Measuring the User Experience of Vibrotactile Feedback on the Finger, Wrist, and Forearm for Touch Input on Large Displays

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We examine vibrotactile feedback delivered on the finger, wrist, and forearm with the goal of enriching the experience of touch input interactions with public displays. We focus on understanding the user experience of such interactions, which we characterize with a wide spectrum of UX measures, including subjective perceptions of the enjoyment, efficiency, input confidence, integration between touch input and on-body vibrations, distraction, confusion, and complexity of vibrotactile feedback for touch input with public displays. Our empirical findings, from a controlled experiment with fourteen participants, show positive and favorable perceptions of vibrotactile feedback as well as a significant preference for feedback on the finger compared to the wrist and forearm.

ACM Reference Format:
Mihail Terenti and Radu-Daniel Vatavu. 2022. Measuring the User Experience of Vibrotactile Feedback on the Finger, Wrist, and Forearm for Touch Input on Large Displays. 1, 1 (June 2022), 11 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Vibrotactile feedback accompanying touch input on mobile devices is known to reduce error rates during touch target acquisition [6,12], improve user performance for text entry [8,13] and dwell mode switching [18] tasks, lower the cognitive demand of touch input interactions [6,12], and even deliver new sensing capabilities to the device, such as identification of the touching fingers [4,21]. Moreover, vibrotactile feedback has been employed as an effective technique to increase the accessibility of mobile devices for users with visual impairments [11,32,33]. Unfortunately, public interactive displays do not offer native support for vibrotactile feedback and, consequently, cannot deliver the usability benefits of haptic sensations accompanying active touch on mobile devices. Although prototypes of large haptic surfaces [10,17,20,28] have been demonstrated in research laboratories, the technology has not yet been incorporated in public touchscreen displays.

However, mobile and wearable devices, such as smartphones, smartwatches, and fitness trackers, are prevalent and their users already familiarized with the language of vibrotactile feedback employed by these devices to deliver "click" and "springy" feelings [24] during touch input. Thus, delivering vibrotactile feedback on the user's body, e.g., on the finger wearing a smart ring or the wrist wearing a smartwatch, may be a feasible design option for augmenting public

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touchscreen displays with vibrotactile feedback, especially in the context where a niche market is forecast for wearables for authentication and payment at public terminals, e.g., smart rings for cashless payments [31]. In this work, we are primarily interested in the user experience (UX) of how distal vibrotactile feedback, physically decoupled from the point of touch on the display feels to users. To this end, we report results from a controlled experiment with N=14 participants and a diversified set of UX measures designed to collect subjective perceptions regarding vibrotactile feedback delivered on the *finger*, *wrist*, and *forearm* during touch input with two, horizontal and vertical, large displays. Our findings show a positive experience in terms of perceived enjoyment, efficiency, confidence, and integration between touch input and vibrations at various locations on the interactive hand as well as low perceived distraction, difficulty, confusion, and complexity for the vibrotactile feedback accompanying touch input. These results open the way towards designing cross-device, wearable-surface user experiences for interactions with public displays.

2 RELATED WORK

Wearable devices come in many form factors to address a variety of goals [30] and ways to manage information [5], from applications in health monitoring and fitness tracking to communication and entertainment to tasks traditionally performed on other types of computers, e.g., writing documents from the smartwatch [22]. In addressing such diverse needs, designers can leverage a specific output modality for meaningful interactions with wearables: by being close to or in contact with the body, wearables can effectively deliver feedback via vibrations and other forms of haptics [12,19,38]. A few works have considered vibrotactile feedback for wearables to accompany interactions with other devices, such as the smartphone. For instance, Schönauer *et al.* [27] examined vibrotactile feedback on the upper arm for gestures performed in mid-air to interact with the smartphone, and focused on aspects of user perception when vibrotactile feedback was physically decoupled from the smartphone. Vatavu *et al.* [34] used vibrations on the index finger to create the illusion of "holding" digital content from the smartphone, e.g., a photograph, after being pinched on the screen, is taken out of the smartphone and brought into the physical world, where it manifests through vibrations of various duration and intensity. Le *et al.* [16] introduced Ubitile, a ring device for vibrotactile feedback during interactions with tabletops. Henderson *et al.* [12] showed that distal vibrotactile feedback, delivered to the user's nondominant wrist by a smartwatch, achieved similar performance characteristics in terms of time and error rate for touch target acquisition on a smartphone as under-the-finger vibrotactile feedback provided by the smartphone. Other work has examined substitution of audio with vibrotactile feedback for various applications, e.g., in healthcare, with devices designed for the upper arm [7] and the wrist [26].

Researchers have also explored designs of large displays that can natively deliver haptic feedback. For instance, HapTable [10] is a multimodal interactive tabletop that integrates electromechanical and electrostatic actuation delivered by four piezo patches mounted at the edges of the tabletop. Poupyrev *et al.* [25] presented a haptic display for pen-based interaction, where the pen was augmented with vibrotactile feedback. Jansen *et al.* [14] introduced a multitouch input device enhanced with active haptic feedback generated by varying the viscosity of the fluid located underneath the display using a magnetic field. Bau *et al.* [3] employed a customized 3M Microtouch panel to study users' perceptions of electro-vibration and reported frequency and amplitude thresholds for which feedback could be discriminated on the touch surface. Yamamoto *et al.* [37] explored small electrostatic tactile displays for VR systems.

Although new display prototypes have integrated creative solutions towards large display haptics, their technology is not available at scale and the displays from public places do not offer the possibility for haptic feedback. In this context, turning to wearables as a form of computing that is becoming mainstream, e.g., about one-in-five Americans use a smartwatch or fitness tracker as of 2020 [35], may represent a feasible design solution to augment public interactive

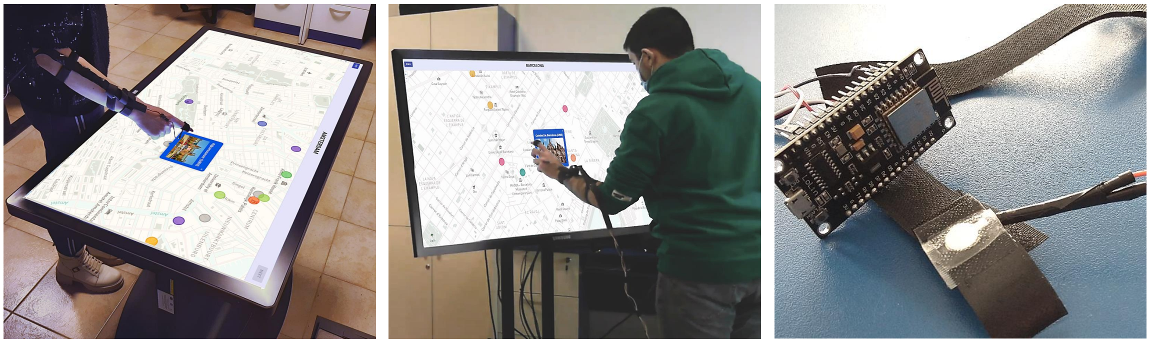

Fig. 1. Participants interacting with the *horizontal* (left) and *vertical* (middle) large displays. On the right, a close-up of the wearable device with vibration motors that we prototyped for our experiment.

displays with vibrotactile feedback on the fly. In this work, we are interested in the user experience of such a technical solution to complement results from prior work [12,27] that focused on usability and user performance aspects for vibrotactile feedback delivered by wearables during touch and gesture input. To this end, we connect to UX reports that evaluated touch input and vibrotactile feedback for interactions with mobile devices with a diversity of UX measures, including preference rankings [6,15,23], adjective ratings [23], and measures of perceived enjoyment, comfortability, and feeling of pressing physical buttons [15], on which we capitalize in the design of our experiment.

3 EXPERIMENT

We conducted a controlled experiment to measure aspects of the user experience of how vibrotactile feedback feels when delivered by a wearable device at various locations on the interactive arm during touch input with a large display.

3.1 Participants

A number of 14 participants (10 male, 4 female), representing young adults aged between 19 and 34 years old (M=25.0, SD=4.1), were recruited via convenience sampling. One participant was left-handed. All of the participants were smartphone users, five (35.7%) were also using tablets on a regular basis, eight (57.1%) were using smartwatches or fitness trackers, and four participants (28.6%) reported using smart earbuds. A number of eight participants (57.1%) had the keyboard vibration feature turned on on their smartphones.

3.2 Apparatus

We implemented an interactive map application using Leaflet,[1] a popular open-source JavaScript library for interactive maps. At startup, the application zooms into a city map with pinpoints shown for selected targets, e.g., the Museum of Contemporary Art of Barcelona; see Figure 1, left and middle. When the user touches a target, a popup window presents a brief description about the target and vibrotactile feedback is delivered to the user's interactive arm by a wearable device that we prototyped for our experiment; see Figure 1, right. The wearable incorporated three 10mm DC coin vibration motors[2] into a velcro band with adjustable length so that the motors could be affixed comfortably to the index finger, the wrist, and the forearm, as shown in Figure 1, left and middle. (An alternative design approach would

[1]https://leafletjs.com
[2]https://nfpshop.com/product/10mm-coin-vibration-motor-3mm-type-model-nfp-c1030

have been to implement three devices, one for the finger, one for the wrist, and one for the forearm, but the participants would have had to don and doff them repeatedly when moving from one experimental condition to the next; see the next subsections for details about the task.) The vibration motors were commanded by a CH340G NodeMcu V3 board based on the ESP8266 Wi-Fi module,[3] a self contained System-on-a-Chip with integrated TCP/IP protocol stack, which we programmed to communicate with the map application via the WebSocket[4] protocol. Vibrations were delivered by each motor independently for a fixed duration of 150ms, a value determined empirically during our technical prototyping so that vibrations could be felt unambiguously on various parts of the arm. We ran the map application in the Google Chrome web browser (full screen mode) of two touchscreen displays: an horizontal 46-inch Ideum Platform[5] (1920×1080 pixel resolution, 12ms touch response time, integrated CPU Intel Core i7-4790S 3.2GHz, RAM 16GB DDR3) and a vertical 55-inch Samsung UE55D display[6] with a CY-TD55LDAH touchscreen overlay[7] (1920×1080 pixel resolution, 13ms touch response time, connected to a Dell laptop with an Intel Core i5-4300U 2GHz processor, RAM 8GB DDR3); see Figure 1, left and middle.

3.3 Design

Our experiment was a within-subjects design with the following two independent variables:

(1) OnBody-Location, nominal variable with four conditions: *finger*, *wrist*, and *forearm*, specifying locations on the interactive arm where vibrotactile feedback was provided during touch input with the large display, and *none*, representing the condition where vibrotactile feedback was absent.
(2) Display-Orientation, nominal variable with two conditions: *horizontal* and *vertical*.

While OnBody-Location examines the effect of wearing a device, Display-Orientation covers potential effects of the presentation of the large display. The dependent variables are represented by several UX measures described in detail in Subsection 3.5.

3.4 Task

Participants were presented the two displays and asked to engage in a neutral task (they made a drawing in Windows Paint) to become familiarized with how touch input felt on each display. Afterwards, they were presented the wearable prototype and briefed about the interactive map application and the specifics of the task. For each combination of OnBody-Location × Display-Orientation, a different city map was presented and participants were asked a question about the targets indicated with pinpoints on the map, e.g., "What is the year of the oldest building?" To answer the question, participants had to touch all of the targets, which revealed their descriptions. Vibrotactile feedback was delivered during touch input by the wearable device (Figure 1, right) affixed to the dominant hand. The order of Display-Orientation was randomized per participant as was the order of the *finger*, *wrist*, and *forearm* vibrotactile feedback conditions of OnBody-Location for each display. The first condition for each display was always touch input without vibrotactile feedback, which was our control condition. On average, tasks were completed in 13.1 minutes (SD=7.7) with participants performing on average 187.9 touches (SD=51.5). At the end of the experiment, participants filled in a questionnaire with UX measures designed to collect their experience; see next.

[3]https://esp8266-shop.com/product/nodemcu-esp8266-esp-12e
[4]https://developer.mozilla.org/en-US/docs/Web/API/WebSockets_API
[5]https://www.ideum.com/products/touch-tables
[6]https://displaysolutions.samsung.com/digital-signage/detail/86/UE55D
[7]https://www.samsung.com/ph/business/smart-signage/touch-overlay-td55ldah/cy-td55ldahen

3.5 Measures

We collected participants' experience of vibrotactile feedback delivered at various locations on the interactive arm with several UX measures representing dependent variables in our experiment. Most of the measures were collected with 5-point Likert-scale ratings encoding participants' level of agreement, from 1 "Strongly disagree" to 2 "Disagree," 3 "Neither agree nor disagree," 4 "Agree," to 5 "Strongly agree," with various statements involving words with positive and negative connotations, respectively:

(1) Perceived-Enjoyment, in response to the statement *"Interacting with the display felt more enjoyable with vibrotactile feedback than without."*
(2) Perceived-Distracteness, in response to the statement *"Interacting with the display felt more distracting with vibrotactile feedback than without."*
(3) Perceived-Efficiency, *"Interacting with the display felt more efficient with vibrotactile feedback than without."*
(4) Perceived-Difficulty, *"Interacting with the display felt more difficult with vibrotactile feedback than without."*
(5) Perceived-Confidence, in response to the statement *"Vibrotactile feedback made me feel more confident when interacting with the display compared to when vibrations were absent."*
(6) Perceived-Confusion, *"Vibrotactile feedback created confusion for me when interacting with the display."*
(7) Perceived-Integration, *"Touching the display and feeling the vibrations integrated well into one experience."*
(8) Perceived-Complexity, *"Vibrotactile feedback was unnecessarily complex when interacting with the display."*

Besides these measures focused on the perception of vibrations, we also elicited preferences, expectations, and desirability for vibrotactile feedback when interacting with a large display:

(9) Overall-Preference, a score from 1 (denoting the most preferred condition) to 9 (the least preferred) for each combination of OnBody-Location × Display-Orientation, including no vibrotactile feedback.
(10) Overall-Perception. We asked participants to provide three words that best described their experience with each combination of OnBody-Location × Display-Orientation, e.g., *"Please use three words to describe your experience of vibrotactile feedback on the [finger] while interacting with the [horizontal] display."*
(11) Expected-Meaningfullness collects participants' expectations for meaningful vibration patterns, i.e., patterns that are more complex than simple on/off vibrations. We measured Expected-Meaningfullness using a 5-point Likert-scale by eliciting agreement or disagreement with the statement *"I would like for the vibrotactile feedback to be more complex than a mere vibration to have more information about the target that I am touching on the display."*
(12) Expected-Implementation collects participants' preferences for the display to implement vibrotactile feedback by using their personal wearable devices, represented by a *ring*, *watch*, and *armband*, e.g., *"I would see myself using vibrotactile feedback delivered to [my smartwatch] when interacting with a public display."*

Overall, we collected twelve UX measures spanning a wide spectrum of perceptions and expectations for vibrotactile feedback delivered by wearables during touch input with a large display.

3.6 Statistical Analysis

We report medians as preferred measures of central tendency for our ordinal variables. To analyze the ordinal data from our two-factor experiment, we employ ANOVA with the Aligned-Rank Transform procedure implemented with ARTool [36].[8] For post-hoc pairwise comparisons, we employ the ART-C algorithm [9] of ARTool.

4 RESULTS

We report findings about our participants' experience with vibrotactile feedback. Overall, our results show that vibrotactile feedback was preferred to no feedback, and that different locations where vibrations were delivered on the interactive arm led to differences in the experience felt during touch input with the large displays.

4.1 Vibrotactile *vs.* No Vibrotactile Feedback

We asked participants to rate, on a scale from 1 (most preferred) to 9 (least preferred), the combined conditions of Display-Orientation × OnBody-Location, including the case of no vibrotactile feedback. We did not find a statistically significant effect of Display-Orientation on Overall-Preference ($F_{(1,91)}$=0.004, p=.951>.05, *n.s.*), but we detected a significant effect of OnBody-Location ($F_{(3,91)}$=12.362, p<.001) of large size (η_p^2=.29). Both the *finger* (Mdn=1) and *wrist* (Mdn=4) conditions of vibrotactile feedback were preferred to no feedback (Mdn=6) with large (η_p^2=.26) and medium (η_p^2=.11) effect sizes, respectively, but not *forearm* (Mdn=5, *n.s.* at α=.05). These results indicate vibrations on the *finger* as a strong candidate for augmenting the user experience of touch input on a large display. Next, we provide a detailed analysis of the three conditions involving vibrotactile feedback.

4.2 Vibrotactile Feedback on the Finger, Wrist, and Forearm

Figure 2 shows participants' overall perception of vibrotactile feedback delivered on the *finger*, *wrist*, and *forearm*, and Table 1 highlights statistically significant effects detected for a significance level of α=.05. Next, we discuss each effect in detail.

4.2.1 Display orientation. Except for the Perceived-Enjoyment measure (p=.041), the orientation of the display did not influence participants' perceptions of the experience they felt with vibrotactile feedback. Participants reported enjoying vibrations more when interacting with the *horizontal* display (Mdn=4) than the *vertical* one (Mdn=3) with a medium to small effect size (η_p^2=.06).

4.2.2 Location of vibrotactile feedback on the body. The location where vibrations were delivered to the interactive arm influenced significantly the experience of touch input as detected by six of our eight UX measures of perception: Perceived-Enjoyment (η_p^2=.28), Perceived-Efficiency (η_p^2=.42), Perceived-Confidence (η_p^2=.28), Perceived-Integration (η_p^2=.33), Perceived-Confusion (η_p^2=.13), and Perceived-Distractеness (η_p^2=.21); see Table 1. Post-hoc contrast tests (Bonferroni corrected) revealed statistically significant differences between vibrations on the *finger* compared to the *wrist* and *forearm*, but no difference between *wrist* and *forearm*. Overall, vibrotactile feedback on the *finger* was preferred in terms of Perceived-Enjoyment (Mdn=5 and 4.5 for the *horizontal* and *vertical* display), Perceived-Efficiency (Mdn=5 and 5), Perceived-Confidence (Mdn=5 and 5), and Perceived-Integration with touch input (Mdn=5 and 4.5), where 5, the maximum rating from our scale, denotes "Strongly agree;" see Figure 2. Also, vibrations on the *finger* were preferable to the *wrist* and *forearm* when the experience was described in terms of

[8] https://cran.r-project.org/web/packages/ARTool/index.html

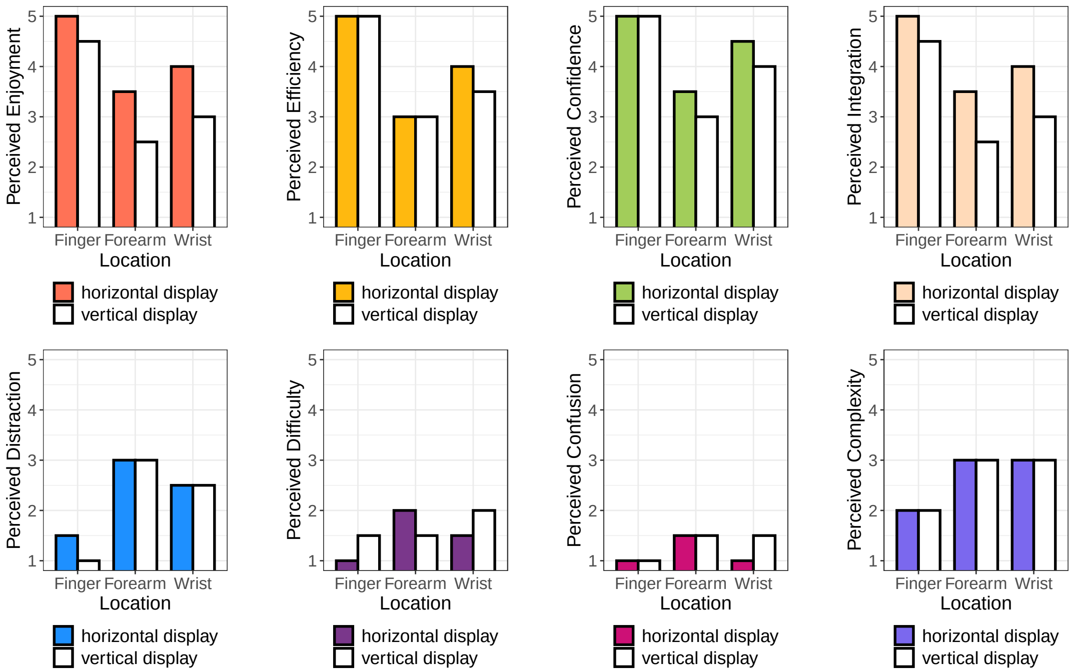

Fig. 2. User experience of vibrotactile feedback on the *finger*, *wrist*, and *forearm* during touch input with the *horizontal* and *vertical* displays. *Notes:* median values are shown in this figure; higher values denote a better experience for the UX measures from the top row; lower values denote a better user experience for the bottom row measures; see Table 1 for statistical tests.

Table 1. Statistical significance tests for the UX measures of the perception of vibrotactile feedback during touch input with large displays; see Figure 2 for the median ratings.

UX measure	Effect of Display-Orientation	Effect of OnBody-Location				Interaction
		main effect	*finger vs. wrist*†	*finger vs. forearm*†	*wrist vs. forearm*†	
Perceived-Enjoyment	$F_{(1,65)}$=4.343, p<.05	$F_{(2,65)}$=12.346, p<.001	p<.005	p<.001	*n.s.*	*n.s.*
Perceived-Efficiency	*n.s.*	$F_{(2,65)}$=23.521, p<.001	p<.001	p<.001	*n.s.*	*n.s.*
Perceived-Confidence	*n.s.*	$F_{(2,65)}$=12.418, p<.001	p<.001	p<.05	*n.s.*	*n.s.*
Perceived-Integration	*n.s.*	$F_{(2,65)}$=15.896, p<.001	p<.001	p<.005	*n.s.*	*n.s.*
Perceived-Distracteness	*n.s.*	$F_{(2,65)}$=8.473, p<.001	p<.001	*n.s.*	*n.s.*	*n.s.*
Perceived-Difficulty	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
Perceived-Confusion	*n.s.*	$F_{(2,65)}$=4.912, p<.01	p<.05	p<.05	*n.s.*	*n.s.*
Perceived-Complexity	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*

† Bonferroni corrections applied.

Perceived-Distracteness (Mdn=1.5 and 1), Perceived-Difficulty (Mdn=1 and 1.5), Perceived-Confusion (Mdn=1 and 1), and Perceived-Complexity (Mdn=2 and 2), where 1, the lowest rating from our scale, means "Strongly disagree."

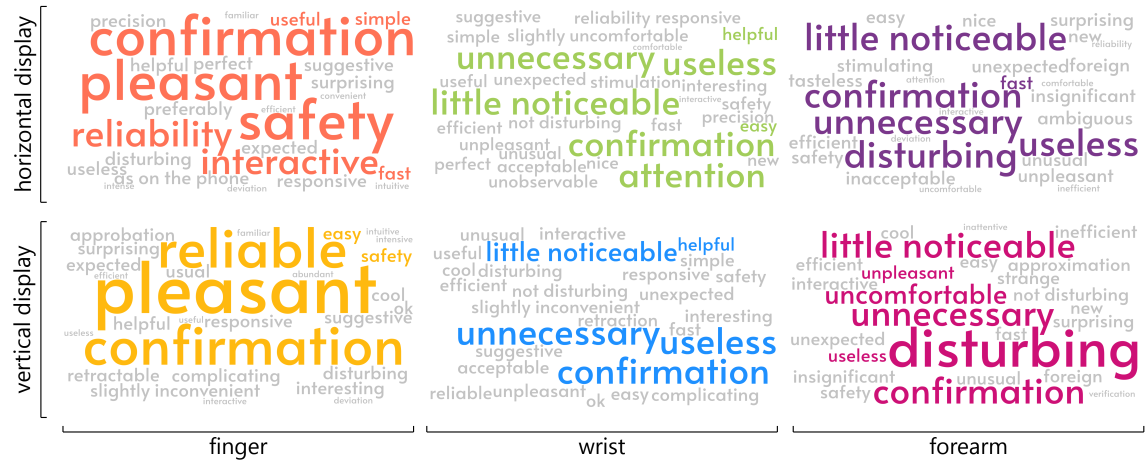

Fig. 3. Word clouds (https://www.wordclouds.com) generated from our participants' free-form descriptions of their experience with vibrotactile feedback accompanying touch input for each combination of Display-Orientation × OnBody-Location.

4.2.3 Free-form description of the experience of vibrotactile feedback. Figure 3 shows word clouds generated from a total number of 209 words proposed by our participants (M=14.9 on average), which they felt best described their experience with vibrotactile feedback for each combination of OnBody-Location × Display-Orientation. The *finger* condition received positive descriptions, such as "pleasant," "interactive," "useful," and "responsive." Positive words were also used to describe feedback on the *wrist*, although some participants considered it "unnecessary" or "little noticeable" compared to other conditions. Finally, the experience of vibrations delivered to the *forearm* received more words with negative connotations, such as "disturbing," "uncomfortable," "little noticeable," and even "useless." These descriptions corroborate the findings obtained with the UX measures from Figure 2 that revealed a preference for *finger* and *wrist* over *forearm*. An interesting finding regards the word "confirmation," which stands out in all of the clouds, revealing the practicality of vibrotactile feedback to confirm successful detection of finger touches on the surface of the display.

4.3 Expectations for a Real-World System Implementation

In our experiment, we employed on/off vibrations of a constant intensity and duration to keep our experiment design simple. However, in order to learn about participants' expectations for more complex vibrotactile patterns for touch input, we measured Expected-Meaningfullness from 1 (participants strongly disagreeing that more complex patterns were needed) to 5 (strong agreement). The median rating of Expected-Meaningfullness was 3.5, located in-between "Neither agree nor disagree" and "Agree," with a mean of 3.4 (SD=1.3). This result shows a slight preference for more complex vibrations, but not statistically significant according to a one-sample Wilcoxon test (V=46.5, p=.235>.05, *n.s.*). Nevertheless, a few participants provided examples of vibration patterns or applications where vibrotactile feedback more complex than an on/off vibration would be useful, which are interesting to report. For example, P_1 said that vibrations could be longer and stronger when the user finds the correct answer in a video game; P_3 considered that errors should be accompanied by longer vibrations; P_{11} exemplified the case of a payment application, where the user could be alerted with a stronger vibration that they are about to confirm payment; and participant P_{10} suggested complementing vibrations on the arm with a visual effect on the display, e.g., ripples, at the touch location.

We also found that our participants were willing to receive vibrotactile feedback delivered from the display to the *finger* via their smart rings (Mdn=4.5), if they had such a wearable device, as well as on the *wrist* via their smartwatches and fitness trackers (Mdn=4), but were overall undecided regarding wearing a smart armband (Mdn=3) to receive vibrations on the *forearm*. This result corroborates our previous findings obtained with the UX measures of perception, where the *forearm* condition was the least preferred.

5 DISCUSSION AND LIMITATIONS

We reported positive reactions from our participants for vibrotactile feedback accompanying touch input on large displays, which recommend future work on designing cross-device, wearable-surface user experiences for public displays. One result that emerged with several of our UX measures was that vibrotactile feedback delivered on the *finger* was preferred to feedback on the *wrist* and *forearm*, respectively. One possible explanation for this result may lie with associations that users may form during their interactions (with the finger) with smartphones that provide vibrotactile feedback, while vibrations delivered by smartwatches and fitness trackers largely represent notifications, not confirmations of touch input. Also, our participants were not familiarized with devices for the forearm, such as smart armbands, which may explain the reported feelings of discomfort or unnecessary feedback at that location on the body. Moreover, the preference for the *finger* might have been influenced by the intensity and the duration of the vibrotactile feedback, for which we used 150ms-long vibrations; see Subsection 3.2. Longer or more intense vibrations, including using multiple actuators, may lead to different results, but also different form factors for wearables. We leave such explorations for future work.

There are two limitations to our experiment design. First, we did not randomize the order of the "no feedback" control condition as we did with vibrotactile feedback on the *finger*, *wrist*, and *forearm*. The control condition was always presented first (see Subsection 3.4) as we used it for our participants to become familiarized with the interactive map application and touch input with the two displays. Further experiment designs could look for significant effects between the control and vibrotactile feedback conditions. Second, we did not attempt to correct the time delay [12] caused by the signal to propagate in the Wi-Fi network between the moment of touching the screen and the actual moment when feedback was provided at various locations on the interactive arm, although none of the participants mentioned any latency issues.

6 CONCLUSION

We focused in this work on understanding the novel user experience of distal, physically decoupled vibrotactile feedback on the interactive arm during touch input on a large display. Interesting future work lies ahead, such as exploring other locations on the body where to deliver distal vibrotactile feedback, technical implementation of such feedback using off-the-shelf wearables, and evaluating the user experience of other user groups. Also, exploration of a diversified set of vibrotactile feedback patterns for various categories of wearables [1,2,29] represents another future work direction for enriching interactions with large public displays.

ACKNOWLEDGMENTS

This work is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 860114.

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