TactileWear: A Comparison of Electrotactile and Vibrotactile Feedback on the Wrist and Ring Finger

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ABSTRACT
Wearables are getting more and more powerful. Tasks like notifications can be delegated to smartwatches. But the output capabilities of wearables seem to be stuck at displays and vibration. Electrotactile feedback may serve as an energy-efficient alternative to standard vibration feedback. We developed prototypes of wristbands and rings and conducted two studies to compare electrotactile and vibrotactile feedback. The prototypes have either four electrodes for electrotactile feedback or four actuators for vibration feedback. In a first study we analyzed the localization characteristics of the created stimuli. The results suggest more strongly localized sensations for electrotactile feedback, compared to vibrotactile feedback, which was more diffuse. In a second study we created notification patterns for both modalities and evaluated recognition rates, verbal associations, and satisfaction. Although the recognition rates were higher with electrotactile feedback, vibrotactile feedback was judged as more comfortable and less stressful. Overall, the results show that electrotactile feedback can be a viable alternative to vibrotactile feedback for wearables, especially for notification rings.

CCS CONCEPTS
• Human-centered computing → Haptic devices; Mobile devices.

KEYWORDS
Wearable Computing; Vibration; Electrotactile Feedback; Notification; Haptic Perception; Tactile Pattern

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1 INTRODUCTION
Wearables have become increasingly popular in recent years. Apart from head-mounted displays, smartglasses, and various PDAs or smartphones, there are also wristbands and rings with integrated
sensing and computing capabilities. In addition to simple fitness tracking devices, which can measure data such as steps taken or pulse rate, there are also more complex devices, like smartwatches. These allow the user to perform a variety of interactive tasks such as reading and writing messages. Thus, it is no longer necessary to take the smartphone out of the pocket. For those devices, it is very common to use vibration feedback as notification method. However, vibration produces characteristic sounds, which are noticeable by others. Electrotactile feedback on the other hand is silent and thus can only be perceived by the user. Additionally, electrotactile feedback is more energy efficient than vibration motors [5, 11, 20]. The design space of sensations that a vibration motor can elicit is limited. In eccentric rotating mass (ERM) actuators, typically found in commercial available wearables, the frequency is coupled to the intensity. In linear resonant actuators (LRAs) the frequency is not coupled to the intensity in this way. A LRA can be driven with lower voltages to create lower vibration intensities. However, the usable frequency range is narrow, because if the LRA is not driven at its resonance frequency, the output intensity is strongly reduced. Moreover, vibration actuators cannot go below a certain minimal size, because the accelerated mass has to create a perceivable force. In contrast, electrodes for electrotactile feedback can be made very small (e.g. [21]). Furthermore, electrotactile feedback has a wide range of usable frequencies and can cause very different tactile sensations [26]. Sufficient skin contact is given even for small wearables like smartwatches and rings. We believe that using electrotactile feedback with on-skin wearables could broaden our interaction with wearables, in particular in the context of delivering notifications. In terms of electronics design, driving an electrode pair is slightly more complex, because of the higher number of controllable parameters compared to an LRA or an ERM actuator.

In this paper, we evaluate the suitability of electrotactile feedback as an alternative output method for interactive wearables. For this purpose, we compare custom wristband and ring prototypes with either electrotactile or vibrotactile feedback in two user studies. In our first study, 12 participants marked in images where they felt a sensation on the skin for each wearable location and feedback modality. Our results show the comparability of the four prototypes as they produce sensations in nearly the same areas. After this confirmation on the comparability, we created several notification patterns based on related work. 18 participants had to learn and recognize them in a second study. We found out that patterns without structural repetition can be recognized more reliably and that vibration feedback on the finger caused problems for some participants.

2 CONTRIBUTIONS

With this paper, we contribute the evaluation and comparison of electrotactile and vibrotactile feedback on wristbands and rings. Especially, the comparison of perceived feedback locations on wristbands and rings is one of our contributions. For this purpose, we provide heatmaps for each prototype and stimulus which show the comparability of the prototypes. Furthermore, we created several notification patterns and provide a comparison of the recognition rates as well as verbal associations and satisfaction scores regarding each wearable prototype and feedback modality. Based on our results we discuss possible limitations for on-skin wearables and formulate design considerations for future prototypes.

3 RELATED WORK

In human-computer interaction electrotactile feedback is mostly associated with electrotactile displays. An electrotactile display consists of two dimensional arrays of electrodes, either single electrodes that can be delegated to be an anode or a cathode or concentric electrodes that include both. Electrotactile displays are able to display fine-granular electrotactile feedback on to the user’s skin, to provide, e.g., sensory substitution [20] or to create an interface to feel virtual objects[24]. Strong and Troxel [46] show that an electrotactile electrode array can produce a texture effect, which is similar to moving the finger across a textured surface. First evaluated in the 1970s, these electrode displays were also explored in the early 2000s in a smaller form factor to analyze their usage in a more modern context [21, 22].

Additionally, Kajimoto et al. [23] show that it is possible to create different sensations with different frequencies. To create different sensations on the skin Saunders [45] suggests frequencies between 2 and 100 Hz. Pohl and Hornbæk [39], for example, create “itch” feedback by using a frequency of 60 Hz with a pulse width of 3.8 ms. According to Pamungkas and Caesarendra [32] an “effective receptor stimulus” will be provided between 50 and 150 μs. Furthermore, electrotactile feedback was used for nerve stimulation to create prickling sensations in fingers and hands [3, 4]. Higashiyama and Hayashi [15] analyze the positions of the electrodes and the positions of the sensations the participants felt. They found substantial deviations between the real positions and those reported by the participants. Additionally, Poletto and van Doren [41] show a correlation between electrode size and current, which influences the intensity of the stimulus.

Electrotactile feedback and electrical muscle stimulation are often compared with vibration feedback, as vibration is a very common feedback method. For example, Pfeiffer and Stuerzlinger [37] compare electrical muscle stimulation and vibration in a virtual 3D environment with a Fitts’ law task. They found that EMS and vibration are both viable feedback methods for 3D virtual hand selection. Ng et al. [30] compare vibro- and electrotactile feedback along the forearm in a medical context, showing that vibrotactile feedback creates more accurate sensations for this actuator placement. Vibro- and electrotactile feedback on the forearm is also investigated by Witteveen et al. [47] for the use of myoelectrical arm prostheses. They show that the use of vibration or electrotactile feedback increased the performance of grasping tasks for healthy user with comparable results for correct hand openings. The use of simultaneous stimulation of electro- and vibrotactile feedback has also been investigated [6]. The authors conclude that the combination of electro- and vibrotactile feedback leads to equivalent or better performance compared to a single electrode or vibration motor setup. Apart from commercial wearables, such as smartwatches and fitness trackers, researchers created wearable prototypes themselves to explore new fields of application and haptic feedback modalities, like thermal feedback [35], on-skin LED feedback [48], indirect skin illumination [40], positional feedback [7], pneumatic compression feedback [38], electrical muscle stimulation [9], and skin drag [17].
Information transfer, by adapting metrics from other work. They amount of information delivered via the tactile channel, also called We wanted to make sure that users feel comfortable wearing the We designed four different prototypes, featuring two different form factors (ring and wristband) as shown in Figure 2. Each prototype is made of an elastic, stretchable ribbon. Regarding sizes, we based our design on commercially available products, like the Fitbit, and average ring sizes for men and women [31], respectively. We wanted to make sure that users feel comfortable wearing the prototypes. For this reason, we created two different ring sizes for each output modality: one with a circumference of 54 mm and a second one with a circumference of 62 mm. In addition, this allows us to analyze whether ring sizes affect the localization of the stimulus. For the wristbands, we chose a circumference of 170 mm. Each wearable has either four electrodes or four vibration motors, as previous work has shown that four actuators are better suited for vibration feedback in terms of speed and accuracy [16]. For comparability, we chose to use four electrodes as well. Like other work [1, 12, 39], we use an electrode pair setup instead of concentric electrodes. We opted for electrode pairs to analyze the sensations created by electrotactile feedback between two spatially separated electrodes. This allows us to create sensations not only beneath the electrodes, but also between these electrodes and thus around the forearm and finger. We believe that stimulating a much larger area is beneficial for notification purposes. Concentric electrodes are not suitable for this purpose as the sensations created are limited to the skin area directly under the electrode. An electrotactile display, containing multiple very small electrodes, is also not suited for our purposes as small electrodes with a huge spatial gap lead to very strong or painful sensations [41]. The electrodes and vibration motors are placed around the wrist. Matscheko et al. [29] have shown that with this placement distractions have a “low impact on the information transfer.” As in related work [16, 29, 34], we placed one electrode or vibration motor each on the dorsal, ventral, left (lateral), and right (medial) sides of the left forearm or finger (see Figure 2). The ERM vibration motors we use are 2 mm in height and 10 mm in diameter [28]. They are driven with a voltage of 3.3 V, to match the vibration frequency specified in the datasheet (130 to 150 Hz). We confirmed this frequency by connecting an accelerometer near the vibration motors on a worn prototype and analyzing the resulting frequency spectrum. When we designed the vibration prototype, we considered using damping for the motors as done in [25]. However, we decided against damping beyond using the flexible band, as this would have required additional physical space. This is especially problematic for the ring prototype, because it leads to unavoidable touching of the vibration motors with other fingers. For consistency and comparability, we also do not use additional damping on the wristband.

The electrodes are made of carbon rubber and have a size of 40×40 mm. For the ring prototype we cut the electrodes into a size of 10×20 mm. For a good connection we used a thin layer of conductive gel between the skin and the electrodes. To generate the electrotactile feedback, we used the Let Your Body Move (LYBM) toolkit [36] with the medically certified pulse generator Sanitas SEM 43. For additional functionality, we developed an adapter board, which is placed between the LYBM toolkit and the Arduino Nano.
Figure 3: The adapter board is placed between the LYBM toolkit [36] and the Arduino Nano. It extends the toolkit with additional features: the activation of up to four vibration motors and up to four electrodes in pairs.

(see Figure 3). With this adapter board it is possible to activate up to four vibration motors and up to four electrodes in pairs, by sending new custom commands to the toolkit via Bluetooth.

5 FEEDBACK LOCATIONS

As already mentioned, we use an electrode pair setup which allows us to analyze the perceived localization of the coarse-grained stimuli around the wrist and finger. Since we use pairs of electrodes for the electrotactile feedback, the vibration motors have also been activated in pairs for comparability, as a single vibration motor activation cannot represent all of the six possible pairings. Figure 4 shows these pairings: Up & Left (UL), Up & Right (UR), Up & Down (UD), Left & Down (LD), Right & Down (RD), and Left & Right (LR). In the studies we used all of these to investigate which pairings are suited for notification purposes.

6 STUDY 1: PERCEIVED FEEDBACK LOCATIONS

This study investigates the perceived locations of electrotactile or vibrotactile feedback via wristband or finger ring. For each combination of output device and feedback modality, participants had to mark the perceived locations in two abstract images. The first image was an abstraction of the left arm and hand from a dorsal view (see Figure 5) [8]. A transversal distal view of the arm or the finger was shown in the second image.

The aim of this study is to analyze which pair causes a sensation in which location, and whether these locations are consistent across the four prototypes. For detailed analysis we defined expected areas for the sensations. Thus, we are able to examine the comparability of the prototypes. For the wristband the expected area is the forearm and for the ring it is the ring finger. For the placement around the wrist or finger, we analyze whether the markings are in the expected areas. As we use pairs, the expected area is on and between these pairs (as marked in Figure 4). Furthermore, we compare the number of pixels that the participants marked to analyze the localization accuracy.

6.1 Study Design

Study 1 has a within-subjects design with the wearable type (wristband or ring), the feedback modality (electrotactile or vibrotactile feedback), and the six pairs (vibration motors or electrodes, cf. Figure 4) as independent variables. For each combination of wearable type and feedback modality, the participants had to perform three blocks. In every block, we played each of the six perceived stimuli (corresponding to the six pairs) once in a Fisher-Yates shuffled randomized order. Every stimulus was played for 500 ms, as in
6.2 Participants

We recruited 12 participants (11 male, 1 female, age 21-29, $\bar{x} = 25.5$, $\sigma = 2.6$). All participants were right-handed. Five participants said to usually wear a watch (two of those wear a smartwatch), but none of the participants stated to usually wear a ring. For the evaluation of our prototype design, we measured the circumference of the forearm and the finger at the location where the prototypes were worn. The average wrist circumference was 170.33 mm ($\sigma = 15.82$ mm) and the average ring finger circumference was 62.42 mm ($\sigma = 5.84$ mm). Five participants already had experience with electrotactile feedback or electrical muscle stimulation, which they had gained in other studies of our institution.

6.3 Procedure

At the beginning of the study, the participants filled out a consent form and a demographic questionnaire. They were then asked to wash their hands and wrists for hygienic reasons. This step was necessary, since each participant wore the same prototypes and electrode gel was used for the electrotactile wristband and ring. The use of the Android tablet application was explained to the participants step by step. As this study has a within-subjects design, the participants wore one prototype at a time. The wristband prototypes were worn on the left forearm and the ring prototypes on the ring finger of the left hand for comparability of the drawings.

During the study, the participants placed the left arm in a comfortable position on the table. We ensured that none of the vibration motors touched the table or the other fingers, as this would have caused the table or the other fingers to vibrate as well. Thus, the participant could have identified the source of the stimulus more easily. For consistency, the same position of the arm and hand was used for the electrotactile prototypes. An individual calibration of the current amplitude for each electrode pair was performed for each participant and electrotactile prototype. This was necessary because the perception of the intensity of the electrical sensation differs from person to person [46]. The vibration actuators were operated at the optimal frequency to stimulate the Pacini corpuscles for vibration perception.

During the calibration of the electrotactile feedback, the participants already felt each stimulus at least once. To ensure a fair comparison between electrotactile and vibrotactile feedback, the participants were able to familiarize themselves with all feedback positions for as long as they wished ($\bar{x} = 51s$) by pressing unlabeled buttons (one button for each pair, randomized mappings). Subsequently, the drawing phase started and the participants marked the locations of the perceived stimuli in the Android application (cf. Figure 5). For each prototype they had to mark in three blocks six stimuli each. For each stimulus the location of the sensation had to be drawn in the two images as ellipses. After finishing a block, they could take a short break.

After the participants had completed all blocks for all prototypes, they had to fill out a final questionnaire, where they had to rank the prototypes and describe the sensations they felt for each feedback modality. Instead of a free-form answer, they selected the matching sensation description from 21 given terms, provided by Pohl and Hornbæk [39]. Multiple choices were possible. After using the related work [10, 29, 44]. To minimize the impact of learning effects, the order in which the participants wore the four prototypes was counterbalanced with multiple balanced Latin squares. Instead of repeating the already used balanced Latin squares after every four participants, we used another balanced Latin square so that no permutation was reused across the participants.

The participants wore the prototypes while sitting in front of an Android tablet. For drawing the perceived feedback locations the participants used a Samsung Galaxy Tab 3 with a Samsung S-Pen. This 9.7-inch tablet was chosen to reduce inaccuracies in drawing caused by the fat finger problem. The Sanitas SEM 43 created biphasic pulses at a frequency of 100 Hz with a pulse width of 50 $\mu$s. These settings are recommended for electrotactile feedback in [32].
electrotactile wearables, the participants were asked to clean their arm to remove any remaining electrode gel. The electrodes were also cleaned and disinfected after each participant. Overall, the study took between 60 and 90 minutes. At the end of the study, the participants received a bar of chocolate.

6.4 Results

For the following evaluation, we interpreted the ellipses drawn by the participants as areas, because the participants felt a sensation in the whole area and not only on the outline. The areas were then overlapped for each prototype and electrode or vibration motor pair (see Figure 5).

At first, we analyzed whether there are significant effects regarding the size of the ring. To this end, we compared the number of marked pixels of the second image, showing the transversal section, for both ring size groups with a Mann-Whitney-U test. The test does not show a significant difference ($U = 18655$, $p = 0.06$) between these groups, indicating that the ring size does not have a significant effect on the size of the localization of the stimuli. Thus, we merged the data of those two groups into one group for the evaluation.

The overlapped markings of the dorsal view of the hand show more localized sensations for the ring prototypes than for the wristbands (see Table 1). For the wristbands, there is a large dispersion across the forearm (e.g., see Figure 5e). These inaccuracies are caused by the completely free drawing of the participants as the worn prototypes were not marked in the provided abstract image. Thus, the participants had to estimate where they felt a sensation and how to map those areas to the abstract image. For the electrotactile wristband, five participants marked sensations that deviate from the expected area. They marked the hand instead of the forearm. This could indicate additional nerve or muscle stimulation for these participants. The electrical stimulation is able to activate the hand nerves (median, ulnar or radial nerve) or muscles that go through the forearm. The most interesting aspects in the dorsal view images are therefore the drawings that deviate from the

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Table 1: All heatmaps of the dorsal view (rows: $R =$ ring, $W =$ wristband, $E =$ electrotactile, $V =$ vibrotactile).
expected areas (wristband = forearm, ring = ring finger) as these could indicate additional nerve or muscle stimulations.

For the individual comparison of the prototypes, the images were grouped by prototype. For the first image (dorsal view), we analyzed the number of pixels in the filled ellipses with a Friedman test, which shows a significant difference between the four prototypes ($\chi^2(3) = 418.6722, p < 0.001$). A subsequent pairwise post-hoc Conover test with Bonferroni correction shows a significant difference ($p < 0.001$) between the wristband and ring prototypes. As expected, significantly more pixels were marked for the wristband prototypes than for the ring prototypes. This is, because the forearm offers a larger area for drawing than the ring finger. A following Wilcoxon signed-rank test comparing only the two wristbands shows a significant difference ($Z = 9623.5, p < 0.05$) for the number of marked pixels. For the electrotactile wristband, a significantly larger area was marked than for the vibrotactile wristband.

As already mentioned, the electrotactile feedback caused prickling in the hand region without contracting muscles for some participants. Thus, they marked a larger area for the electrotactile feedback, since these additional sensations (away from the point of stimulation) are not created by vibrotactile feedback.

To compare the two rings, a Wilcoxon signed-rank test was used, which shows a significant difference ($Z = 7647, p < 0.001$) for the number of marked pixels. For the vibrotactile ring the participants marked significantly more pixels than for the electrotactile ring. They described the stimuli of the vibrotactile ring as diffuse and difficult to localize and that the localization required high cognitive effort. We analyzed the area of the filled ellipses (number of pixels) for the transversal view as well. A Friedman test shows a significant difference between the four prototypes ($\chi^2(3) = 36.6889, p < 0.001$). A pairwise post-hoc Conover test with Bonferroni correction shows significant differences for the electrotactile ring with all other conditions ($p < 0.01$), which suggests more localized sensations. The heatmaps show that the funneling illusion [27] occurs.

Table 2: All heatmaps of the transversal view (rows: R = ring, W = wristband, E = electrotactile, V = vibrotactile).

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For the transversal view, the markings were in the expected areas for the pairs UL, UR, LD, and RD (see Table 2). The localization of the pairs UD and LR caused problems for the participants. For these pairs, the markings differ for each prototype and scatter even more. However, for the vibrotactile ring the markings deviate more strongly from the expected area than for the other prototypes. The participants mentioned that for the localization of the sensation, this condition felt the most difficult.

The results of the final questionnaire (see Figure 6) show that the participants primarily perceived a localized, prickling sensation caused by the electrotactile stimuli. For the vibrotactile stimuli, the participants described the sensation predominantly as vibrating and diffuse. The participants were asked to rate five statements on a 5-point Likert scale regarding the two feedback modalities. As shown in Figure 7, there are no strong differences. Both feedback modalities were judged as pleasant and the participants got used to them after a few attempts.

Additionally, the participants ranked the prototypes according to their preference as the following (median rank in braces): first wristband electrotactile (1.5), second wristband vibrotactile (2), third ring electrotactile (3), and fourth ring vibrotactile (3.5). The median rank shows that the participants prefer electrotactile over vibrotactile feedback and the wristband over the ring design. We asked the participants to explain their ranking. They mentioned that they experienced the electrotactile feedback as more localized, but the vibrotactile feedback as more comfortable and less stressful. They preferred the wristband over the ring, stating that it was a more convenient location than the ring finger.

7 STUDY 2: EVALUATION OF NOTIFICATION PATTERNS

In this second study, the participants had to learn and recognize notification patterns. The participants completed the pattern recognition for each combination of output device and feedback modality. With the notification patterns as a usage scenario, we directly compare the four prototypes in terms of suitability.

7.1 Pattern Design

Due to the use of pairs of vibration motors and electrodes it is not possible to use existing pattern designs without modification. Thus, the nine notification patterns we created are based on patterns from the literature but are not exactly the same. All of the patterns are shown in Figure 8. We adapted five patterns that include a single repetition from [33] and two patterns that do not include repetitions from [29] to be able to investigate the impact of repetitions on recognition rates. For the patterns Clockwise and Counter Clockwise we took two of the eight patterns from [29]. We have mapped them from a single actuator to actuator pairs by additionally activating the next electrode or vibration motor in sequence (see Figure 8, right). Our patterns Right, Left, Up, Down, and Ascending are based on the patterns Right, Left, Front, Back, and Emergency Exit by Panèels et al. [33]. The pattern Descending was added, e.g. for notifications like decreasing stock prices or temperatures. Because the pairs UD and LR were not included in these patterns, we added the pattern Cross to analyze the suitability of these pairs in the notification context. Each pattern contains four pairs. As in Study 1 each pair was played for 500 ms, giving each pattern a total length of 2000 ms, which was also used in [29].

Figure 8: The patterns we designed are based on [29, 33]. The two patterns on the right do not contain a repetition, the other patterns are played twice. Each pattern contains exactly four actuator/electrode pairs. Every single pair is played for 500 ms, giving a total pattern length of 2000 ms. The numbers and the coloring indicate in which order the pairs are played.
7.2 Study Design

Study 2 has a within-subjects design like Study 1. The three independent variables are (1) the type of wearable (wristband or ring), (2) the feedback modality (electrotactile or vibrotactile feedback), and (3) the nine notification patterns. Again, we counterbalanced the condition order with multiple balanced Latin squares to minimize learning effects. The notification patterns were randomized through Fisher-Yates shuffling.

In this study, a 5.1-inch Samsung Galaxy S6 was used by the participants to select the recognized patterns instead of the 9.7-inch Samsung Galaxy Tab 3. The fat finger problem was not relevant for this study as the participants just had to make a selection by using large buttons on the screen. The participants wore a Bose QuietComfort 25 acoustic noise cancelling headset during the pattern recognition phase. A second Samsung Galaxy S6 played uniformly distributed white noise via these headphones. The white noise was meant to avoid distractions caused by external noises and especially block sounds generated by the vibration motors so that the vibrations could only be sensed by the skin. For consistency, the participants also wore the white noise playing headphones while wearing the electrotactile prototypes.

7.3 Participants

For the second study, we recruited 18 participants (15 male, 3 female, age 21-29, 3 = 25.5, σ = 2.8), 9 of them also attended Study 1. 17 participants were right handed, 1 participant was left handed. 7 participants usually wear a watch (3 of those wear a smartwatch). The average wrist circumference was 169.28 mm (σ = 13.62 mm). In contrast to the first study, 2 participants usually wear a ring. The average ring circumference was 61.33 mm (σ = 5.73 mm). 12 participants had already used electrotactile feedback or electrical muscle stimulation before.

7.4 Procedure

The procedure of the second study was similar to Study 1, but instead of drawing, the participants had to learn and recognize notification patterns. We used the same questionnaires with additional questions concerning the patterns. The wristbands were worn on the left forearm and the rings on the left ring finger. For each electrotactile prototype and participant, we performed an individual calibration. We included a dedicated training phase before the actual recognition phase started. The participants could repeat the notification patterns as often as they liked in order to learn them. They spent an average of 2 minutes in this phase and thus knew which pattern causes which sensation on the skin before the actual trials started. For each of the four prototypes, the participants had to complete three blocks with nine notification patterns each. This study also took 60-90 minutes per participant.

7.5 Results

At first, we analyzed for the electrotactile wristband whether muscle contractions and other effects have a significant effect on the pattern recognition rate. Eight participants had minor muscle contractions ranging from twitching fingers to moving the hand slightly up. We compared the recognition rates of the two groups (with and without observed muscle contractions) with a Mann-Whitney-U test, which showed no significant difference (U = 2848.5, p = 0.08). In the following analysis, we will thus not distinguish between users with and without muscle contractions.

We analyzed the impact of different ring sizes on the recognition rates as well. 10 participants wore the ring with 62 mm circumference and 8 participants wore the ring with 54 mm circumference. Again, a Mann-Whitney-U test showed no significant differences (U = 2986.5, p = 0.19) between these groups (small and large ring) regarding the recognition rates. Given this result, we again do not distinguish between users with smaller and larger finger circumferences. As shown in Figure 9, there are differences in the recognition rates of patterns with and patterns without repetition. For the patterns with repetition, the participants achieved much lower recognition rates as for the patterns without repetition (mean: RE=46.8 % vs 76.0 %, RV=33.3 % vs 44.4 %, WE=62.2 % vs 90.7 %, WV=62.7 % vs 85.2 %). We compared the recognition rates of each pattern with a Friedman test, which shows significant differences (χ²(8) = 88.63, p < 0.001). Again, we conducted pairwise post-hoc Conover tests with Bonferroni correction, which show a significant difference between the patterns without and with the patterns with repetition (p < 0.001). Thus, the pattern Clockwise was the most difficult and the pattern Counter Clockwise were the easiest to identify.

In the final questionnaire of this second study, the participants described the sensations caused by the electrotactile stimuli as prickling, pulling, and localized (see Figure 10). The sensations of the vibrotactile stimuli were again described as vibrating and diffuse. As in Study 1, the participants rated five statements on a 5-point Likert scale (see Figure 11). In comparison to the first study, more participants found the electrotactile feedback unpleasant. The vibrotactile feedback was again rated as pleasant. Contrary to Study 1, the participants found the electrotactile feedback to be tiring. The vibrotactile feedback was again rated as non-tiring. The participants performed a ranking of the prototypes as in Study 1. According to their preferences, sorted by median rank, the participants ranked the vibrotactile wristband best (1.5), followed by the electrotactile wristband (2), the electrotactile ring (3), and the vibrotactile ring (3.5). They justified their choice by stating that the vibration feedback was more comfortable but less accurate than the electrotactile feedback. The ring with vibrotactile feedback was ranked worst. The participants mentioned during the study that with this prototype all patterns felt the same and that it is very difficult to identify the patterns. The participants ranked the patterns according to their preference as shown in Table 3. For this ranking, the participants just had to rank the patterns they could imagine using in daily life. If a pattern was not ranked by a participant, we gave this pattern a rank of 10, as there were 9 patterns and thus the maximum possible given rank was 9. Sorting the patterns first by median and then by mean rank shows that the participants prefer the two patterns without repetition (Clockwise and Counter Clockwise). The pattern Clockwise is ranked last. The ranking of these patterns corresponds to their recognition rates.
Figure 11: The participants rated five statements on a 5-point Likert scale with better results for the vibrotactile feedback.
was not possible to calibrate in such a way as to create a perceptible vibration motors, which are present in many commercial products. A main result is that the pairs of frequency and intensity, could be especially beneficial for the study. The localization of the sensations and the pattern recognition were most difficult with the vibrotactile ring. Therefore the vibrotactile ring, the recognition rates were below 50%. This confirms the statements and drawings of the participants in the first study: the localization of the sensations and the pattern recognition were most difficult with the vibrotactile ring. Therefore the vibrotactile ring is not suitable for notification purposes. For rings, electrotactile feedback is thus a better alternative to vibration. Both studies showed that the participants preferred the wristbands over the rings. The studies also showed that electrotactile feedback produces more localized sensations, but vibration is judged as more comfortable overall.

Despite prior calibration, some participants experienced slight muscle contractions during both studies. With the given hardware it was not possible to calibrate in such a way as to create a perceptible tactile sensation without any muscle contraction. However, we found no significant differences for participants with and without muscle contractions.

The frequency of the ERM actuators that we used are coupled to the operating voltage. We provide a constant voltage of 3.3 V resulting in a fixed frequency and intensity for the vibration motors. We chose these actuators, because we wanted to evaluate off-the-shelf vibration motors, which are present in many commercial products. Other types of vibration actuators, which allow the separate control of frequency and intensity, could be especially beneficial for the vibrotactile ring, as lower intensities could lead to better results with this prototype.

The use of two vibration motors simultaneously is also a limitation of this work. However, this design was necessary to represent all of the sensations created by the electrotactile feedback. Activating only one vibration motor could not represent the sensations created by the electrode pairs UD and LR. Furthermore, using concentric electrodes was not possible as they are not suitable for the analysis of sensations created between two spatially separated electrodes.

8 DISCUSSION AND LIMITATIONS

Study 1 shows the comparability of the four prototypes; the sensations generated by all four prototypes are comparable, with slightly different levels of dispersion for each prototype. Inaccuracies in the free hand drawings by the participants might affect the results as the prototypes were not depicted in the drawing areas. This affects all prototypes and therefore does not invalidate the results.

A main result is that the pairs UD and LR, which produced the most scattered markings, are not suitable for notification purposes as their recognition results are poor.

Contrary to the most localized markings for the electrotactile ring in Study 1, the second study shows higher recognition rates for the wristbands. Across all four prototypes (RE, RV, WE, WV) patterns without repetition had higher recognition rates than patterns with repetition. With the prototypes RE, WE and WV, the participants achieved recognition rates from 70.4% up to 90.4% for patterns without repetition after relatively little practice. For the vibrotactile ring, the recognition rates were below 50%. This confirms the statements and drawings of the participants in the first study: the localization of the sensations and the pattern recognition were most difficult with the vibrotactile ring. Therefore the vibrotactile ring is not suitable for notification purposes. For rings, electrotactile feedback is thus a better alternative to vibration. Both studies showed that the participants preferred the wristbands over the rings. The studies also showed that electrotactile feedback produces more localized sensations, but vibration is judged as more comfortable overall.

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9 CONCLUSION

We presented a comparison of energy-efficient electrotactile feedback and commonly used vibration feedback for wearables worn on the wrist and ring finger, respectively. We analyzed the sensations caused by pairs of electrodes and vibration motors. The heatmaps for the transversal views show that the activation pairs are identified well and that the electrotactile feedback creates a more localized sensation around the wrist. The heatmaps for the dorsal views show that vibrotactile feedback is more localized along the forearm than the electrotactile feedback. Electrotactile feedback can cause sensations away from the point of stimulation. Based on these findings and on patterns from prior work we investigated which pairs, patterns, and wearables are suitable for notifications.

The recognition rates concerning the patterns without repetition on the vibrotactile wristband are comparable to the results of [29]. Overall, the results suggest that pairs with opposing electrodes and vibration motors, as well as the vibrotactile ring, lead to low pattern recognition rates and are thus not suitable for notification purposes.

Furthermore, we showed that the participants achieved slightly better results with energy-efficient electrotactile feedback than with vibrotactile feedback. However, for the wristbands the participants preferred vibration feedback, because of higher comfort. For the ring design electrotactile feedback was superior to vibration feedback, as patterns could not be reliably recognized with the latter. Regardless of the moderate individual recognition rates of the patterns, our results indicate that overall electrotactile feedback is more accurate than vibration. Our findings can be used in choosing suitable feedback layouts and pattern designs for hand- and fingerworn notification devices.

Table 3: The participants ranked the 9 patterns according to their preferences. If a pattern was not ranked by a participant, we gave the pattern a rank of 10. The two right hand columns show median (M) and mean rank (\( \bar{x} \)).


