Vibrotactile Funneling Illusion and Localization Performance on the Head

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ABSTRACT

The vibrotactile funneling illusion is the sensation of a single (non-existing) stimulus somewhere in-between the actual stimulus locations. Its occurrence depends upon body location, distance between the actuators, signal synchronization, and intensity. Related work has shown that the funneling illusion may occur on the forehead. We were able to reproduce these findings and explored five further regions to get a more complete picture of the occurrence of the funneling illusion on the head. The results of our study (24 participants) show that the actuator distance, for which the funneling illusion occurs, strongly depends upon the head region. Moreover, we evaluated the centralizing bias (smaller perceived than actual actuator distances) for different head regions, which also showed widely varying characteristics. We computed a detailed heat map of vibrotactile localization accuracies on the head. The results inform the design of future tactile head-mounted displays that aim to support the funneling illusion.

Author Keywords

Tactile Feedback; Funneling Illusion; Phantom Sensation; Centralizing Bias

CCS Concepts

•Human-centered computing → Haptic devices; Interaction techniques;

INTRODUCTION

Tactile feedback on the head has been explored in detail (e.g., [5, 8, 9, 11, 22, 23]). In particular, Kerdegari et al. [24] investigated a tactile sensation known as the funneling illusion (FI) or phantom sensation on the forehead. This phenomenon emerges when multiple vibrotactile actuators are within close proximity of each other on the human skin. Depending on the intensities chosen, the user may only feel a single stimulation point in-between the actuators with a tendency towards the higher-intensity actuator(s) [3, 24]. Kerdegari et al. found that the FI appears, when the distance between actuators is less than 5 cm on the forehead and that there is a centralizing bias, where users systematically underestimate the distance between two actuators, even when the FI does not occur [24].

Figure 1. Measuring the FI and centralizing bias on the head. A study participant showing two perceived actuator locations on the forehead.

This paper aims to extend this investigation to five other regions all around the head in order to get a more complete picture of the conditions for the occurrence of the FI on the head. We aim to answer the following research questions:

- Can the results reported in [24] be reproduced and validated?
- At which actuator distances does the FI occur for different regions on the head?
- What characteristics does the centralizing bias show for distances between 2.5 and 15.0 cm at these regions?
- How well are users able to localize single actuators all around the head?

The results of this paper can be used in a variety of existing (e.g. [6, 8, 11, 13, 22, 23, 25, 36, 38]) and future works in Virtual and Augmented Reality as they inform the design of any kind of tactile display on the head in terms of required actuator density depending on task and head region. For example, the work of Dobrzynski et al. [11] who presented a 12-actuator vibrotactile headband for localization could increase or decrease their actuator density depending on head region in such a way that the FI is felt by more than half of the users for any location on the headband and further use the resulting FI to make users localize positions in-between the actuators. Another example would be the guidance algorithm presented in [22] which could be enhanced by incorporating knowledge about the localization precision on the different head regions. Instead of actuating three actuators, it could be modified to stimulate one to four actuators depending on the localization performance of the head region. This could in turn potentially increase guidance performance by reducing stimulation overload on head regions with low localization accuracy.

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Terminology

As the terms *phantom sensation* and *funneling illusion* (FI) are often used interchangeably [24, 39], we feel the need to define these terms and motivate why we settled on using the term *funneling illusion*. A *vibrotactile phantom sensation* is created by presenting multiple vibrotactile stimuli at nearby locations on the skin. If the locations are close enough (depending on body site), the user may perceive only a single sensation somewhere in-between the stimulus locations, depending on actuator intensities [1]. While the sensation that a user feels is called *phantom sensation*, the phenomenon is called *funneling illusion*, which is one of the human sensory illusions [7].

We will consistently use the term *funneling illusion* (FI) [7,24], as *phantom sensation* is occupied in medical research to refer to phantom sensations and phantom pain in amputated limbs, which is an entirely different area. Thus, when we refer to measuring the FI, this means that we asked our participants whether they felt a single or multiple stimuli during a trial.

Midline bias

In line with [24], we define the *tactile midline bias* as the phenomenon where humans tend to perceive tactile stimuli as being closer to the mid-sagittal body plane than they actually are in some but not all body regions. The *mid-sagittal body plane* splits the mostly symmetric left and right hemispheres of the human body.

Centralizing bias

In line with [24], we define the *tactile centralizing bias* as the phenomenon in which humans tend to perceive multiple tactile stimuli as being closer together than they actually are, even if the FI did not occur.

RELATED WORK

In 1957 by Geldard et al. [12] presented early work on tactile displays, which was summarized alongside more recent work and general guidelines by Jones and Sarter [17]. In their review of research in the area they conclude that different levels of vibrotactile intensity and frequency are hard to distinguish and even interfere with each other, while stimulus location and duration are easier to identify.

Myles et al. [34–37] investigated the vibrotactile sensitivity of different head regions and hair densities and used a headband with four actuators to provide navigational cues to soldiers. They found that soldiers preferred a tactile to a visual or auditory display for directional cuing and that the forehead, frontal, parietal, and temple regions were most sensitive to tactile stimuli.

Funneling Illusion

The tactile FI through direct skin stimulation was first investigated by Alles in 1970 (he referred to them phantom sensations) as a means to convey non-audiovisual data to users [1]. In his experiment, he used two vibrotactile actuators on the forearm and upper arm to find vibration amplitude profiles maintaining even perceptual strengths for several intended locations in-between the actuators. He found that log intensity profiles are superior to linear profiles for encoding locations between actuators, among several other observations about the nature of the FI.

Cha et al. [7] evaluated the perception of smooth motion with two vibration actuators stimulating the forearm to create a 1D moving FI. They varied the distance between the two actuators and the movement speed of the FI, i.e., how fast the sensation travelled between actuators. Their goal was to find suitable stimulation parameters for a *smoothly* moving FI. In a followup study, Barghout et al. [3] investigated the accuracy of perceiving intermediate locations in-between four actuators placed in a line on the forearm using stationary and moving FIs.

Using three voice-coil actuators on the forearm, Raisamo et al. [42] investigated saltation perception, pleasantness, and the effects of temporal variables. They also published a followup work on three methods of stimulation (linear amplitude modulation between actuators, saltation implemented as three fast pulses per actuator, and a hybrid version) using the same three Tacton C2 actuators as in the first work on the forearm [43]. They found the modulation method to be significantly less arousing and more pleasant than the saltation and the hybrid version.

T-hive [44, 50] is a hemispherical device with a total of 13 independent vibrotactile actuators. It uses the vibrotactile FI to display directions on the hands of users. In their study they found that participants were able to discriminate between nine illusory locations in-between three actuators with an accuracy of 76.8 %. A later system by the same authors [49] has a 3×4 actuator grid, attached to the back of a smartphone, for the same use case of displaying directions. Study results show an accuracy of 81.2 % for discriminating between nine illusory locations generated by three actuators. Yatani et al. [51] attached five vibration actuators to the back of a smartphone and explored the pattern recognition accuracy for five static and six moving FI patterns, which were easy to discriminate for the participants of their study with an accuracy of 85 % for the six non-static patterns.

Israr et al. presented two works on a moving FI for the purpose of increasing the enjoyment of movies and video games. The first work [14] investigated the effects of various parameters (including body site, on the forearm and back) on rendering FIs. *Tactile Brush* [15] is a 2D interpolation concept for multiple tactile actuators arranged in a grid in order to purposefully generate a moving FI. Recently, the Tactile Brush algorithm was improved by J.Park et al. [40] in terms of similarity to the target trajectory and uniformity of the stroke motion and was tested on the palm. G.Park et al. [39] continued further work on stationary FIs in 2D cases, quantifying information transfer capacity and measuring the accuracy of perceived positions. An algorithm similar to Tactile Brush was used in various works around our *HapticHead* concept [20–22] for rendering tactile feedback at different locations on the head, in order to guide users to physical and virtual targets and to increase immersion in games and movies. We also proposed a tactile pattern design framework that lets users draw strokes on modeled body parts, which in turn are also rendered by an algorithm similar to Tactile Brush to create a moving FI [19].

VibrationCap [10] is a concept similar to HapticHead, but miniaturized into a beanie and without the chin strap. They evaluated tactile sensitivities and localization accuracies ("accuracy score" using three categories) of stimuli on the head, mostly confirming the conclusions of Myles et al. [34–37].

Funneling Illusion through Objects and Out-of-Body

Apart from creating a FI through direct skin stimulation, there are also several other works on utilizing the FI through rigid objects (e.g., smartphones) [16, 18, 26, 27, 45–47] or even out-of-the-body sensations (e.g., feeling something between two fingers or two hands when holding a tablet or smartphone without touching the actuators) [4, 28–33, 41, 52]. However, these investigations are more distant from this work, as the explored methods are less applicable to the head.

Localization and Funneling Illusion on the Head

A work on vibrotactile localization accuracies on four head regions is [9], which investigates the vibrotactile spatial resolution on the head in a user study with 12 participants on the forehead, frontotemporal, temporal, and occipital head regions. They found that acuity on the head can be estimated as a function of skin type and distance of the stimulated location from the head midline.

The investigations by Kerdegari et al. [24] are closely related to this work, as they explore the FI and the centralizing bias on the forehead. They found that while the FI almost always occurs when the two actuators are 2.5 cm apart on the forehead, it only occurs in 20 % of the trials at a distance of 5 cm. They also found that there is a centralizing bias, meaning that the perceived distance between two simultaneously active actuators was around 2.5 cm less than the actual distance. In addition, they claim a strong midline bias when locating single actuators on the forehead. However, we believe that the study design regarding the claimed midline bias is problematic. The scale extended from 0 to 17 cm (actuators at 0 to 15 cm) and the participants saw their forehead, the scale, and the actuators in a mirror. Hence through visual feedback the participants could exclude actuator locations beyond positions 0 and 15 cm, respectively. In the study reported below we corrected this issue and explored five additional locations on the head, beyond the forehead. Our study had more than twice the number of participants in order to get more reliable results. Moreover, we give an error estimation for each measurement, and discuss a potential bias through the participants' dominant hands when pointing to the locations.

PROTOTYPE

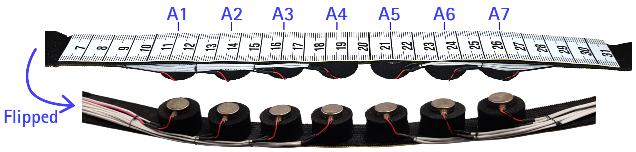


Figure 2. Our prototype built after the template of Kerdegari et al. [24]. Seven actuators (A1-A7) are placed at scale positions 11 to 26 cm, with 2.5 cm distance between the centers. Tolerances are less than 1 mm.

Our hardware prototype is a reconstructed version of Kerdegari et al.'s [24] prototype. We contacted the authors on the specifics of their prototype (e.g., foam material) and built a slightly enhanced but otherwise very similar version. Just like [24], our prototype consists of seven vibrotactile coin actuators (A1-A7) mounted 2.5 cm apart (less than 1 mm tolerance) on a scale that is attached to a stretchable Velcro fastener. The actuators used are 10×3.4 mm coin-style actuators (Precision Microdrives 310-117, frequency 250 Hz at 3.3 V, 1.9 g normalized amplitude). Kerdegari et al. used the PM 310-113 which is a slightly weaker, no longer available predecessor of the PM 310-117. We used a similar 10 mm thick × 17 mm diameter neoprene polymer, which is naturally vibration absorbent to isolate the actuators from each other.

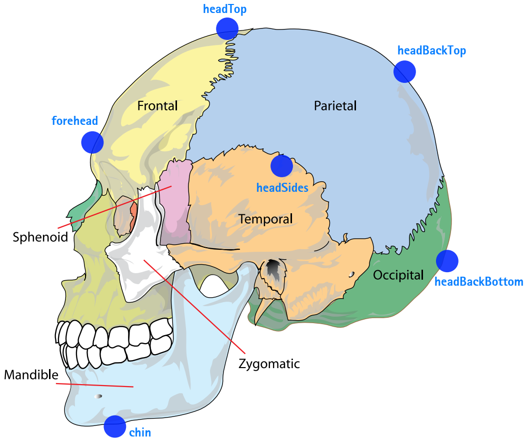


Figure 3. Locations of the head regions, side view. Blue markers show the locations of the central actuator A4 (Fig. 2) at position 18.5 cm of the scale. (Image source: Wikimedia Commons, public domain, modified)

Different to [24], we stamped round forms from the neoprene polymer instead of square ones. We also did not use an additional polymer layer apart from the neoprene polymer as the other plastic polymer used in [24] acted as a glue (our actuators came with a self-adhesive surface). We also moved our actuators a bit on the scale so that participants were able to point to locations up to 4 cm outside the actuator area whereas [24] mounted the first actuator on 0 cm and the last on 15 cm on a 0 to 17 cm scale, making it impossible to point at a location outside that area.

The actuators in our prototype are driven by a Raspberry Pi 3 using the pigpio library [2] and a custom-built actuator driver board. The Raspberry Pi was updated at 100 Hz through Wi-Fi using a Unity v5.6.6f scene [48] for the experiment. For further details on the implementation of this driver board we refer to related work [22].

EXPERIMENT

Based on our prototype, constructed after the example of [24], we designed an experiment to answer the research questions posed in the introduction. In addition, we formulated the following hypotheses for the experiment:

- (H1) We expect our results for the forehead to be comparable to Fig. 4 left in [24], in terms of localization performance of single actuators.
- (H2) We expect a significantly smaller midline bias for the forehead compared to Fig. 4 right in [24], as we use a scale

(a) forehead (b) chin

(c) headTop (d) headBackTop

(e) headBackBottom (f) headSide (left)

Figure 4. Our prototype on different head regions for the user study. It was always attached in the same orientations, as shown in this figure for the different head regions so that the scale always went from low to high from the perspective of the experimenter to prevent reading errors.

and study design that does not limit participants to show locations only between 0 to 15 cm.

- (H3) We expect a similar occurrence of the FI compared to Fig. 5 left in [24] for the distances 0 to 10 cm.
- (H4) We expect a similar occurrence of the centralizing bias compared to Fig. 5 right in [24] for the distances 2.5 to 10 cm.
- (H5) We expect the localization accuracy of single actuators for the forehead to be significantly better than for any other head region, as Myles et al. found the forehead to have the smallest vibration perception threshold [34–36].
- (H6) We expect the FI to appear at larger distances when comparing the forehead to any other head region, for the same reasons as given in H5.
- (H7) We expect the centralizing bias to be larger, the larger the maximum distance for the FI for a given head region, as the data in [24] suggests a correlation between these two parameters.

For the experiment, we invited 24 participants with technical backgrounds from around our university (22 male, 2 female, mean age 24.5 years, SD = 5.8 y). The experiment took 46 minutes on average per participant, excluding filling out questionnaires and the introduction. One of the participants (P5) was left-handed and another one (P10) ambidextrous.

Experiment Design

Since a major goal of this experiment is to map the entire head in terms of the localization precision of single actuators and of the occurrence of the FI for different distances between actuators, we chose a total of six head regions for this evaluation, as shown in Figures 3 and 4.

Counterbalancing on the six head regions was applied through a balanced Latin square. For every head region, there were a total of 42 trials, shuffled randomly to prevent order effects. These 42 trials consisted of single actuations for each of the seven actuators (repeated three times) and all 21 possible combinations between pairs of two actuators (2.5 to 15.0 cm distance between the actuators). The side of the head to which the actuators were applied (right or left) was counterbalanced between participants. We made sure not to introduce confounds between the head side assignment and the head regions. To keep the counterbalancing fully operational, we had to recruit a multiple of 12 participants.

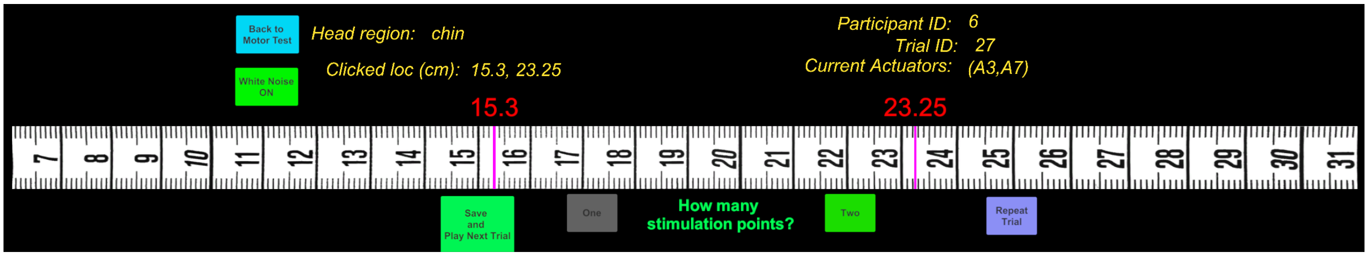
The participants wore Sony WH-1000XM3 headphones playing white noise at 74 dB during the experiment in order to mask actuator noise. The participant pointed to the single location or the two locations at which they felt a stimulus. Pins were mounted on their index fingers to improve pointing precision (see Fig. 5). The experimenter read the positions on the scale and entered them into the study app (see Fig. 6). The reading accuracy is expected to be about ±0.5 mm. We did not mention or explain the FI effect to the participants.

Figure 5. The small metal pointing pins.

Experiment Procedure

The participants filled out an informed consent form, an optional photographic-release form, and an introductory questionnaire. They were subsequently made familiar with the prototype before putting it on at the first of six possible head locations. We ensured a similarly tight but comfortable fit for all our participants by adjusting the straps ourselves to a pressure of about 4.5 N when pulling the center of the prototype strap 1 cm away from the participant using a BaseTech HS-11 scale. Before starting the trials for a head region, all vibration actuators were tested one after another on proper functioning. Finally, they put on headphones that played white noise.

Each individual trial consisted of the participant signaling readiness through a hand gesture, the experimenter verifying that the participant did not touch the scale with his or her fingers, and then pressing a start button, upon which a 1 s vibrotactile stimulation played on either one or two actuators at full intensity. The participant then pointed to one or two locations on the scale with their index fingers and the attached pins, depending on the number of perceived stimuli. If desired, a trial could be repeated, which happened only in 0.4 % of the trials. For each trial, the system logged a timestamp, the participant id, the head site, the active actuator(s), the perceived location(s) (read and entered by the experimenter), and the


Head region: chin

Clicked loc (cm): 15.3, 23.25

Participant ID: 6

Trial ID: 27

Current Actuators: (A3,A7)

Figure 6. The experiment UI was used by the experimenter to guide a participant through the study and record data. The two vertical lines can be moved by clicking and dragging them along the scale.

repetition count. Most of the participants performed the trials while having their eyes closed as per our recommendation so they were less distracted by the environment.

In the end every participant filled out a final questionnaire with qualitative questions on the experience of tactile feedback on the head. The prototype and earpieces of the headphones were disinfected between participants for hygienic reasons.

We implemented this study design and procedure into a Unity [48] application as seen in Fig. 6. When designing the user interface of this experiment app, we made sure that only the correct procedure through the experiment could be followed, and that the experimenter could not forget to enter a location due to being reminded by the test application.

RESULTS

Analyzing the results, we first take a look at quantitative results of the single-actuator trials. Second, we focus on the localization performance and occurrence of the FI in the multi-actuator trials. Third, we discuss qualitative results and feedback of our participants.

In order to isolate effects caused by possibly larger errors when pointing to locations on the left side of the head (side of the non-dominant hand) using the right hand (dominant hand) and to ward against a possible influence on the midline bias effect, we reordered all data so that actuator A1 is always on the left of the head and A7 always on the right for the evaluations (see Figures 2, 3 and 4 for actuator locations). We chose to flip the data for the left-handed participant P5 and leave it unchanged for our ambidextrous participant P10 since an evaluation of left vs. right-handed individuals makes no sense with only a single left-handed person in the experiment.

For the head side locations, we oriented the data so that A1 is always located towards the front and A7 towards the back of the head. Furthermore, we merged the data of the left and right head sides into a *headSides* location (see Fig. 3, blue labels) for most evaluations.

Quantitative Results – Single Actuator Trials

Table 1 shows the mean absolute deviations for each of the head regions. It is apparent that the forehead offers the most precise localization performance while all other head regions were much less precise. A one-way ANOVA with Holm-Bonferroni corrected comparisons showed that the forehead location was significantly more precise than all other head regions ($F_{5,162} = 15.44$, $p < 0.0001$, confirms hypothesis H5) and all other head region combinations were also significantly different from each other ($p < 0.05$) in terms of localization performance except for the following combinations: chin–(headTop,headBackTop,headBackBottom), headBackBottom–(headBackTop,headSides), and headBackTop–headSides (Fig. 3 shows the locations). Furthermore, Table 1 also depicts the percentage of misclassifying a single actuator as multiple stimulation locations. If this happened, we took the midpoint between the two locations for all further evaluations.

Head region	Mean absolute deviation of all actuators [cm]	SD [cm]	Misclassification as multiple actuators [%]
forehead	0.72	0.56	0.20
headTop	0.94	0.81	1.79
chin	1.17	0.89	2.38
headBackBottom	1.21	0.92	5.56
headBackTop	1.40	1.12	6.15
headSides	1.50	1.25	2.78
mean	**1.16**	**0.93**	**3.14**
headSide(left)	1.53	1.24	2.38
headSide(right)	1.47	1.26	3.17

Table 1. Mean absolute localization accuracy and misclassification of single actuators for different head regions (Fig. 3, blue labels).

Head region	Mean deviation A1&A2&A3 (left) [cm]	SD [cm]	Mean deviation A5&A6&A7 (right) [cm]	SD [cm]
forehead	0.14	0.85	0.17	1.00
headTop	-0.02	1.15	0.00	1.09
chin *	1.11	1.23	-0.85	1.15
headBackBottom	-0.15	1.46	0.10	1.64
headBackTop *	-0.81	1.60	-0.04	1.52
mean (symmetric HR)	**0.05**	**1.26**	**-0.12**	**1.28**
headSides	0.51	2.04	-0.06	1.73
headSide(left)	0.38	2.20	0.38	1.45
headSide(right) *	0.65	1.87	-0.50	1.86

Table 2. Midline bias for different head regions. A positive value for the left actuators (negative for right) shows the average bias towards the midline (red background). A blue background shows a bias away from the midline. Head regions with significant differences between the groups of left and right actuators are marked with a star. For both headSide regions, A1 is on the front and A7 on the back of the head.

Table 2 shows the midline bias of different head regions. Multiple one-way ANOVAs comparing the left actuators (A1,A2,A3) vs. the right actuators (A5,A6,A7) for every single head region found significant effects of actuator group on deviation for the chin ($F_{1,70} = 90.3$, $p < 0.0001$), headBackTop ($F_{1,70} = 8.67$, $p < 0.005$), and headSide(right) ($F_{1,34} = 6.64$, $p < 0.05$). The differences for all other head regions were not significant ($p > 0.05$).

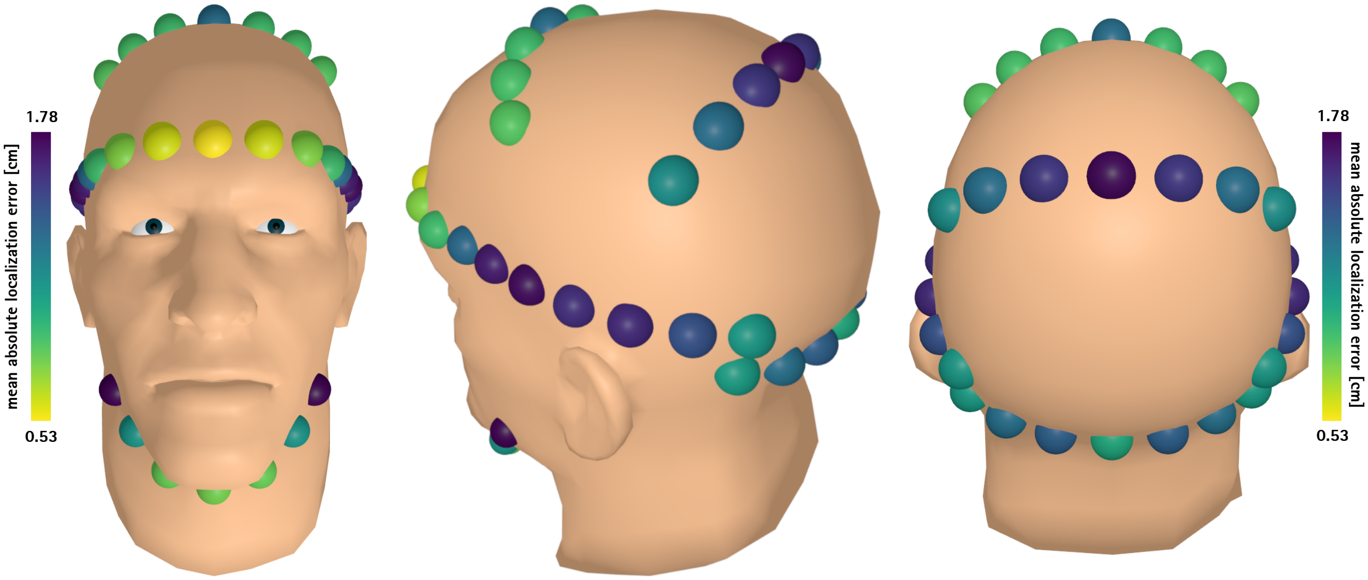


Figure 7. Heat map of mean absolute localization accuracies for all single actuator locations. From left to right: frontal, left, and back view of the model head. Data from symmetric head regions is merged to reduce noise. The color scale is viridis (a perceptually uniform color scale), ranging from 0.53 cm as the minimum error on the forehead to 1.78 cm on the headSides.

Fig. 7 shows a heat map of absolute localization accuracies. We merged the data from the symmetric head regions so that e.g. A1 and A7 show the average of those two actuators in order to reduce noise. For the headSide regions, we merged the data of the individual actuators of both sides.

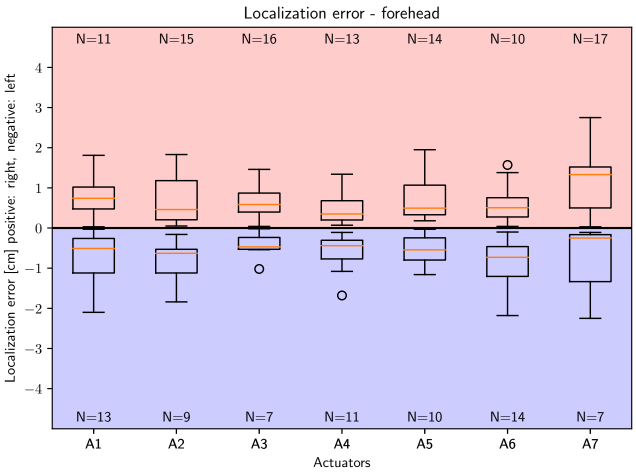


Figure 8. Localization error of each tactor on the forehead. Deviation towards the left is shown in blue, deviation towards the right in red. If the N for an actuator does not sum up to 24 (number of participants, median of 3 repetitions for each location), this means that the other trials were within ± 0.5 mm of the correct location.

Fig. 8 presents boxplots of the left and right deviations of actuators on the forehead. This is directly comparable to Fig. 4 right in [24], but shows very different data. We suspect that this is the result of a methodological error in the study design of [24], as discussed below. We decided to only highlight the detailed evaluation of left and right deviations for the forehead and the chin, as these are the two extremes of having no (or rather insignificant, slight negative) midline bias (forehead, Fig. 8) and the highest midline bias (chin, Fig. 9).

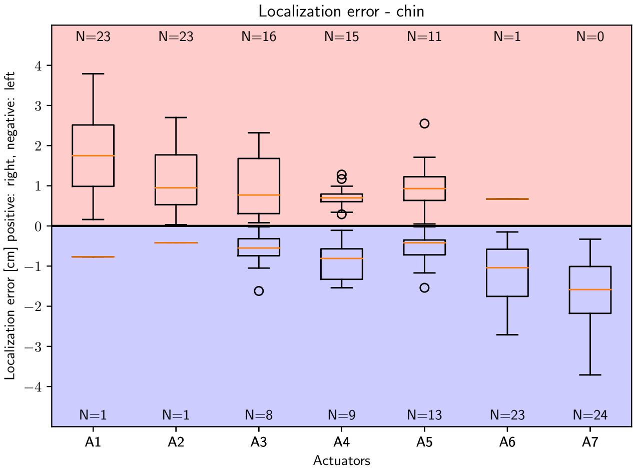
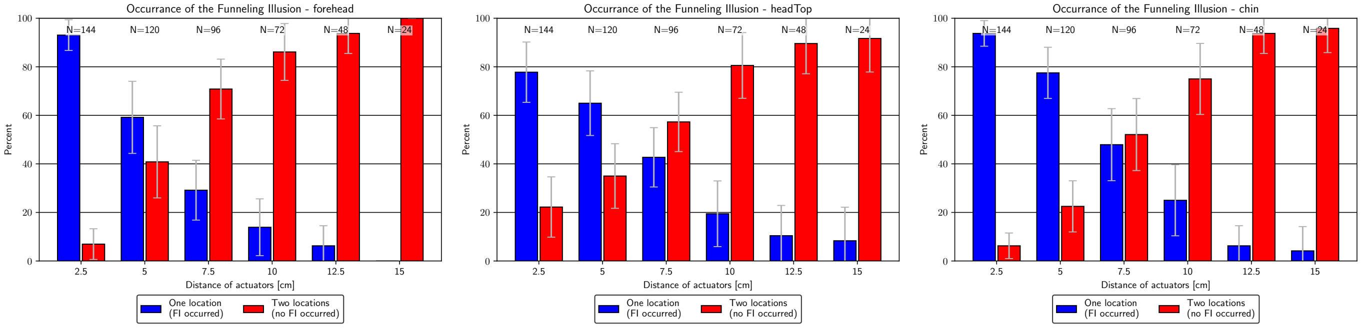


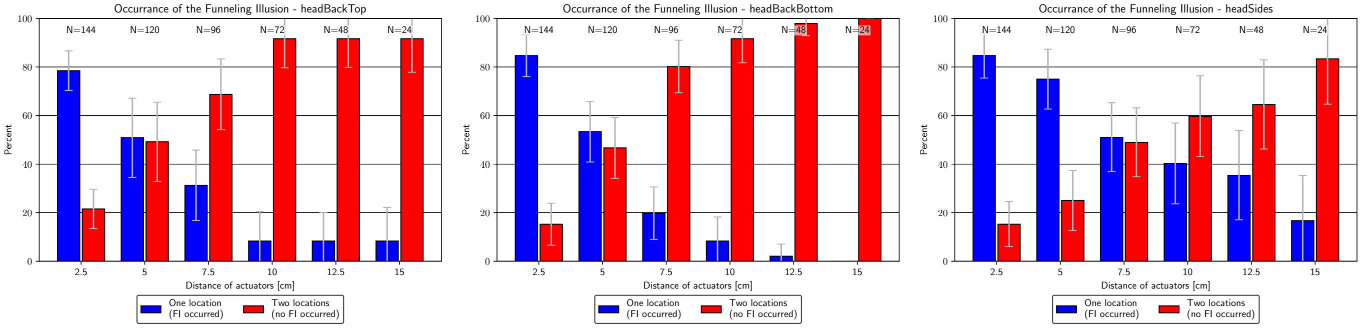
Figure 9. Localization error of each tactor on the chin. Deviation towards the left is shown in blue, deviation towards the right in red. If the N for an actuator does not sum up to 24 (number of participants, median of 3 repetitions for each location), this means that the other trials were within ± 0.5 mm of the correct location. A1 is the left-most actuator, and A7 is the right-most actuator.

Quantitative Results – Multi Actuator Trials

Fig. 10 shows the occurrence of the FI by distance for all head regions. The error bars on these barcharts represent the standard deviation. In general, the different head regions feature very different distances for which the FI still occurs for most users. The threshold at which more than 50 % of users still experience the FI varies between about 5.1 cm for headBackTop to about 7.7 cm for headSide.



(a) forehead (b) headTop (c) chin



(d) headBackTop (e) headBackBottom (f) headSides

Figure 10. Occurrence frequency of the FI in two-actuator trials for different actuator distances at different head regions. Blue bars show trials in which a participant indicated a single location, red bars show trials in which a participant indicated two locations. Error bars represent the standard deviation between participants.

The centralizing bias of the different head regions is shown in Fig. 11. Error bars represent standard deviation of all data at certain distances between two locations. Interestingly, there are large biases around 2.5-5.0 cm for the head regions chin, headTop and headSide. On the other hand, headBackTop and headBackBottom feature comparatively low biases for most distances.

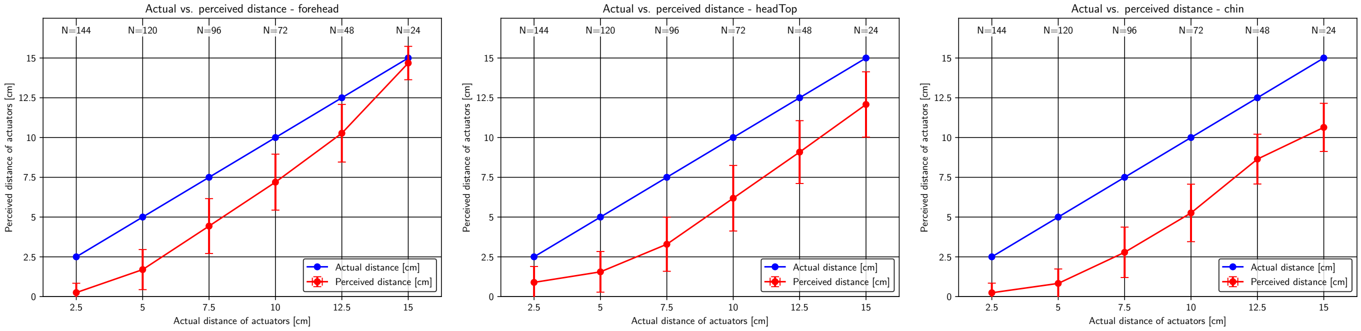
Qualitative Results

Fig. 12 shows the subjectively judged sensitivity. In order to measure sensitivity, we asked the participants to order the six different head regions by sensitivity ("How sensitive are the different head regions? Please sort them in terms of vibration sensitivity."). This is influenced by how strongly the actuators (all running at the same intensity) were perceived at different head regions due to more or less hair and nerve density of the skin below. The forehead was judged as most sensitive, followed by the chin. The head sides were judged as least sensitive.

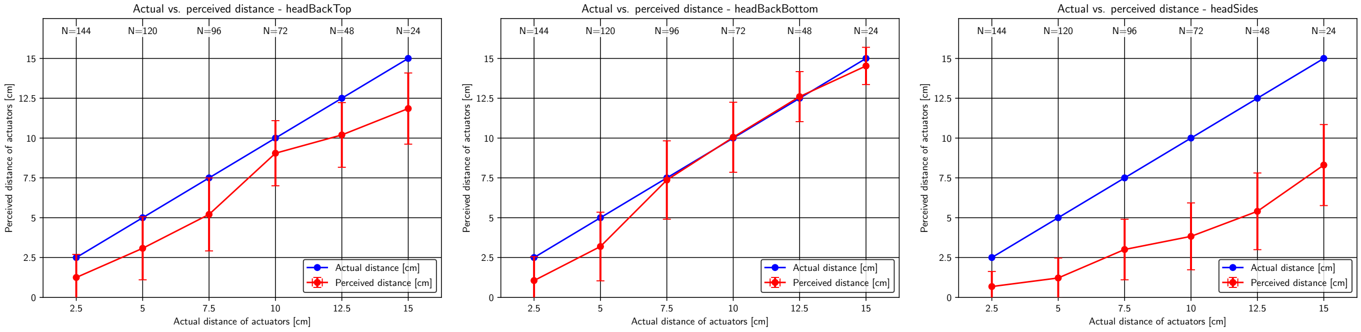
Fig. 13 presents qualitative results from the final questionnaire of the experiment. Generally, all head regions were rated as rather comfortable, with the least agreement for headSide. The participants commented that the headSide region was less comfortable, because some of the actuators were close to the ears with some audible noise, despite the white noise being played in the study, and these actuators were generally harder to localize.

In terms of fatigue, the experiment only took 46 minutes on average and only one out of 24 participants agreed that the vibrations were exhausting so we do not expect exhaustion or tiredness to have an influence on results. The two participants who indicated that they did not adapt to the vibrations after a few trials commented that the vibration intensity was too high for them and one found it difficult to relax when concentrating on the localization of the actuators. Participants were split in their opinions on whether they could imagine recurring use of the prototype concerning well-being. The prototype was specifically designed for the experiment and is rather clunky. For actual use, it would need to be miniaturized and integrated into a VR headset, beanie or other garment (e.g., [10]). 16 of 24 participants could imagine themselves or other people using a commercial head-based tactile feedback system for various applications. Out of the 8 participants who could not imagine themselves or others using a head-based tactile feedback system, 6 could not think of proper use cases and 2 thought head-based tactile feedback was uncomfortable in the first place.

We also asked the participants in which scenarios they could imagine using a tactile feedback device on or around the head. They suggested a variety of use cases, such as pedestrian guidance and guidance for the visually impaired, silent notifications, movies and games (VR and AR), head massage and relaxation, firefighting, as well as medical applications.



(a) forehead (b) headTop (c) chin



(d) headBackTop (e) headBackBottom (f) headSides

Figure 11. Actual and perceived distance between locations with multiple stimulation points. Error bars represent standard deviation between participants. In case a participant indicated only a single location when multiple stimulations were given, a distance of zero is assumed.

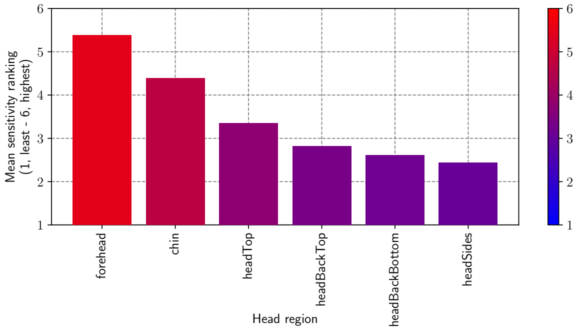


Figure 12. Average qualitative head sensitivity rating. Participants were able to sort the head regions by sensitivity from score 6 (highest) to score 1 (lowest).

In other written comments, three participants complained about discomfort when wearing the prototype for a longer time, out of which two specifically mentioned the chin region.

DISCUSSION

We start the discussion by providing a thorough comparison to [24], first on single actuator localization and midline bias and subsequently on multi-actuator localization and the occurrence of the FI. Furthermore, we compare our work in terms of localization accuracies with [9] and [10].

Single Actuator Localization Performance

When directly comparing the data in Table 1 to Kerdegari et al.'s [24] data for the forehead, the midpoint of their range of mean deviations from 0.51 to 0.76 cm per actuator is slightly lower than ours at 0.53 cm to 0.9 cm, mean 0.72 cm. However since our average still falls within the range, we can accept H1.

With this in mind, we found large differences in localization accuracy for the different head regions (Table 1). Localization was most accurate on the forehead, with the closest contestant (headTop) already much less accurate, thus we can accept hypothesis H5. Also, the accuracy of headSide was less than half of the accuracy of forehead, so we recommend avoiding the region close to the ears in tactile system design, not just from a noise perspective but also because localization performance is much worse than for other head regions.

Heat Map of Localization Accuracies

Fig. 7 shows a heat map of localization accuracies for all head regions covered in this paper. Diener et al. [10] created an "accuracy score" heat map for 18 different head regions excluding the chin. However, they only provide a three-shaded color scale representing a rather coarse accuracy score. Our heat map is more detailed, provides a continuous color scale and is based on more data: 6 head regions × 7 actuators × 24 participants × 3 repetitions = 3024 trials. [10] is based on 20 participants × 60 trials = 1200 trials. Furthermore, in [10] participants entered actuator locations in a GUI showing a visual representation of a head from above and participants could only choose between 19 positions. In our study, participants could point at any location on the scale, without the possibility of a bias through the design of the GUI.

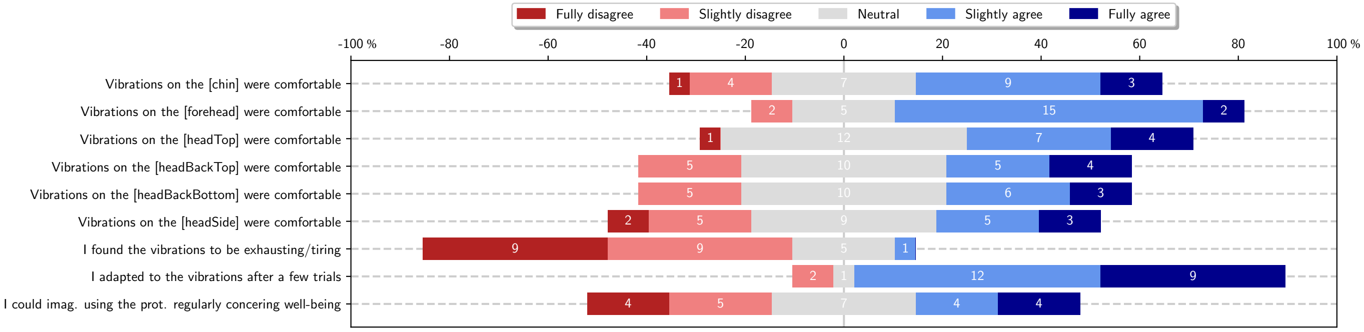


Figure 13. Diverging stacked bar chart of qualitative results of our experiment, measured through the final questionnaire.

When comparing our heat map with that of [10], it is apparent that they are very different. Diener et al. measured the lowest accuracies in the frontal region of the head while our corresponding headTop region performed rather well in localization accuracy. Furthermore, they measured the best localization accuracy on an area corresponding to headBackBottom, while we measured the best accuracy on the forehead. We attribute these differences to the very different prototype and aforementioned study designs and data input methods.

De Jesus Oliveira et al. [9] studied vibration localization accuracies for four head regions: forehead, frontotemporal (overlaps forehead and headSides in our study), temporal (same as headSides) and occipital (overlaps headBackBottom). Their results mostly agree with what we found. However, we cannot confirm their predictive model of acuity on the head as a function of skin type and distance of stimuli from the head midline. This model does not work for the regions headBackTop and headTop, which were not studied in [9]. These seem to be inverted compared to other head regions in that they show the lowest localization accuracy in the center (see Fig. 7).

Midline Bias

A midline bias was noticed by Kerdegari et al. for the forehead (Fig. 4 right in [24]). However, due to a supposed methodological flaw in their study design, the results for the forehead appear to be biased, and different to ours. In [24], actuator 1 was located at position 0 cm and the scale ended there, whereas actuator 7 was located at position 15 cm (the scale went on to 17 cm). The participants indicated the perceived stimulus positions themselves in front of a mirror, knowing that the first actuator was at 0 cm and the last actuator at 15 cm. It was not possible for them to indicate locations less than 0 cm. Therefore, the participants were obviously biased not to indicate locations outside the range 0 to 15 cm, even if they felt a stimulus there. Thus, their conclusion that there is a strong bias towards the forehead midline is invalid, as evident from our corrected study design and Table 2 and Fig. 8. These results suggest that we can accept hypothesis H2.

However, we did find a significant midline biases for the chin and supposedly for headSide(right). For the latter this bias is most likely caused by pointing difficulties as headSide(left) features almost no midline bias but appears shifted towards the back of the head instead (likely also due to pointing issues). The midline bias for the chin is the strongest by a large margin and can be explained by the yaw bones which transfer part of the vibration intensity from the outside actuators so that it feels like the vibration point is more towards the midline / chin (see also Fig. 9).

headBackTop features a rather inexplicable significant bias towards the outside of the scale but only for the left side (non-dominant hand). The median deviation to the outside (0.68 cm) is not much different to the average (0.81 cm, see Table 2), so outliers are not the reason for this bias. We see a possible explanation in localized influences from pointing with the non-dominant hand but since we did not find an overall dominant hand effect (see below), we will leave a confirmation of this hypothesis to future work.

Possible Dominant Hand Effect

In order to find a possible effect of the dominant hand on localization accuracy on the left and right hemispheres of the head, we further analyzed the data shown in Table 2. The absolute of the mean of the symmetric head regions between actuator groups shows a possible but very small effect, as there is a 0.7 mm difference when it should be equal on both sides. Just taking the absolute values of both sides and comparing them against each other would erase midline and outside biases. Instead, we inverted the data of the left actuators and compared them to the non-inverted data of the right actuator group. A one-way ANOVA shows that there is no statistically significant difference between the actuator groups for inverted vs. non-inverted deviations on all symmetric head regions ($F_{1,357} = 0.44$, $p = 0.51 > 0.05$). Thus, we did not find a significant effect of the dominant hand when averaging over symmetric head regions.

Occurrence of the FI

Regarding the occurrence of the FI, Fig. 10a is directly comparable to the results of [24] (Fig. 5 left). We measured a much higher occurrence of the FI for the 5 cm distance on the forehead: 59 % vs. 21 %. As this data point is of more importance than the others because it is around the tipping point where participants either feel the FI or not, we have to reject H3. This result might be explained with the low number of 10 participants in [24], with the different study design, or with slight differences in prototype design. For the other head regions, except for headBackTop and headBackBottom, the threshold distance at which a FI still occurs for the majority of the participants is always higher than for the forehead, which is expected because of obstruction through hair. Myles et al. [34, 36] found lower absolute tactile detection thresholds for the other head regions. However, headBackTop and headBackBottom actually feature a slightly lesser occurrence of the FI at 5 cm distance than the forehead. Thus, hypothesis H6 has to be rejected. However, due to the small differences between the head regions and due to large variances between users, this result could also be attributed to noise (see error bars at 5 cm distance in Fig. 10a vs. Fig. 10d and 10e).

Using linear interpolation, we estimate the thresholds for the FI to occur for 50 % of the users on the forehead to be around 5.8 cm, for the chin 7.3 cm, for headTop 6.7 cm, for headBackTop 5.1 cm, for headBackBottom 5.2 cm, and for headSides around 7.7 cm. These thresholds apply only to prototypes constructed in a similar fashion with appropriate vibration insulation between actuators using, e.g., neoprene polymer. Even with a slightly different prototype design, the thresholds will vary and they will likely decrease, the better the insulation between the actuators is. Kerdegari et al. [24] estimated around 3.95 cm for the forehead, however this result is again most likely influenced by their study design.

Occurrence of the Centralizing Bias

Concerning the centralizing bias, the forehead region shown in Fig. 11a is again directly comparable to Fig. 5 right in [24]. We found very similar centralizing biases for distances 2.5 to 10.0 cm, thus hypothesis H4 can be accepted. For the other head regions, we measured very different centralizing biases (Fig. 11). The headSides regions in particular seem to have the largest centralizing bias, especially at distances 10-15 cm along with the FI occurring for more users even at these distances compared to the other head regions. This can be explained by the closeness of these head regions to an ear.

Interestingly, headTop and chin both feature relatively large centralizing biases especially compared to headBackTop and headBackBottom. This is peculiarly interesting because headTop and chin were both more precise than headBackTop and headBackBottom in single actuator localization (see Table 1). We are not entirely sure on why this phenomenon occurs and leave this to future research.

In order to find out whether there is a correlation between occurrence of the FI and size of the centralizing bias (H7), we averaged the occurrence frequency of the FI and the size of the centralizing bias over all distances for all head regions. A Pearson correlation test shows that these features are indeed correlated ($r = -0.952, p < 0.005$), so hypothesis H7 can be accepted.

Head Sensitivities and Qualitative Feedback

As mentioned in the related work section, Myles et al. [36] found the forehead by far as most sensitive, and the occipital (headBackBottom) and temple (slightly overlaps forehead and headSide) regions to be more sensitive to vibration stimulation, with a lower vibration perception threshold compared to other regions. While it seems obvious to compare our work with [36], they actually had very different research goals. They studied absolute detection thresholds (ADTs) by head region while this paper uses a vibration intensity well above the ADT to measure other parameters. Still, some of our findings seem to be in line with [36], as our participants also rated the forehead as the most sensitive region and forehead is the most accurate region for localization of single stimuli (see Fig. 12 and Table 1).

The qualitative feedback collected by the final questionnaire and verbal comments suggests that tactile feedback on the head is on average well-received with minor differences between the head regions. Certain positions should be avoided however (ears). Also, a per user calibration of maximum vibration intensities for the different head regions is desirable to deal with possible discomfort experienced by some participants.

LIMITATIONS

This paper does not evaluate the effect of different hair densities on accuracy. We had participants with very different hair densities and we chose not to evaluate a possible effect of different hair densities as related work found no significant effect of hair density on localization performance on the head [10]. Furthermore, while [37] did find a significant effect of hair density on vibration perception threshold, as long as a tactile display operates above that threshold, as our prototype did, this should have no strong influence on localization performance [10].

CONCLUSION AND FUTURE WORK

In conclusion, this paper provides several contributions to further understand vibrotactile feedback on the head. These findings can serve as the basis for designing future tactile head-based systems:

- Experiment validation and correction of the problematic midline bias conclusion for the forehead in [24].
- Quantitative results on localization precision and midline bias evaluation of single actuators on the head.
- Quantitative results on maximum distances for the FI at different head locations.
- Characterization of the centralizing bias effect for multiple stimuli and different distances on the head.

When designing head-mounted tactile interfaces at individual or multiple different head regions, developers have to consider several parameters. There are widely differing localization accuracies for single actuators and maximum distances for the occurrence of the FI on different head regions. If the FI shall be utilized (e.g., for precise guidance) developers have to be aware of the widely varying centralizing biases for different head regions, which should be considered in the guidance algorithm.

There is a large variety of different systems for use cases in Virtual and Augmented Reality that are enabled with a tactile display on or around the head. These are hinted at in the introduction and related work section. All of these systems, even if they use just a single actuator, can benefit from implementing their tactile feedback according to the findings of this work. For example, hardware prototypes [6,8,11,13,22,23,25,36,38] and guidance algorithms [15,22] can be modified to take into account the varying localization performance, centralizing bias and FI occurrence for different head regions to implement different actuator densities depending on task and head region (hardware optimizations) and to potentially provide better guidance performance (algorithm optimizations).

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