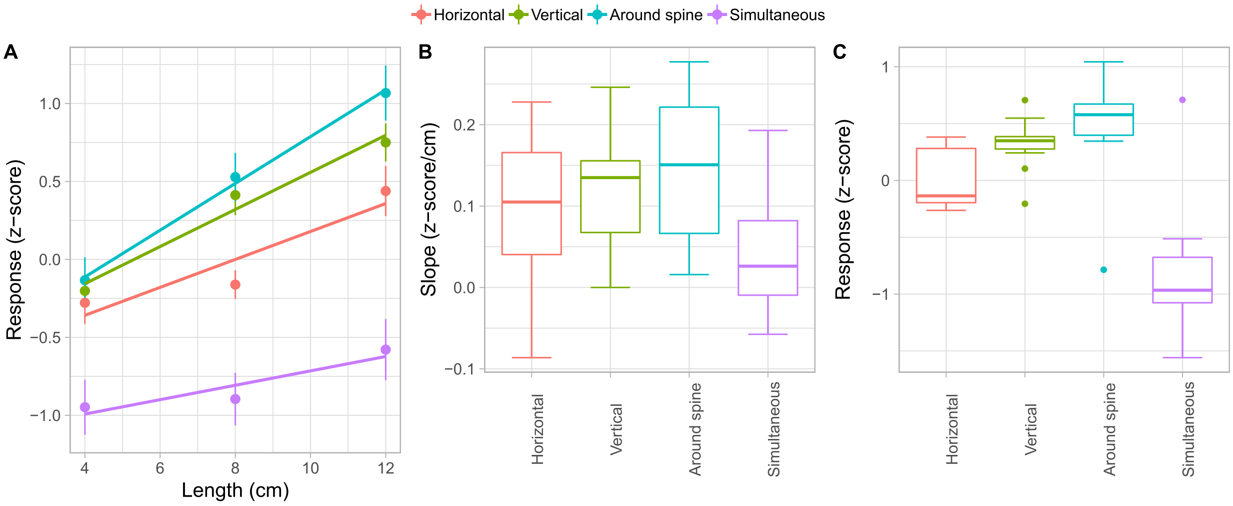

Figure 1. Results. (**A**) The perceptual distance ratings as a function of the presented distance. Dots indicate the mean and error bars the SE across participants. The lines indicate linear regression to the averaged distance ratings. (**B**) Boxplots of the slopes for linear regression to the individual participant's data and (**C**) the average distance ratings for each condition. Thick lines indicate the median and the boxes indicate the 25–75% intervals. The whiskers indicate the smallest value within the 25% minus 1.5 times the inter-quartile range and the largest value between 75% plus 1.5 times the inter-quartile range. Dots indicate values outside the aforementioned ranges.

The Friedman test showed a significant effect ($\chi^2(3) = 22.7, p < 0.0001, W = 0.6$). We followed this up with Wilcoxon signed rank tests to compare each condition against the "Horizontal" condition. We applied Bonferroni correction to the p levels reported here. This analysis showed that distance was perceived to be significantly smaller in the "Horizontal" condition than in the "Around spine" ($p = 0.02$) and "Vertical" conditions ($p = 0.02$). Furthermore, the distance in the "Horizontal" condition was perceived to be significantly longer than in the "Simultaneous" condition ($p = 0.03$).

Discussion

Our results show that the orientation in which a distance is presented on the back, the location and temporal aspects of the stimulation all systematically influence the perceived distance between two points of vibrotactile stimulation. We found that vertical distances were perceived to be significantly larger than horizontal distances when both points of stimulation were located on the same side of the spine. This is different from previous studies reporting that distances across the body width are generally perceived to be longer than along the body length when using pressure stimuli[12–16]. When using vibrotactile stimulation different receptors are activated than when pressure stimulation is used. However, the explanation proposed by Longo and Haggard in terms of receptive field density in general, which is related to spatial acuity, might also apply to vibrotactile stimulation[12]. There are studies reporting enhanced spatial acuity for vibrotactile stimulation near the spine[9,10]. Hoffmann and colleagues, however, have found a decrease in sensitivity directly on the spine[11]. This discrepancy might actually be due to stimulation directly on the spine compared to in the area directly next to the spine. Hoffmann and colleagues have argued for such an explanation as the spread of vibration is largely influenced by the underlying tissue[11]. Directly on the spine there is not much fleshy tissue. In the same study Hoffmann and colleagues also reported that spatial acuity in the horizontal direction was higher than in the vertical direction[11]. Based on the receptive field theory of Longo and Haggard[12], our finding of vertical distances being perceived to be longer than horizontal, indicate that the vertical acuity in the area where we presented the vertical distances was higher than the horizontal acuity in the area of the more peripherally presented horizontal distances. Since we presented the vertical distances near the spine, but explicitly not directly on the spine, this is not unlikely. Our finding that distances were perceived to be larger when vibration motors were placed on the left and right sides of the spine compared to when both vibration motors were placed on the same side of the spine seems also in agreement with increased spatial acuity near the spine. However, when the motors were on the left and right sides of the spine they could also have been more easily distinguishable due to hemispheric separation[9].

Finally, when both motors were turned on simultaneously we did not find a significant slope for the perceived distance as a function of the presented distance. This implies that a distance of 4 cm was not clearly distinguishable from a distance of 12 cm. Various studies on vibrotactile spatial acuity on the back have estimated the two-point-threshold between 13 and 60 mm depending on the vibration motor type, sequential or simultaneous presentation, the exact location of stimulation, and the psychophysical method used[10,11,24–28]. Our largest distance of 12 cm was thus twice as large as the largest estimate of the two-point-threshold. This means that participants were probably able to perceive that there were two separate points stimulated, but this of course does not mean that they could make a good estimate of the distance between these two points. Our results suggest that distance perception was much more imprecise for simultaneous stimulation than for sequential stimulation. This is in agreement with a previous study by Van Erp in which spatial localisation of vibrotactile stimuli was found to improve with increasing stimulus onset asynchronicity[10]. If stimuli can be better localised with respect to one another we would expect distances to feel longer based on Weber's illusion. This is in agreement with our results as we found that for simultaneous stimulation distances felt shorter than for sequential stimulation. A similar effects have been reported for pressure stimuli for which the distances of simultaneously applied stimuli were perceived as closer together than sequentially applied stimuli[29]. For pressure stimuli that were presented simultaneously and relatively closely together it has been reported that the illusion can occur that a single point in between the two sites of stimulation was pressed[30].

In fact, the absence of a significant slope for the perceived distance as a function of distance between vibration motors in the "Horizontal simultaneous" condition suggests that participants might have perceived this stimulus as single point of vibration. This is actually a known tactile illusion that can occur for vibrotactile sitmulation[31]. Two simultaneously presented vibrotactile stimuli can be perceived as a single vibration in between the two sites of stimulation. This effect can be exploited for drawing trajectories that are perceived as smoother when vibration motors are switched on sequentially with a small temporal overlap between the two. The tactile brush is an example of an algorithm which exploits this perceptual illusion[32]. The illusion is also used to increase the precision for navigational displays that convey directionality using vibration[33].

Overall, our results have important implications for the design of vibrotactile displays worn on the back. Based on our results we can make some recommendations. First, our results suggest that dynamic patterns are easier to perceive than static patterns as distances between vibrations were poorly perceived in the static case. This is in agreement with previous studies that have found that dynamically presented patterns and shapes are easier to perceive than static ones[4,6–8,34]. Secondly, presented shapes will feel distorted due to anisotropies in perceived distance for different locations on the back. These anisotropies in distance perception need to be compensated for in order for the perceived shape to feel as the intended shape. Specifically, distances close to the spine and those that cross the spine will be perceived to be longer than those further away or not crossing the spine.

Methods

Participants. Twelve students of Eindhoven University of Technology participated in this experiment (4 male, 8 female). Two participants were self-reported left handed and the other ten were right handed. Their ages ranged from 19 to 23 years. Participants were asked to wear thin clothing like a t-shirt and not a thick sweater during the experiment. They received financial compensation for their participation and gave written informed consent prior to the start of the experiment. All participants were naive as to the purpose of the experiment. This study was approved by the ethical committee of the Human Technology Interaction group at Eindhoven University of Technology and the study was performed according to the local guidelines and regulations. A power analysis was performed to determine the necessary number of participants. This analysis was also included application for ethical approval.

Experimental set-up and stimuli. Coin-style eccentric rotating mass (ERM) vibration motors were used to deliver the vibrotactile stimuli (Adafruit mini motor disc). These motors were incorporated in a vest which had small pockets in which the vibration motors could be placed (Fig. 2A). This vest was custom designed at University of Borås as part of the European project SUITCEYES. The vest was especially designed to allow for the placement of the motor to be easily adjustable and had many straps to allow tightening of the motors to the skin. The experimenter assisted the participants with putting on the vest. The motor in the center of the cross was located about 3–4 cm to the right of the T10 and T11 vertebral spinous processes. Care was taken that the motors for the "Around spine" condition were indeed positioned on the left and right sides of the spine. The experimenter also made sure that the motors for the horizontal conditions were indeed aligned horizontally and those for the vertical condition were aligned vertically. Due to variations in trunk size between participants there was some variation on the exact placement of the motors on the back. Furthermore, we asked participants to lean with the back against the backrest of the chair on which they were seated. This ensured that all motors pressed onto the skin of the participant throughout the experiment.

The vibration motors were provided with a voltage of 5 V using a power bank. Whether a motor received power or not was controlled using an Arduino Nano. In the "Horizontal simultaneous" condition power was supplied to both motors at the same time. In the other conditions the power to the second motor was supplied as soon as the first one was switched off. ERM motors have a a ramp-on and a ramp-off time. The ramp-on time is due to the eccentric mass having to gain momentum and the ramp-off time is because when the current is switched off the mass gradually slows down. We experimentally determined the ramp-on and ramp-off time of the type of ERM used here with the motors fixed in the same way as they were during the experiment. We performed this measurement for the motor positioned in the center of the cross by switching it on for 200 ms and measuring the accelerations using an accelerometer (Adafruit ADLX345) sampling at 460 Hz. A Hilbert transform was used to determine the waveform envelope and a Butterworth filter with a cut-off frequency of 10 Hz was subsequently used to smooth the envelope (see Fig. 3). The ramp-on time was determined as the time between the envelope raising above 5% of the peak value until 95% of the peak value was reached. The ramp-off time was of course determined as the time between the envelope dipping below 95% of the peak value and the moment at which it was below 5% of the peak value. Using this procedure the ramp-on time was determined to be 105 ms and the ramp-off time was 136 ms. This means that in the conditions where motors were switched on sequentially, there was overlap in the activity of the motors due to the ramp-off time of the first motor.

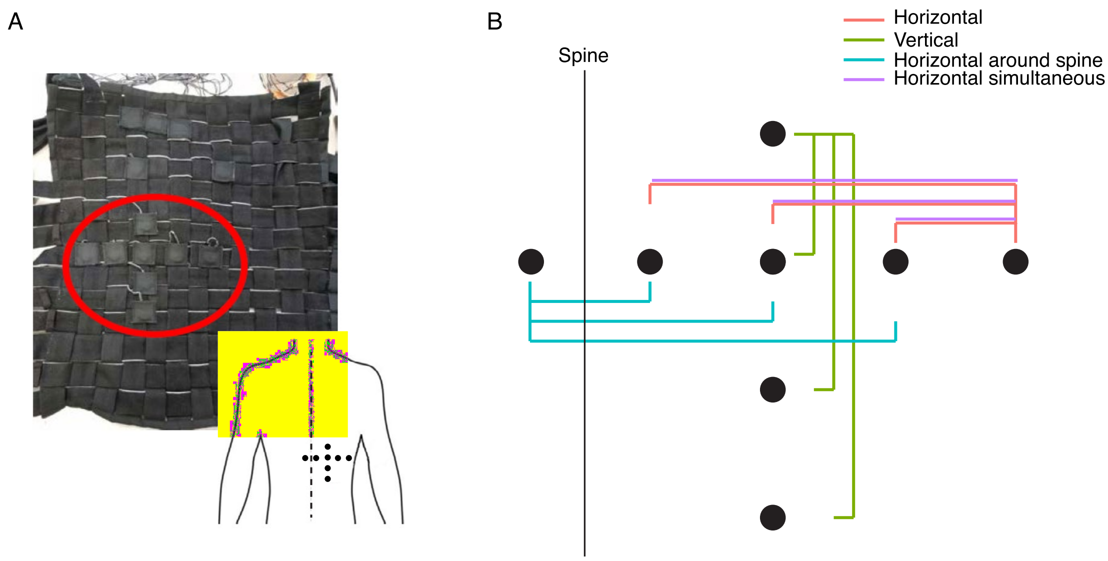

Figure 2. Experimental set-up and design. (**A**) A picture of the inside of the vest with the motors inserted in the pockets. The inset shows where the motors were located on the back of the participant while the vest was being worn. (**B**) Schematic representation of the configuration of the motors. The dots indicate the motors and the lines are used to indicate which motors turned on for the three distances (4, 8 and 12 cm) used.

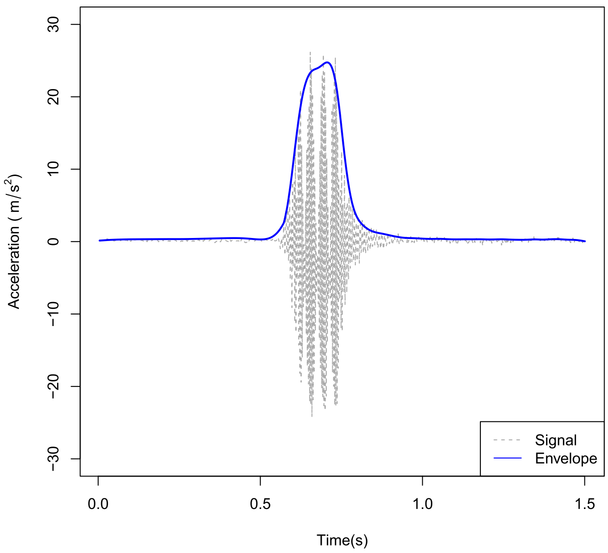

Figure 3. Accelerations measured when the vibration motor was switched on for 200 ms. The grey dotted line indicates the measured signal and the blue line represents the waveform envelope.

Experimental design and task. A trial consisted of two motors turning on, either sequentially or simultaneously, and participants had to give an estimate of the distance between the two motors. The distance between the motors was 4 cm, 8 cm, or 12 cm. Motors were switched on for 200 ms. Participants were asked to rate the distance using the method of free magnitude estimation[23]. This means that they were instructed that they just had to choose an arbitrary number for the first stimulus and continue from there. They were also instructed that larger numbers should correspond with larger distances.

There were four conditions. In the "Horizontal condition" two motors that were horizontally spaced were switched on sequentially. The most rightward motor switched on first. Both motors were always on the same side of the spine. The "Vertical condition" was the same as the "Horizontal condition" except that motors were spaced vertically and the motor and the highest location switched on first. In the "Around spine condition" the motors were horizontally spaced apart and switched on sequentially, but the motors were always on opposite sides of the spine. Finally, the "Simultaneous condition" was the same as the "Horizontal condition" except that the motors were switched on simultaneously. See Fig. 2B for an overview of the spatial layout used in the different conditions. Conditions were presented randomly interleaved in a blocked random order. This means that all distances for all conditions were presented randomly interleaved. A total of ten of these randomized blocks was presented without breaks between the blocks. This method ensured that conditions were homogeneously distributed over the whole experimental session. The participants were not aware of the ordering of the trials and no breaks were introduced between blocks. Furthermore, participants wore a pair of headphones playing white noise during the experiment to mask the sound from the vibration motors. Prior to starting the experiment a block of practice trials was performed to familiarise participants with the task. The practice block consisted of all trial types in random order and therefore contained 12 trials.

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Author contributions
All authors conceived the experiment, L.S. conducted the experiment, L.S. and M.P. analysed the results, M.P. and A.K. prepared the manuscript. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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Annex 2

Perception of Vibratory Direction on the Back

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Abstract. In this study, we investigated the accuracy and precision by which vibrotactile directions on the back can be perceived. All direction stimuli consisted of two successive vibrations, the first one always on a centre point on the spine, the second in one of 12 directions equally distributed over a circle. Twelve participants were presented with 144 vibrotactile directions. They were required to match the perceived direction with an arrow they could see and feel on a frontoparallel plane. The results show a clear oblique effect: performance in terms of both precision and accuracy was better with the cardinal directions than with the oblique ones. The results partly reproduce an anisotropy in perceived vertical and horizontal distances observed in other studies.

Keywords: Vibrotactile stimulation · Direction perception · Haptic matching.

1 Introduction

Vibrotactile displays provide ways to convey information in circumstances where vision or audition are occupied with different tasks or are not available at all. For persons with deafness, blindness or even deafblindness such devices might be helpful in daily tasks such as navigation and communication. In many situations a hands- and head-free device is preferred, and then the back is an obvious choice. Although there certainly has been done some research on the perception of vibrotactile stimulation on the back, the fundamental knowledge at this stage is far from sufficient to design an optimal device. Therefore, the current paper focuses on vibrotactile stimulation on the back, and more in particular, on the perception of direction.

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There are a few concepts that are of relevance here, and one of these is anisotropy. Weber [9] already found that vertical two-point pressure thresholds on the back are larger than the horizontal thresholds. Although pressure and vibration do not stimulate the same receptors, and thus Weber's observation on pressure thresholds does not necessarily apply to vibratory stimulation, the study by Hoffmann and colleagues [3] points in the same direction: they found that the accuracy of determining the direction of two subsequent vibration stimuli was higher for horizontal than for vertical directions.

Another relevant concept is the "oblique effect". Although this term has been used in many different experimental settings (both visual and haptic), the basic idea is that performance with oblique stimuli is worse than with stimuli oriented in cardinal (i.e. horizontal and vertical) directions. Performance can apply to both accuracy and precision. A task is performed accurately if the setting of the participant is close to the intended physical setting, so this is related to bias or systematic directional error. A task is performed precisely if subsequent measurements consistently lead to the same setting that is not necessarily the correct physical setting. So precision is related to variability or spread. Appelle and Gravetter [1], for example, found that rotating a bar to a specified orientation led to larger *variable* but not systematic *directional* errors for oblique orientations in both visual and haptic conditions. Lechelt and Verenka [6] asked participants to match the orientation of a test bar with that of a reference bar in the frontoparallel plane, again in both visual and haptic conditions. They also found much larger *variable* errors for the oblique orientations, but no *directional* bias. On the other hand, Kappers [5] reported systematic *directional* errors when the orientation of a bar had to be matched haptically to a bar at a different location in the horizontal plane. It remains to be seen how representative all these findings are for vibrotactile stimuli on the back.

Finally, it is important to take the difference between simultaneous and successive presentation into account. For pressure stimuli, Weber [9] already observed that the thresholds were smaller if stimuli were presented one after another. Similarly, for vibrotactile stimulation, both Eskilden and colleagues [2] and Novich and Eagleman [7] found better performance with sequential stimulation. Therefore, in the current study, we will only make use of successive stimulation.

In this study, we will investigate the perception of vibrotactile directions on the back. More in particular, we will investigate whether there are biases in the perception of direction, and whether there are differences in spread between the settings for cardinal and oblique directions.

2 Methods

2.1 Participants

Twelve students (7 female, 5 male) of Eindhoven University of Technology participated in this experiment. Their ages ranged between 18 and 23 years. Ten participants were right-handed, two were left-handed (self-report). They were unfamiliar with the research questions and the set-up. Before the experiment they gave written informed consent. They received a small financial compensation for participation. The experiments were approved by the Ethical Committee of the Human Technology Interaction group of Eindhoven University of Technology, The Netherlands.

2.2 Set-Up, Stimuli and Procedure

Twelve tactors (coin-style ERM vibration motors from Opencircuit, 8 mm diameter) were placed in velcro pockets at every 30° on a circle with a radius of 110 mm on the back of an office chair; an identical pocket with tactor was placed in the centre of the circle (see Fig. 1). A distance of 110 mm is well above the vibrotactile two-point discrimination threshold of 13–60 mm reported in several papers (e.g. [4,7,8]), and is about the maximum radius that could be presented on the back. Each trial consisted of a 1-s vibration of the centre tactor, followed by a 1-s break and a 1-s vibration of one of the other 12 tactors. This timing guaranteed that all vibration motors were always easy to distinguish. The vibrations were strong enough to be easily perceived for all locations on the back, but they were not necessarily perceived to be equally strong. During the practice session it was ensured that participants could indeed perceive all motors. Random blocks of the 12 different stimuli were presented 12 times, so the total number of trials per participant was 144.

The task of the participant was to indicate the direction in which the stimulus was felt by means of rotating an arrow located on a frontoparallel plane at about eye height and within easy reach (see Fig. 1d). They were explicitly instructed to touch the arrowhead with one of their finger tips. The participants put on blurred glasses that still allowed them to see the arrow, but prevented them from reading off the degrees on the protractor. Participants were not informed about the actual directions, nor the number of different directions. The experimenter was able to read off the adjusted orientation with a precision of 1°. Noise-cancelling headphones with white noise and earplugs were used to mask the sound of the vibrators.

Participants were asked to wear thin clothing to guarantee they could feel the vibratory stimulation. At the start of the experiment, the tactors on the chair were covered with a cloth so that the participant remained unware of the actual locations. The participants had to sit down on the chair with their back pressed against the back of the chair. With the help of a line marked on the chair (Fig. 1b), the experimenter made sure that the spine of the participant was aligned with a vertical line through the centre of the circle. The back of the chair was not adjusted in height for the individual participants, but as a difference in body height would result in at most a few cm difference on the back, the stimulated back areas were still quite similar. The participant was instructed explicitly that s/he should not move to ensure both contact and alignment were kept constant; the experimenter made sure they indeed remained with the back centered on the back rest throughout the experiment.

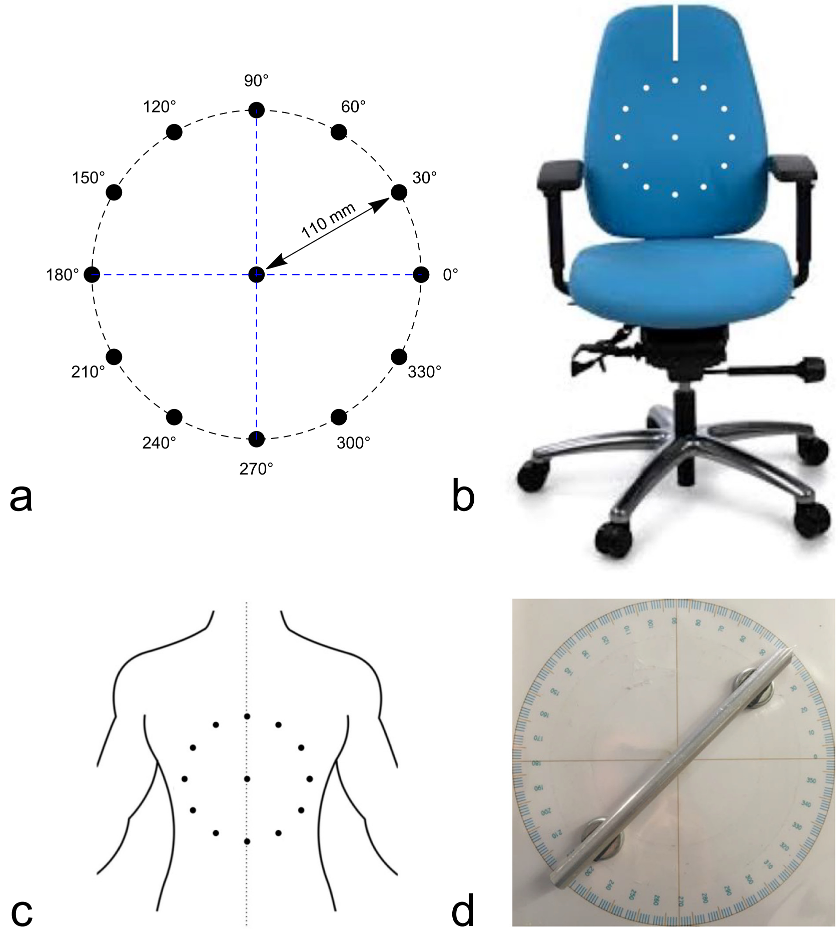

Fig. 1. Set-up. a) Circle with the 12 directions; b) Chair with the positions of the vibration motors (white dots) and the reference line for the spine (white line) indicated; c) Location of the circle of tactors on the back of the participant when seated on the chair; d) Arrow and protractor used to indicate the perceived direction.

The experiment started with a block of 12 different practice trials, after which the participant could ask remaining questions. Neither during the practice trials nor during the actual experiment feedback was given.

2.3 Data Analysis

In total there were 1728 (12 participants × 144) trials. 14 trials were discarded due to technical problems with the tactors. In 17 occasions the matched directions were about 180° off. This could either be due to a misperception of the participant or ignorance of the arrowhead. As the latter explanation seems much more likely than the former (some participants indeed confessed that they sometimes forgot to attend to the arrowhead), we decided to correct these cases. Finally, there were 16 clear outliers (leaving out such points led to a reduction in the standard deviation by at least a factor 2, but often much more). As these would have enormous effects on the standard deviations without being representative, it was decided to discard these 16 trials (less dan 1%).

For all analyses, we first computed mean and standard deviations per participant and per direction. Subsequently, we computed means and standard deviations over participants but per direction. We also compared results for cardinal (0°, 90°, 180° and 270°) and oblique (all other) directions.

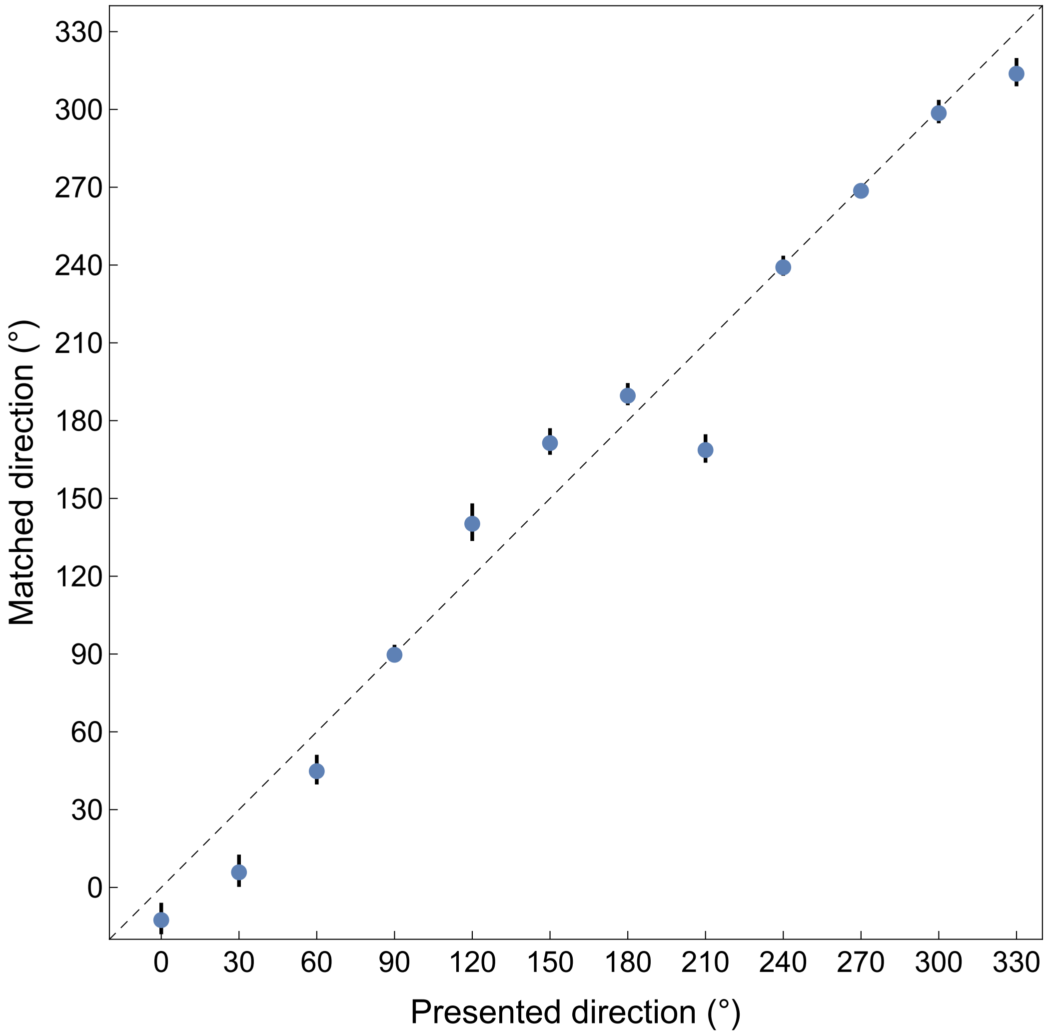

Fig. 2. Matched directions as a function of presented directions averaged over all participants. The error bars indicate standard errors of the mean and the dashed line the unity line.

3 Results

In Fig. 2 the matched directions are shown as a function of the presented directions. The error bars indicate standard errors over the averages of participants.

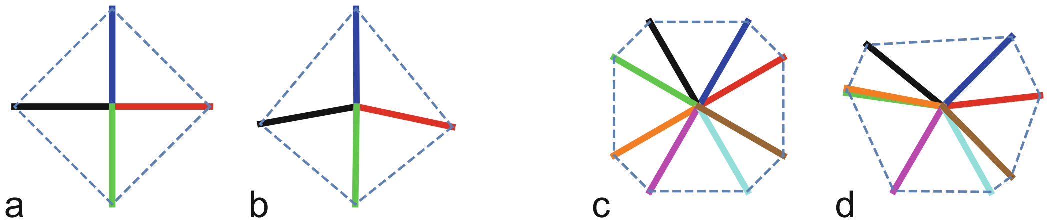

Fig. 3. Graphical representation of the deviations shown in Fig. 2. a) Presented cardinal directions; b) Matched cardinal directions; c) Presented oblique orientations; d) Matched oblique orientations. The same colours in a and b, and in c and d indicate pairs of presented and matched directions. (Color figure online)

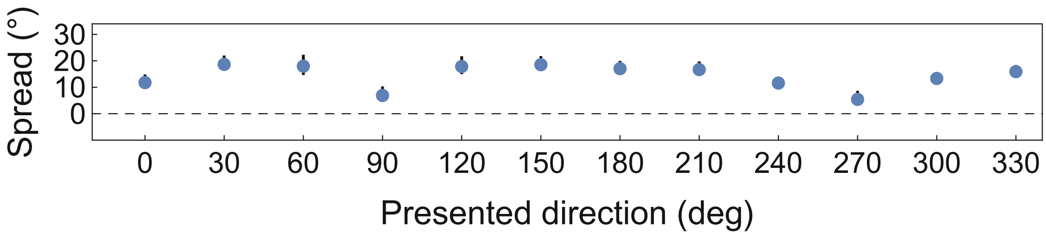

Fig. 4. Standard deviations (spread) averaged over participants as a function of presented directions. The error bars (these are so small that they are hardly visible) indicate standard errors of the mean.

It can be seen that there is quite some variation: some directions are clearly underestimated, whereas some other directions are overestimated. A graphical representation of these mismatches is shown in Fig. 3 for the cardinal and oblique directions separately. In Fig. 3a and b it can be seen that the vertical directions are matched correctly, whereas the horizontal directions point somewhat downward. The upward oblique orientations are all adjusted more horizontally, whereas the downward oblique directions do not show a clear pattern (Fig. 3c and d).

In Fig. 4 the standard deviations (spread) averaged over participants is shown. These values give an indication about how precise the participants are in their matching performance. It can be seen that especially the spread of the two vertical directions (90° and 270°) is quite small.

One of the research questions is whether there are differences in performance between cardinal and oblique direction as has been found in other studies not using vibrotactile stimuli and not presented on the back (e.g. [1,5,6]). To investigate this, we need to look at the *absolute* values of the mean deviations per participant, because *signed* values might average out over the various directions (see Fig. 2). In Fig. 5a we show the absolute mean deviations averaged over participants for both the cardinal ($M = 9.4$, $SD = 6.2$) and oblique ($M = 20.2$, $SD = 5.5$) directions. It can clearly be seen that the values of the oblique directions are higher than those of the cardinal directions. A paired t-test shows that this difference is highly significant: $t(11)=5.5$, $p < 0.0002$. In Fig. 5b we compare the

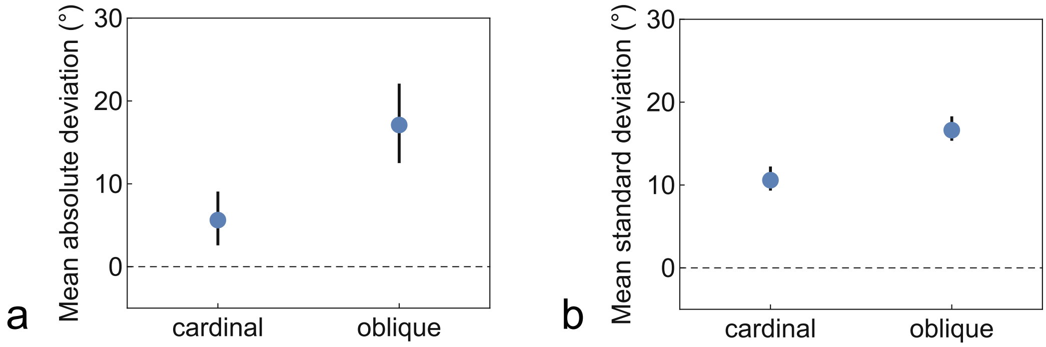

Fig. 5. Comparison of performance on cardinal and oblique directions. a) Absolute mean deviations averaged over participants for both the cardinal and oblique directions; b) Standard deviations in the cardinal and oblique directions averaged over participants. The error bars indicate standard errors of the mean.

spread of the deviations in the cardinal (M = 10.8, SD = 4.4) and oblique (M = 16.8, SD = 4.5) directions. Also this difference is significant: $t(11) = 4.2$, $p <$ 0.002.

4 Discussion and Conclusions

The aim of this study was to investigate the perception of vibrotactile directions presented on the back. The results show that the participants were well able to do this task, although they made some systematic directional errors. In Figs. 2 and 3, it can be seen that vertical directions (90° and 270°) were perceived veridical and in Fig. 4 it can be seen that also the variable errors for these directions were small. As the tactors used to generate these directions were all located on the spine of the participants, it is likely that perception was helped by the spine serving as anchor point. Other studies on vibrotactile perception also mention improved performance on or near the spine (e.g. [3,8]).

For the horizontal directions (especially 0°) the directional and variable errors are also relatively small, although perception is not veridical. Both horizontal directions are perceived as somewhat downward. Interestingly, Weber [9] already observed a somewhat oblique orientation for a two-point pressure threshold measurement on the back, albeit that this seems a rather informal observation without a mention of the actual direction. Novich and Eagleman [7] did not find confusions of their horizontal vibrotactile stimuli with oblique stimuli. However, in their 8-alternatives forced-choice experiment participants had the choice of 4 cardinal directions and 4 diagonal directions. Confusing horizontal with oblique would imply a misperception of 45° which is probably a too large difference.

The oblique directions caused both larger directional errors (biases) and larger variability of the errors than the cardinal directions. The type of deviations can best be appreciated in Fig. 3d. Especially the upward oblique directions appear to be perceived as closer to horizontal. A similar finding was reported by Novich and Eagleman [7]. Using somewhat smaller distances, they showed that especially the upward oblique directions were perceived as horizontal. Also relevant here are the results of the study by Hoffmann et al. [3] who found an anisotropy in horizontal and vertical acuity: their vertical distances were perceived as smaller than the horizontal distances. In our experiment, such an anisotropy would lead to oblique directions being perceived towards the horizontal and that is what we found for 5 out of the 8 oblique directions.

This study provides insights into how accurate and precise vibrotactile directions can be perceived. This is useful information for the design of vibrotactile devices intended to convey information to the users. In the current study, the first active tactor was always located on the spine. As the spine may have served as an anchor point, it remains a question whether the results are representative for a similar off-centre presentation of directions.

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Annex 3

The role of the spine in the perception of vibrotactile direction

Myrthe A. Plaisier, and Astrid M.L. Kappers

Abstract—Vibrations on the back of a person can be used to convey information about direction. When switching on two vibration motors sequentially the angle of the line connecting the two vibrations can be estimated. In this case an effect called the oblique effect can occur. This means that perception of cardinal directions is more accurate and precise than perception of oblique directions. This effect might be influenced by the positioning of the vibrations with respect to the spin because some studies have suggested that the spine might act as an anchor point. We investigated the effect of the positioning of vibration motors with respect to the spine on the oblique effect. In the first condition all vibration motors were placed in a circle around the spine ('Circle' condition) and direction was conveyed by switching on vibration motors on opposite sides of the circle. In the second condition the motors were placed in two semi-circles of which the centers were on the left and right sides of the back ('Semi-circle' condition). In this condition first one of the motors in the center of one of the semi-circles was switched on followed by a vibration motor on the semi-circle. We found that participants made larger errors and showed a larger spread for oblique angles than for cardinal angles in both conditions. This indicates that the oblique effect occurred. This shows that centring the vibrations around the spine is no prerequisite for the oblique effect to occur. Furthermore, we found that both errors and spread were larger in the 'Semi-circle' condition than in the 'Circle' condition. This suggests that centring the vibration motors in a circle centred around the spin improved task performance, although this result could also have been influenced by the distance between vibration motors.

Index Terms—Vibrotactile, haptic perception, direction

1 Introduction

A way to convey information through touch is by tracing shapes on, for instance, the back of another person. Most people will be familiar with this as a game from childhood. It is, however, also used as a way of communication by persons with a combination of vision and hearing loss. This is known as Social Haptic Communication and is mostly used in the European Nordic countries. It was developed by Palmer and Lahtinen in the early nineties [1], [2]. Since then the number of countries in which a version of Social Haptic Communication has been introduced is increasing. Often it is used to give situational information such as the lay-out of a room, whether there is applause, or about emotions. While usually shapes are traced with the finger applying pressure, it has been shown repeatedly that shapes can also be traced using vibration. For example, it has been shown that geometric shapes or letters that are traced with vibration can be recognized by participants [3], [4], [5]. Vibration could provide an opportunity to enable Social Haptic Communication over large distances, to send messages to multiple users at the same time or to even automate it. Therefore, it is important to advance understanding of how shapes that are traced using vibration are perceived.

Like several other studies, we decided to focus on perception of vibration on the back. The reason for this is that the back provides a large surface area which is an advantage despite the fact that the back has relatively low spatial acuity. Furthermore, in Social Haptic Communication also often the back is used for the area of communication. While the back provides a rather large surface area, it is also potentially quite inhomogeneous. For instance, localisation of vibration is better near the spine than at other positions around the torso [6], [7]. Directly on the spine sensitivity is, however, reduced [8]. In addition localisation of vibrations with respect to one another was found to be more accurate in the horizontal direction than in the vertical direction [8]. In a recent study, we looked into the perceived distance between two vibrations [9]. We found that distances were perceived as being larger in the vertical direction than in the horizontal direction. Also distances were perceived as larger when two vibrations were on opposite sides of the spine compared to when they were not. Such anisotropies might lead to the traced shapes being perceived in a distorted way.

In another recent study we found that the perceived angle between two vibrations is subject to systematic biases [10]. We found that cardinal angles were perceived more accurately and with higher precision than oblique angles. This is known as the 'oblique effect' and this effect is known to exist for vision as well as haptics. In the same study we also found that oblique angles were perceived to be more biased towards the horizontal direction. This can lead to traced shapes feeling compressed in the vertical direction. In a pilot test we actually found that this appears to be the case. Therefore, we wanted to investigate this effect further. In the first study that we have done on perceived vibrotactile direction we always presented a vibration at the center point of a circle located on the spine before presenting a vibration at a certain angle on the circle around it. As

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the center point was located on the spine, the spine may have functioned as an anchor point [11]. Often anchor points are joints and localisation of stimuli is better near such an anchor point such as the wrist or elbow [12]. It has been argued that the spine also functions as an anchor point given that localisation is more accurate near the spine than on other locations on the back and due to its location at the body mid-line [6], [8]. This might, for instance, be the reason that perceived distances are larger when vibration points were presented on opposite sides of the spine [9]. In the current study we investigated the role of the spine in perception of vibrotactile direction.

We included two conditions. In one condition a set of vibration motors were placed on a circle that was centred around the spine similar to our previous study [10]. This time, however, we did not provide a vibration in the center of the circle. A direction was conveyed by sequentially switching on vibration motors on opposite sides of the circle (Figure 1A). We will refer to this as the 'Circle' condition. In a second condition we did not center the circle around the spine, because even if we didn't provide a vibration at the center of the circle, the spine might still be used as an anchor point relative to which the direction between the two points on the circle is perceived. To this end we positioned the motors in two semi-circles with the center points on the far left and right sides of the back (Figure 1B). This condition will be referred to as 'Semi-circle' condition. We tested whether the oblique effect occurs in both cases. If so, this indicates that the occurrence of the oblique effect is largely independent of the positioning of the vibrations with respect to the spine. Furthermore, we tested whether performance differed between the two conditions in terms of accuracy and precision of the perceived angles.

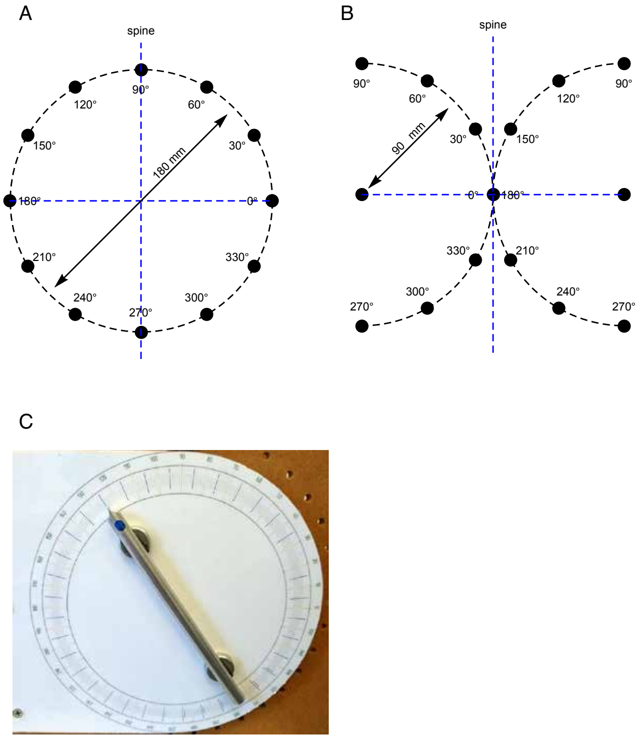

Fig. 1. A) Lay-out of the vibration motors in the 'Circle' condition. B) Lay-out of the vibration motors in the 'Semi-circle' condition. C) Arrow that participants rotated to indicate the perceived direction between the two sequential vibrations. The blue dot was positioned at the end with the arrow head. The arrow head could also be felt.

2 METHOD

2.1 Participants

Twelve participants (2 were self-reported left-handed and the others right-handed, age range 21 – 25) participated in this study. All participants were students of Eindhoven University of Technology and received financial compensation for their participation. They signed informed consent prior to the start of the experiment and the study was approved by the ethical committee of the Human Technology Interaction section of Eindhoven University of Technology.

2.2 Setup and stimuli

The hardware consisted of a micro controller (Arduino mega) and coin-style ERM vibration motors (0834 flat vibration motor via Opencircuit). The vibration motors had a diameter of 8 mm. The motors were fixed to the backrest of an office chair. The motors could be positioned in a circle or in two semi-circles with a radius of 9 cm (Figure 1 A and B). The position of the backrest was kept fixed, so the exact positioning of the motors on the back varied with the height of the participants. The radius of the circle was chosen such that the motors were in contact with the back also for the participants with the narrowest back. The motors were positioned well below the shoulder blades for all participants.

Participants were seated on the office chair with their back centred on the back-rest. On the table directly in front of them was an arrow that could be rotated in the frontoparallel plane (Figure 1C). The arrow was within easy reach and roughly at eye height. Participants wore blurring goggles to prevent them from reading the degrees on the protractor around the arrow. It was important that participants were aware which direction the arrow head was pointing. They could feel the arrow head, but due to the blurring goggles they couldn't clearly see the arrow head. Therefore, the arrow head was emphasised with a blue dot. To dampen the sounds of the vibration motors the participants wore noise-canceling head phones playing white noise.

2.3 Experimental procedure and design

All participants performed each of the two conditions. The order in which the conditions were performed was counter-balanced across participants. The conditions were performed in separate experimental sessions of 45 minutes with at least 2 hours between the sessions, but mostly they were performed on different days. Prior to the start of a testing session they performed a block of practice trials to become familiar with the task. During a practice block each direction was presented once in random order. Participants were not aware of the spatial lay-out of the motors and the motors were obscured from view with a black sheet at all times.

During a trial a motor was switched on for 1 second and after a break of 1 second the second motor was switched on

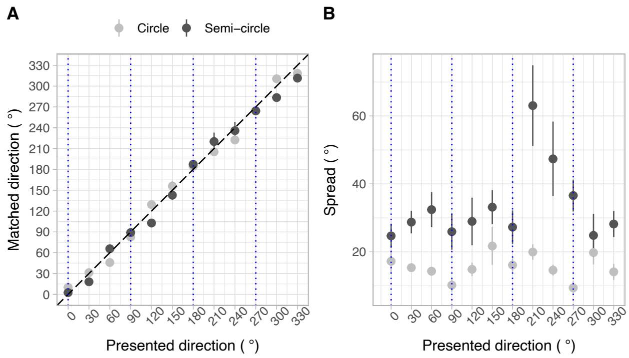

Fig. 2. Results as a function of the presented angle for both conditions. A) The responded angle averaged over participants. B) The spread (standard deviation) averaged over participants. The vertical dashed lines indicate the cardinal angles and the error bars indicate standard error of the mean.

for 1 second. After the second motor was switched off the participant was asked to match perceived direction between the first and the second motor by rotating the arrow. The experimenter read off the setting on the protractor and entered it into the computer before starting the next trial. All 12 directions were presented in random order within a block; all participants received 12 such blocks. Participants were not aware of these blocks of trials as there were no breaks in between blocks. The procedure and the directions that were presented were the same for both conditions. Note, however, that in the 'Semi-circle' condition 90° and 270° were presented twice as often as in the 'Circle' condition because they were presented on the left and on the right sides of the back.

3 Results

Due to technical difficulties sometimes the second motor did not switch on. Trials where this happened were excluded (less than 2% of all trials). Figure 2A shows the matched angle as a function of the presented angle collapsed over participants. It can be seen that for both conditions the data follows the unity line indicating that participants were able to perform the task. It can also be seen that some under- and over-estimations occurred. A graphical representation of the resulting deformation is shown in Figure 3. It can be seen that there was a tendency for matched angles in the oblique case to be biased towards the horizontal in the 'Circle' condition. The cardinal angles were also somewhat deformed, with the matched vertical directions being tilted to the left or right and especially in the 'Semi-circle' condition the matched horizontal angles were tilted downwards. Deformations appear to be smaller for the cardinal angels than for the oblique angles. This can also be seen in Figure 2A in which responses appear to be closest to the unity line for cardinal angles (indicated with the vertical dashed lines). We used the spread as a measure of the precision of the matched angle shown in 2B. This is the standard deviation of the individual participant's responses as a function of presented angle collapsed over all participants. It can be seen that the standard deviation was systematically larger for the 'Semi-circle' condition than the 'Circle' condition.

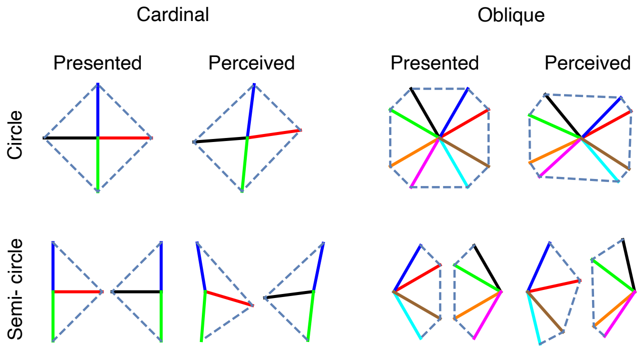

Fig. 3. Graphical representation of the presented and match angles averaged over all participants for each angle. This is shown separately for the two conditions and cardinal/oblique angles.

To investigate a possible 'oblique effect' and whether there was an effect of condition, the data were aggregated over all angles for cardinal and oblique angles separately. We did this for the absolute error and the spread. We took the absolute error just before collapsing over all oblique and cardinal angles because the signed error might average out across the different angles. Figure 4A shows the absolute error for both conditions and cardinal and oblique angles. The same is shown for the spread in Figure 4B. It can be seen that the absolute error as well as the spread were larger for the 'Semi-circle' condition than the 'Circle' condition. Both the absolute error and spread were also larger for oblique angles than cardinal angles. To analyse possible effects we performed a 2x2 (Condition x Cardinal/Oblique) repeated measures ANOVA on the absolute errors and on the spread. For the absolute error this analysis showed a main effect of Condition ($F(11,1) = 16.7, p = 0.002$) as well as for Cardinal/Oblique ($F(11,1) = 24.5, p = 0.0004$), but no interaction effect. For the spread the ANOVA showed a main effect of Condition ($F(11,1) = 34.2, p = 0.0001$) and of Cardinal/Oblique ($F(11,1) = 7.1, p = 0.02$), while no interaction effect was found.

4 Discussion and Conclusions

Our results show that accuracy and precision of the matched angles was higher for cardinal than oblique angles. This is a clear demonstration of the oblique effect and is in agreement with our results from a previous study [10]. Given that we found the oblique effect also for the 'Semi-circle' condition it is not likely that the spine being in the center of the circle induced the oblique effect. There was, however, a clear difference in the performance between the two conditions. Performance in terms of the size of the bias and the precision was better in the 'Circle' condition than in the 'Semi-circle' condition. This could be due to the distance between the two points of vibration (18 cm in 'Circle' condition and 9 cm in the 'Semi-circle' condition). Vibrations that are located further apart might be easier to locate and therefore lead to higher precision and increased accuracy of the matched angles. The two-point discrimination threshold for vibrotactile stimuli does depend on several factors such as the type of vibration motors [13], but also increases with inter-stimulus

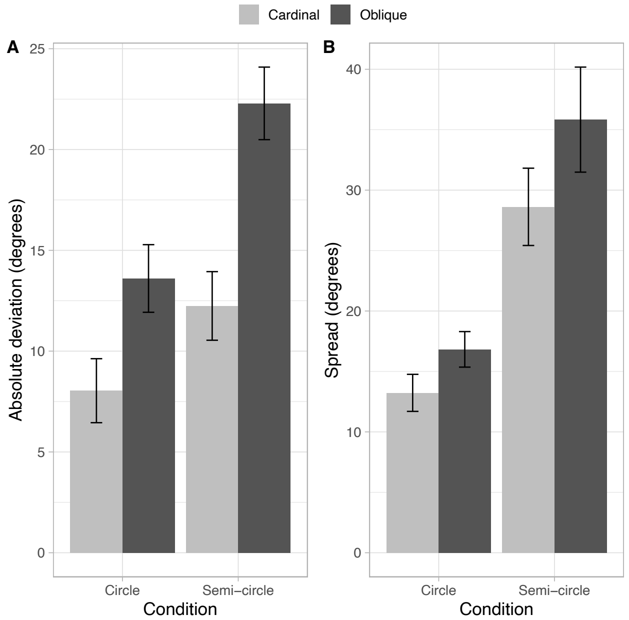

Fig. 4. Results averaged over cardinal and oblique angles. A) The absolute deviation for both conditions averaged over participants. B) The spread (standard deviation) averaged over participants. The error bars indicate the standard error of the mean.

onset asynchronicity [14]. In a study that resembled our set-up most closely a two-point threshold of about 2.8 cm at a stimulus onset asynchoronicity of 200 ms [14]. In the current study the onset asychronicity of the two vibrations was 1 s and in both conditions the distances were larger than this two-point threshold. Furthermore, in our previous study we used a circle centered around the spine, but with a center vibration, the distance between the two vibrations was 11 cm [10]. In that case we found a spread of $10.8 \pm 4.4(SD)$ for cardinal angles and $16.8 \pm 4.5(SD)$ for oblique angles. This is comparable to the spread in the 'Circle' condition (Cardinal: $13.2 \pm 1.53(SEM)$, Oblique: $16.8 \pm 1.47(SEM)$) of the current study. The spread in the 'Semi-circle' condition was, however, about twice as large (Cardinal: $28.6 \pm 3.20(SEM)$, Oblique: $35.8 \pm 4.35(SEM)$). Although an effect of the distance between the two vibrations cannot be excluded, given the size of the difference it is likely that the position relative to the spine also played a role. This is supported by participants indicating upon informal debriefing that they found the 'Semi-circle' condition quite confusing. This suggest an advantage for tracing shapes centred around the spine.

Besides the fact that the vibration motors were positioned in a circle centred on the spine in the 'Circle' condition and not in the 'Semi-circle' condition, there is another interesting difference between the two conditions. In the 'Circle' condition the two vibrations were almost always located on opposite sides of the spine except for the vertical directions (90° and 270°) when both motors were located on the spine. In the 'Semi-circle' condition both motors were almost always on the same side of the spine except for the horizontal direction (0° and 180°) for which one of the motors was located on the spine. Previously, we have found that distances between vibrations on opposite sides of the spine feel larger than on the same side of the spine [9]. This could be due to the cortical separation between the left and right sides of the back. Possibly, this makes it easier to locate the two stimuli. Similarly, cortical separation might make it also easier to estimate the direction between two vibrations when they are on opposite sides of the spine such as in the 'Circle' condition or when one vibration is located at the spine like in our previous study [10].

We found that oblique angles were perceived to be biased towards the horizontal direction. This can lead to traced shaped to feel compressed in the vertical direction. This would also be in agreement with another study showing that localisation of vibration is better in the horizontal direction than in the vertical direction [8]. Interestingly, we found in an earlier study that distances in the vertical direction felt longer than in the horizontal direction [9]. Given the deformation of the matched angles it would be expected that distances in the vertical direction would be perceived as shorter than in the horizontal direction. However, in the study where we investigated perceived distance the vertical distances were presented quite close to the spine (about 6 cm). For the horizontal directions the distance between the spine and one of the vibrations could be as much as 14 cm. As spatial acuity for vibration varies around the torso and is largest near the spine [6], [7] the perceived distance between two vibrations in the vertical direction might be strongly dependent on the distance to the spine.

Our results show an oblique effect regardless of whether vibrations were presented centred around the spine. This indicates that the oblique effect does in this case not occur due the spine being used as an anchor point. Centring the vibration around the spine, however, seems to increase performance as both deviations and spread were lowest in the 'Circle' condition. Overall these results show that there are systematic biases in the perceived direction between two vibrations which might cause traced shapes to feel deformed and that there might be a benefit of tracing shapes centred around the spine.

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