# The Eclectic User Experience of Combined On-Screen and On-Wrist Vibrotactile Feedback in Touchscreen Input


Mihail Terenti
MintViz Lab, MANSiD Center
Ştefan cel Mare University of Suceava
Suceava, Romania
mihail.terenti@usm.ro

Matthieu Rupin
Hap2U
Grenoble, France
matthieu.rupin@hap2u.net

Baptiste Reynal
Hap2U
Grenoble, France
baptiste.reynal@hap2u.net

Laurent Grisoni
University of Lille
Villeneuve d'Ascq, France
laurent.grisoni@univ-lille.fr

Radu-Daniel Vatavu
MintViz Lab, MANSiD Center
Ştefan cel Mare University of Suceava
Suceava, Romania
radu.vatavu@usm.ro


**Figure 1: In this work, we contrast the user experience of conventional on-screen vibrotactile feedback (left) against that of combined on-screen and on-wrist vibrations (right) for augmenting mobile touchscreen input through a wearable device.**


## ABSTRACT

On-wrist vibrotactile feedback, such as provided through smartwatches, has been shown to have a positive impact on users' touch input performance with mobile devices, but the user experience of combined on-screen and on-wrist vibrations has been scarcely examined. In our experiment involving twenty-two participants, an eclectic three-faceted UX emerged: (i) both on-screen and combined on-screen and on-wrist vibrations resulted in high ratings with no significant differences in UMUX scores or user preferences; (ii) negatively-connoted UX descriptors, e.g., difficulty or complexity, generally revealed less favorable UX for combined on-screen and on-wrist vibrations; (iii) positively-connoted descriptors, e.g., enjoyment or efficiency, revealed that vibrations on the wrist were not detrimental to touchscreen input UX. We use our findings to propose future work opportunities in cross-device smartphone and smartwatch interactions, which we discuss through the lenses offered by two identified dichotomies of vibrotactile feedback technical implementation: on-fingertip *vs.* on-wrist and single-point *vs.* multi-point vibrations.



## CCS CONCEPTS

• **Human-centered computing** → **Touch screens**; *Haptic devices*; **Empirical studies in interaction design**; **Gestural input**; • **Hardware** → Touch screens; Haptic devices.

## KEYWORDS

User experience, touch input, touchscreens, vibrotactile feedback, wearables, smartwatches




*CHI EA '24, May 11–16, 2024, Honolulu, HI, USA*



ACM ISBN 979-8-4007-0331-7/24/05
https://doi.org/10.1145/3613905.3650835

**ACM Reference Format:**
Mihail Terenti, Matthieu Rupin, Baptiste Reynal, Laurent Grisoni, and Radu-Daniel Vatavu. 2024. The Eclectic User Experience of Combined On-Screen and On-Wrist Vibrotactile Feedback in Touchscreen Input. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA*. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3613905.3650835

# 1 INTRODUCTION

Vibrotactile feedback integrated into mobile devices, such as smartphones and tablets, is known to enhance the user experience (UX) of touchscreen input through tactile sensations delivered on the screen. A similar effect can be achieved with distal vibrations on the hand and arm implementing touch input, e.g., the finger [30], wrist [10], forearm [26], or upper arm [15], through wearables, such as smartwatches and electronic rings. Previous research has shown that vibrotactile stimuli accompanying touchscreen input determine not only increased user performance [10,15], but also augmented perception of the efficiency and enjoyment of the corresponding interactions [21,26,27]. Furthermore, on-screen vibrotactile feedback can be complemented [10] and even replaced [30] by distal vibrations on the hand and arm, such as through a conventional smartwatch. Due to the prevalence of smartphones and smartwatches, their conjoint use for combined on-screen and on-wrist vibrotactile feedback represents a feasible technical solution to augment touchscreen interactions; see Figure 1 for an illustration.

In this work, we report findings from a controlled experiment involving twenty-two participants that performed touch input on a mobile device accompanied by vibrotactile feedback delivered either on the screen, at the touch point, or through combined on-screen and on-wrist vibrations. Our results reveal an eclectic, multi-faceted UX of combined vibrotactile feedback with respect to the baseline of on-screen vibrations only. First, we found that both on-screen and combined on-screen and on-wrist vibrations resulted in a highly-rated experience with no significant differences in UMUX scores or users' preference ratings. Second, negatively-connoted UX descriptors, such as difficulty or complexity, generally revealed a less favorable UX of combined on-screen and on-wrist vibrations. Third, positively-connoted UX descriptors, such as enjoyment or efficiency, revealed that on-wrist vibrations delivered supplementarily to those on the screen, were not detrimental to touchscreen interaction UX from the perspective of statistical significance. These preliminary findings reveal an UX of combined on-screen and on-wrist vibrotactile feedback to be further examined in future work about cross-device interactions involving touchscreen input augmented with vibrotactile output. To this end, we propose two dichotomies to guide future research: on-fingertip *vs.* on-wrist vibrations, two locations that delineate the hand as the dexterous body part involved in touchscreen interaction, and single-point *vs.* multi-point vibrations towards vibrotactile feedback across the body.

# 2 RELATED WORK

Vibrotactile feedback has been used for notifications delivery [3,11] and augmenting touchscreen input [7,15,30]. For example, Liao *et al.* [13] introduced Dwell+, a feedback technique that uses rapid haptic ticks to increase the effectiveness of typical dwell selection. Besides improving user performance, vibrotactile feedback also creates the feeling of more confident and pleasant touches, contributing to an increased user experience. Furthermore, the benefits of vibrotactile feedback remain present even when vibrations are not precisely aligned with the interaction point [12,23,29,33].

Vibrotactile feedback on different body parts has been previously investigated as a mechanism to convey information during touchscreen interaction in various contexts of use. For instance, McAdam and Brewster [15] presented users with vibrations at different locations on the body where a smartphone could be affixed, and examined text entry performance with a touchscreen device. They found significant improvements in terms of entry speed without accuracy being affected. Henderson *et al.* [10] evaluated users' touchscreen input performance with vibrotactile feedback delivered on the screen or wrist, and reported both being equally effective in reducing task times and error rates. Qin *et al.* [24] examined how vibrotactile feedback involving patterns of varying frequency, delivered through a smartwatch, affected users' preferences for receiving notifications, while Tan *et al.* [28] explored users' preferences for diverse parameters of vibrotactile feedback in relation to touchscreen input, such as vibration duration and intensity.

Distal vibrotactile feedback delivered at multiple locations on the body, i.e., multi-point vibrations, can be used to convey even more information to users. For instance, multi-point vibrations are a feasible method for navigation assistance [22], eyes-free interaction [9], and increased awareness [1]. Pielot *et al.* [22] presented PocketNavigator, a navigation assistance application that employs vibrotactile feedback, delivered through the smartphone, to provide navigation cues on the user's body. Flores *et al.* [9] implemented vibrations through a belt to complement audio feedback for users with visual impairments. An enhanced navigation technique, involving diverse types of tactile feedback delivered on different regions of the arm, was proposed in [5]. For indoor guidance, Lim *et al.* [14] developed Vi-Bros, a system employing multi-point vibrotactile feedback through the smartphone and smartwatch for presenting navigation directions. Vibrotactile stimuli have also been employed to reproduce Braille characters on digital devices, rendered either on the screen [2,25] or through wearables designed for the hand [18–20].

While many studies have focused on either the delivery of vibrotactile feedback or examination of various locations on the body to present information to users through vibrations, research on the potential benefits of combined on-screen and distal vibrotactile feedback has been scarce, especially in respect to evaluating the corresponding UX. In this space, Vo and Brewster [34] examined user performance with selection tasks for in-vehicle touchscreens while receiving vibrotactile feedback on the steering wheel. Dupin *et al.* [6] reported that users perceive vibrotactile and kinesthetic stimuli applied to different hands as if originating from the same hand. Additionally, distal vibrotactile feedback on the finger, wrist, or forearm has been shown to increase users' perceived enjoyment and efficiency of touchscreen input [30]. However, while the impact of single-point vibrations has been examined to some extent, the UX of combined vibrations, such as on the screen and wrist delivered through smartphones and smartwatches operating in conjunction, has been barely addressed [10], despite these devices' prevalence.

In conclusion, research on combined on-screen and on-wrist vibrotactile feedback has been limited to few examinations primarily centered on user input performance [10,15]. The study most relevant to our scope is Terenti and Vatavu's [30] evaluation of the UX of vibrations localized on the finger, wrist, and forearm during touchscreen input. However, in their evaluation, those locations were considered in isolation, unlike in our work where they are combined. Next, we present an experiment designed to evaluate the UX of combined on-screen and on-wrist vibrotactile feedback.


**Figure 2: *Top:* photograph taken during our experiment where participants interacted with a touchscreen augmented with vibrotactile feedback delivered on the screen and wrist. *Bottom:* close-up of the haptic touchscreen (left) and wristband (right).**

## 3 EXPERIMENT

We conducted a controlled experiment to evaluate the user experience of vibrotactile feedback delivered both on the screen and wrist during touchscreen input. The experiment was conducted at the University of Lille and the University of Suceava, and followed the ethical procedures in place at each institution.

### 3.1 Participants

We used convenience sampling to recruit twenty-two participants (seventeen self-identified as male and five as female), aged between 21 and 45 years old (M=29.7, SD=6.5). Except one, all of the participants reported using smartphones on a regular basis, and eleven (50.0%) said that the keyboard vibration feature was activated on their smartphones. All of the participants reported using PCs or laptops regularly, eight (36.4%) were using tablets in their everyday activities, ten (45.5%) smartwatches, and ten (45.5%) reported using smart earbuds. To evaluate any potential effects of prior experience with haptics on the UX of touchscreen input, we formed two equally sized groups, according to participants' technical background and professional experience, constituting *novice* and *experienced* users in haptics/HCI. The latter group (nine males and two females, aged between 25 and 44 years old) consisted of PhD students or researchers in haptics/HCI with at least two years of experience, whereas the former group (eight males and three females, aged between 21 and 45 years old) was formed by individuals with no haptics experience beyond conventional smartphone vibrotactile feedback.

### 3.2 Apparatus

The participants engaged with a mobile application displaying an interactive map, implemented in JavaScript using Loafelt,[1] which was deployed to a tablet device (1024x600 pixels and 170dpi). The application presents a city map with highlighted tourist attractions that, when touched, open a popup window with a brief description. Touchscreen input was augmented with vibrotactile feedback delivered directly on the screen and, respectively, with vibrations on the screen reinforced by vibrations on the wrist delivered through a

[1] Loaflet is a free software library for creating interactive maps, https://leafletjs.com.

custom-built wristband consisting of a 10mm DC (ERM) coin vibration motor[2]; see Figure 2. To ensure that vibrotactile feedback was delivered at the touch point on the screen, we employed Xplore-Touch,[3] a haptic touchscreen that uses ultrasonic waves to reduce the friction between the finger and glass, creating the sensation of a click [16] when the finger touches the screen. The bracelet was designed to provide a consistent vibrotactile stimulation at a frequency of 180Hz for a duration of 90ms. Furthermore, to ensure that vibrations delivered through the two devices would be perceived as synchronous [10], we connected both the haptic touchscreen and wristband through the serial port (maximum delay of 3ms), and triggered the wristband signal 45ms before the signal sent to the touchscreen to allow the former to reach its working state.

## 3.3 Procedure

After signing a consent form, the participants underwent a training stage to become familiarized with our application, two devices, and vibrotactile feedback delivered on the screen and wrist. The task consisted of inspecting all of the highlighted targets on the map to identify the oldest one, a piece of information that was revealed in the pop-up descriptions displayed upon touching the targets. Targets could be revisited any number of times, and all of the corresponding touches were augmented with vibrotactile feedback delivered either on the screen or both the screen and wrist, respectively, depending on the experimental condition; see Subsection 3.4 for our experiment design. The order of the location of vibrotactile feedback was randomized per participant. The participants used their dominant hand and wore noise cancelling headphones to alleviate the effect that sound, originating from vibrations, might have had on reported UX; see Figure 2 for photographs of our setup. The interactive part of the experiment lasted about 7 minutes during which each participant performed, on average, 223 touches (SD=34).

## 3.4 Design

We designed our experiment with repeated-measure trials and two independent variables:

- Location, within-subjects nominal variable with two conditions, *screen* and *screen and wrist*. In the former condition, representing our baseline, vibrotactile feedback was delivered on the screen at the touch point. In the latter, vibrations were delivered simultaneously on the screen and wrist.
- Experience, between-subjects nominal variable with two conditions, *novice* and *experienced* users; see Subsection 3.1 for details about our two equally-sized groups of participants.

The dependent variables were represented by UMUX, preference ratings, and a set of ten specific UX measures, as follows:

- The Usability Metric for User Experience (UMUX) [8] is a generic instrument designed to evaluate the perceived usability of interactive systems, which we applied for touchscreen input augmented with vibrotactile feedback. UMUX is computed from four Likert-scale ratings of perceived effectiveness, efficiency, frustration, and satisfaction, and takes values between 0 (low usability) and 100 (high usability).
- Overall preference rating of vibrotactile feedback accompanying touchscreen input was collected using a 7-point Likert scale with items ranging from 1 (low) to 7 (high).
- We employed specific UX measures, inspired from [30], for an in-depth characterization of the subjective experience of vibrotactile feedback accompanying touchscreen input. Five of these measures employed positively-connoted descriptors (Enjoyment, Efficiency, Confidence, Suitability, and Integration) and the remaining five negatively-connoted ones (Distractedness, Difficulty, Confusion, Complexity, and Desynchronization). Each measure was evaluated using a 7-point Likert scale with items from 1, "strongly disagree" to 7, "strongly agree" provided in response to statements involving the various descriptors, e.g., "Vibrotactile feedback felt enjoyable when vibrations were delivered on the screen" and "Vibrotactile feedback felt enjoyable when vibrations were delivered both on the screen and wrist," respectively; see Terenti and Vatavu [30] for details about eight of these measures. In addition to Terenti and Vatavu's set, we included Suitability and Desynchronization in our experiment to evaluate the perceived suitability of synchronized vibrations delivered conjointly on the screen and wrist, an experience dimension involving dual-point vibrotactile feedback that was beyond the scope of [30].

Given the ordinal nature of our dependent variables, we used rank-based statistical testing methods, of which we chose the Brunner-Domhof-Langer ANOVA for between-by-within designs[4] due to its good performance in terms of controlling the probability of Type I errors when tied values occur; see Wilcox [35, p. 554] for details. We also used Wilcoxon signed-rank tests for post-hoc analysis of differences between specific experimental conditions. We report effect sizes in the form of relative effects ($\hat{p}$) [35].

# 4 RESULTS

The experience of vibrotactile feedback, either on *screen* or both on *screen and wrist*, was generally perceived as equivalent in terms of UMUX scores (M=83.0, SD=15.1 *vs.* M=82.8, SD=15.9) with no statistically significant effects of Location ($F_{(1,\infty)}$=0.059, $p$=.809, *n.s.*) or Experience ($F_{(1,19.726)}$=0.124, $p$=.728, *n.s.*). This result was corroborated by similar preference ratings (Mdn=6, M=5.5, SD=1.6 *vs.* Mdn=6, M=5.4, SD=1.7), not statistically different in terms of Location ($F_{(1,\infty)}$=0.021, $p$=.886, *n.s.*) or Experience ($F_{(1,16.04)}$=0.131, $p$=.722, *n.s.*). Overall, these findings reveal a favorable UX of vibrotactile feedback accompanying touchscreen input, which was appreciated with ratings in the upper-part of both measuring scales.

The specific UX measures revealed in-depth findings. The ratings corresponding to the five measures employing positively-connoted descriptors were not affected by either Location or Experience ($p$>.05, *n.s.*). Post-hoc tests, conducted within each user group, revealed that the experts did rate vibrations on the *screen* as more confident than combined vibrations delivered both on *screen and wrist* (5.5 *vs.* 4.9, $p$=.048); see Figure 3, top. Results were similar for the negatively-connoted UX descriptors, except for the Difficulty ratings that were significantly affected by Experience (Mdn=1,

[2]https://nfpshop.com/product/10mm-coin-vibration-motor-3mm-type-model-nfp-c1030
[3]https://www.hap2u.net
[4]Implemented with the bwrank R function from Rand Wilcox's robust statistics software library, https://osf.io/xhe8u.

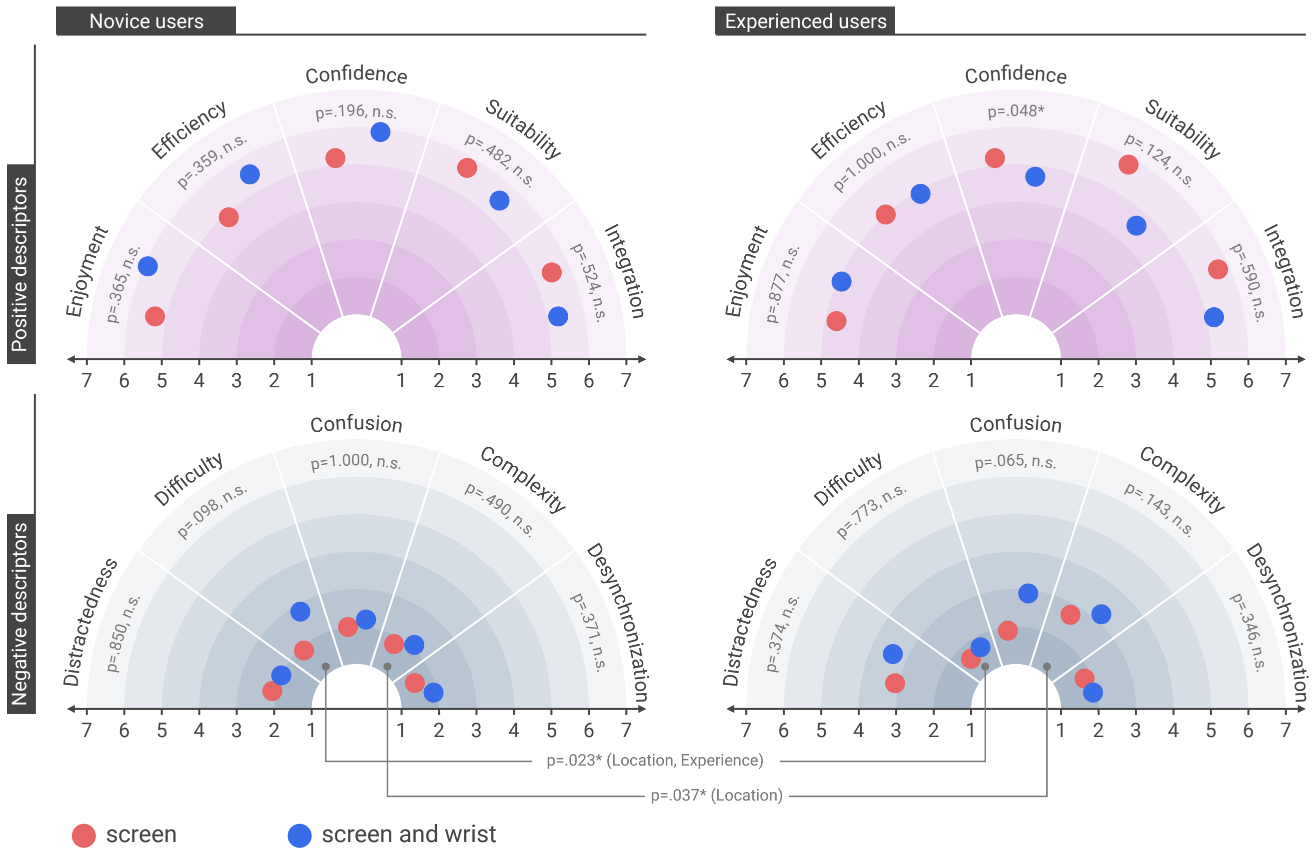


**Figure 3: UX of vibrotactile feedback accompanying touchscreen input for *novice* (left) and *experienced* (right) users, characterized in terms of positively (top) and negatively (bottom) connoted descriptors. *Notes:* the $p$-values from inside each sector show post-hoc tests comparing the UX of *screen vs. screen and wrist* vibrotactile feedback within each user group.**

M=1.5, SD=1.1 for *experienced vs.* Mdn=2, M=2.4, SD=1.6 for *novice* users, $F_{(1,19.876)}$=6.064, $p$=.023), and DIFFICULTY (Mdn=1, M=1.7, SD=1.2 for *screen vs.* Mdn=2, M=2.2, SD=1.6 for *screen and wrist*, $F_{(1,\infty)}$=5.186, $p$=.023) and COMPLEXITY (Mdn=2, M=2.2, SD=1.7 for *screen vs.* Mdn=2, M=2.6, SD=1.7 for *screen and wrist*, $F_{(1,\infty)}$=4.365, $p$=.037), significantly affected by LOCATION. Overall, vibrations on the screen and wrist were felt more difficult and slightly increasing the complexity of the interaction. Relative effects ($\hat{p}$) fell between .350 and .685 for DIFFICULTY and between .377 and .596 for COMPLEXITY across the combinations of EXPERIENCE and LOCATION.

## 5 DISCUSSION

We discuss our findings in terms of potential future work towards combined on-screen and on-wrist vibrotactile feedback in the general context of cross-device interaction [4] involving a touchscreen device external to the body, such as a smartphone or tabletop [10, 12], and a smartwatch worn on the hand implementing touch input. According to Brudy *et al.*'s [4] cross-device taxonomy, conjoint touchscreen and smartwatch vibrotactile feedback can be characterized as synchronous, mirrored and spatially distributed, one user to many devices, near and personal, mobile, and co-located interaction. In this context, we focus in the following on new potential scientific discoveries and practical opportunities about fingertip-to-wrist vibrotactile feedback through two dichotomies subsumed by our exploration of combined *screen and wrist* vibrations:

- *Fingertip vs. wrist.* Vibrations delivered on the touchscreen, sensed via the fingertip, constitute the conventional approach to vibrotactile feedback on modern mobile devices and, thus, formed the baseline in our experiment. On-wrist vibrations are equally the norm for smartwatches that use them to deliver notifications. In this context, conjoint delivery of vibrotactile feedback takes place at the two extremities of the hand, constituting a dichotomy of on-hand locations—*fingertip* and *wrist*—that delineate the hand as the dexterous body part involved in touchscreen interaction.
- *Single-point vs. multi-point output.* Unlike single-point vibrations, either on the smartphone or smartwatch, the technical feasibility of multi-point vibrations enable new design opportunities for presenting information to users during touchscreen interaction. The dichotomy of one *vs.* multiple (in our case, two-point output) creates the premises for designing vibrotactile patterns beyond single-point approaches [31] that would scale in terms of the number of originating sources.

The first dichotomy is qualitative in nature by referring to the hand regions receiving vibrotactile feedback, while the second is quantitative by specifying how many devices deliver vibrations. In this interplay of hand regions and number of devices lie several future work opportunities. Our participants valued equivalently the UX of *screen* and combined *screen and wrist* vibrations during touchscreen input, whether those vibrations were single-point on the fingertip or multi-point on the fingertip and wrist. This finding suggests new applications involving cross-device smartphone and smartwatch interactions. For example, vibrations on the wrist can complement on-screen visual and haptic feedback with an additional layer of responsiveness and realism in video games or when consuming media content. For applications featuring multi-layer data manipulation, dual-point vibrotactile feedback could be leveraged to encode, through spatially-distributed vibrations across the hand, depth information to assist 3D mental representation of the visual data. Multi-level menus or navigating in file system trees could equally benefit from multi-point vibrotactile feedback.

The observed differences between *novice* and *experienced* users are equally interesting and recommend further examination. While not statistically significant, the experienced group generally rated combined *screen and wrist* vibrations as a worse experience. Dual-point vibrotactile feedback at both extremities of the hand, fingertip and wrist, was perceived as too much feedback, while novices, not familiar with haptics beyond conventional smartphone vibrations, perceived dual-point feedback more favorably. Nevertheless, there are specific contexts of use, to be examined in future work, where we expect on-screen vibrotactile feedback to go undetected, such as when users focus their attention on other tasks and engage in eyes-free input. In such cases, where interactions are fast or inattentive, the benefits of on-screen vibrations [10,15] may be lost, whereas dual-point feedback may represent a feasible design alternative.

Our experiment presents a few limitations. The potential novelty effect of simultaneous on-screen and on-wrist vibrations might have influenced the ratings of the novice users' group, while the limited duration of the interactions, approximately seven minutes per participant, might have provided insufficient time to form more representative opinions. These limitations can be addressed in future work by replicating our findings with new participants and experiment designs. Also, running the experiment with a smartphone that users actually hold in a mobile context may reveal a different user experience of combined on-screen and on-wrist vibrations.

## 6 CONCLUSION

We centered in this work on the user experience of vibrotactile feedback, delivered simultaneously on the screen and wrist, for augmenting touchscreen interactions. The perceived experiences of on-screen and combined on-screen and on-wrist vibrations were similarly rated when they were described in terms of positively-connoted measures, such as perceived enjoyment or efficiency, whereas several differences surfaced in terms of negatively-connoted descriptors, such as difficulty or complexity. These results indicate that the dichotomies of fingertip *vs.* wrist and single-point *vs.* multi-point vibrotactile feedback can be leveraged for cross-device interactions involving smartphones and smartwatches in contexts of use where haptic feedback needs reinforcement or extension on the hand implementing touch input. We also recommend follow-up studies, involving different user categories and contexts of use, e.g., users with visual impairments [32] or encumbrance during mobile interactions [17], to further examine the UX of touchscreen input augmented with both on-screen and on-wrist vibrotactile feedback.

## 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 Sklodowska-Curie grant agreement no. 860114. The prototype, consisting of the software application running on the haptic touchscreen and the wearable device designed for the wrist, was developed while the first author was at Hap2U.

## REFERENCES


[1] Adrian Aiordăchioae, David Gherasim, Alexandru-Ilie Maciuc, Bogdan-Florin Gheran, and Radu-Daniel Vatavu. 2020. Addressing Inattentional Blindness with Smart Eyewear and Vibrotactile Feedback on the Finger, Wrist, and Forearm. In *Proc. of the 19th Int. Conference on Mobile and Ubiquitous Multimedia (MUM '20)*. ACM, New York, NY, USA, 329–331. https://doi.org/10.1145/3428361.3432080

[2] Zakaria Al-Qudah, Iyad Abu Doush, Faisal Alkhateeb, Esalm Al Maghayreh, and Osama Al-Khaleel. 2011. Reading Braille on mobile phones: A fast method with low battery power consumption. In *Proc. of the Int. Conf. on User Science and Engineering*. IEEE, USA, 118–123. https://doi.org/10.1109/iUSEr.2011.6150549

[3] Lorna M. Brown and Topi Kaaresoja. 2006. Feel Who's Talking: Using Tactons for Mobile Phone Alerts. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems (CHI EA '06)*. ACM, New York, NY, USA, 604–609. https://doi.org/10.1145/1125451.1125577

[4] Frederik Brudy, Christian Holz, Roman Rädle, Chi-Jui Wu, Steven Houben, Clemens Nylandsted Klokmose, and Nicolai Marquardt. 2019. Cross-Device Taxonomy: Survey, Opportunities and Challenges of Interactions Spanning Across Multiple Devices. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, 1–28. https://doi.org/10.1145/3290605.3300792

[5] Francesco Chinello, Claudio Pacchierotti, Nikos G. Tsagarakis, and Domenico Prattichizzo. 2016. Design of a wearable skin stretch cutaneous device for the upper limb. In *Proceedings of the IEEE Haptics Symposium (HAPTICS '16)*. IEEE, USA, 14–20. https://doi.org/10.1109/HAPTICS.2016.7463149

[6] Lucile Dupin, Vincent Hayward, and Mark Wexler. 2015. Direct coupling of haptic signals between hands. *Proceedings of the National Academy of Sciences* 112, 2 (2015), 619–624. https://doi.org/10.1073/pnas.1419539112

[7] Senem Ezgi Emgin, Amirreza Aghakhani, T. Metin Sezgin, and Cagatay Basdogan. 2019. HapTable: An Interactive Tabletop Providing Online Haptic Feedback for Touch Gestures. *IEEE Transactions on Visualization and Computer Graphics* 25, 9 (2019), 2749–2762. https://doi.org/10.1109/TVCG.2018.2855154

[8] Kraig Finstad. 2010. The Usability Metric for User Experience. *Interacting with Computers* 22 (2010), 323–327. https://doi.org/10.1016/j.intcom.2010.04.004

[9] German Flores, Sri Kurniawan, Roberto Manduchi, Eric Martinson, Lourdes M. Morales, and Emrah Akin Sisbot. 2015. Vibrotactile Guidance for Wayfinding of Blind Walkers. *IEEE Transactions on Haptics* 8, 3 (2015), 306–317. https://doi.org/10.1109/TOH.2015.2409980

[10] Jay Henderson, Jeff Avery, Laurent Grisoni, and Edward Lank. 2019. Leveraging Distal Vibrotactile Feedback for Target Acquisition. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300715

[11] Georgios Korres, Camilla Birgitte Falk Jensen, Wanjoo Park, Carsten Bartsch, and Mohamad Eid. 2018. A Vibrotactile Alarm System for Pleasant Awakening. *IEEE Trans. on Haptics* 11, 3 (2018), 357–366. https://doi.org/10.1109/TOH.2018.2804952

[12] Khanh-Duy Le, Kening Zhu, Tomasz Kosinski, Morten Fjeld, Maryam Azh, and Shengdong Zhao. 2016. Ubitile: A Finger-Worn I/O Device for Tabletop Vibrotactile Pattern Authoring. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction (NordiCHI '16)*. ACM, New York, NY, USA, Article 87, 4 pages. https://doi.org/10.1145/2971485.2996721

[13] Yi-Chi Liao, Yen-Chiu Chen, Liwei Chan, and Bing-Yu Chen. 2017. Dwell+: Multi-Level Mode Selection Using Vibrotactile Cues. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 5–16. https://doi.org/10.1145/3126594.3126627

[14] Hyunchul Lim, YoonKyong Cho, Wonjong Rhee, and Bongwon Suh. 2015. Vi-Bros: Tactile Feedback for Indoor Navigation with a Smartphone and a Smartwatch. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 2115–2120. https://doi.org/10.1145/2702613.2732811

[15] Christopher McAdam and Stephen Brewster. 2009. Distal Tactile Feedback for Text Entry on Tabletop Computers. In *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers (BCS-HCI '09)*. BCS Learning & Development, Swindon, 504–511. https://dl.acm.org/doi/10.5555/1671011.1671076

[16] Jocelyn Monnoyer, Laurence Willemet, and Michael Wiertlewski. 2023. Rapid Change of Friction Causes the Illusion of Touching a Receding Surface. *J. Royal Soc. Interface.* 20, 199 (2023), 20220718. https://doi.org/10.1098/rsif.2022.0718

[17] Alexander Ng, Stephen A. Brewster, and John Williamson. 2013. The Impact of Encumbrance on Mobile Interactions. In *INTERACT 2013*. Springer, Berlin, Heidelberg, 92–109. https://doi.org/10.1007/978-3-642-40477-1_6

[18] Hugo Nicolau, João Guerreiro, Tiago Guerreiro, and Luís Carriço. 2013. UbiBraille: designing and evaluating a vibrotactile Braille-reading device. In *Proc. of the 15th Int. ACM SIGACCESS Conf. on Computers and Accessibility (ASSETS '13)*. ACM, New York, NY, USA, Article 23, 8 pages. https://doi.org/10.1145/2513383.2513437

[19] Hugo Nicolau, Kyle Montague, Tiago Guerreiro, André Rodrigues, and Vicki L. Hanson. 2015. HoliBraille: multipoint vibrotactile feedback on mobile devices. In *Proceedings of the 12th International Web for All Conference (W4A '15)*. ACM, New York, NY, USA, Article 30, 4 pages. https://doi.org/10.1145/2745555.2746643

[20] Oliver Ozioko, Prakash Karipoth, Marion Hersh, and Ravinder Dahiya. 2020. Wearable Assistive Tactile Communication Interface Based on Integrated Touch Sensors and Actuators. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 28, 6 (2020), 1344–1352. https://doi.org/10.1109/TNSRE.2020.2986222

[21] Chaeyong Park, Jinhyuk Yoon, Seungjae Oh, and Seungmoon Choi. 2020. Augmenting Physical Buttons with Vibrotactile Feedback for Programmable Feels. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. ACM, New York, NY, USA, 924–937. https://doi.org/10.1145/3379337.3415837

[22] Martin Pielot, Benjamin Poppinga, and Susanne Boll. 2010. PocketNavigator: Vibro-Tactile Waypoint Navigation for Everyday Mobile Devices. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*. ACM, New York, NY, USA, 423–426. https://doi.org/10.1145/1851600.1851696

[23] Ivan Poupyrev, Makoto Okabe, and Shigeaki Maruyama. 2004. Haptic feedback for pen computing: directions and strategies. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems (CHI EA '04)*. ACM, New York, NY, USA, 1309–1312. https://doi.org/10.1145/985921.986051

[24] Tao Qin, Le Chang, and Haining Wang. 2023. Perception of the Vibration Intensity of Smartwatches in the Notification Scene. In *Design, User Experience, and Usability*. Springer Nature, Switzerland, 270–283. https://doi.org/10.1007/978-3-031-35702-2_20

[25] Jussi Rantala, Roope Raisamo, Jani Lylykangas, Veikko Surakka, Jukka Raisamo, Katri Salminen, Toni Pakkanen, and Arto Hippula. 2009. Methods for Presenting Braille Characters on a Mobile Device with a Touchscreen and Tactile Feedback. *IEEE Trans. on Haptics* 2, 1 (2009), 28–39. https://doi.org/10.1109/TOH.2009.3

[26] Christian Schönauer, Annette Mossel, Ionut-Alexandru Zaiti, and Radu-Daniel Vatavu. 2015. Touch, Movement & Vibration: User Perception of Vibrotactile Feedback for Touch and Mid-Air Gestures. In *Proceedings of the 15th IFIP TC.13 International Conference on Human-Computer Interaction. LNCS 9299 (INTERACT '15)*. Springer, Cham, 165–172. https://doi.org/10.1007/978-3-319-22723-8_14

[27] Sang-Won Shim and Hong Z. Tan. 2020. palmScape: Calm and Pleasant Vibrotactile Signals. In *Proceedings of the 9th International Conference on Design, User Experience, and Usability (DUXU '20)*. Springer-Verlag, Berlin, Heidelberg, 532–548. https://doi.org/10.1007/978-3-030-49713-2_37

[28] Jun Tan, Yan Ge, Xianghong Sun, Yubo Zhang, and Yanfang Liu. 2019. User Experience of Tactile Feedback on a Smartphone: Effects of Vibration Intensity, Times and Interval. In *Cross-Cultural Design. Methods, Tools and User Experience.* Springer, Cham, 397–406. https://doi.org/10.1007/978-3-030-22577-3_29

[29] Mihail Terenti, Maria Casado-Palacios, Monica Gori, and Radu-Daniel Vatavu. 2024. What Is the User Experience of Eyes-Free Touch Input with Vibrotactile Feedback Decoupled from the Touchscreen?. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3613905.3650804

[30] 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. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA '22)*. ACM, New York, NY, USA, Article 286, 7 pages. https://doi.org/10.1145/3491101.3519704

[31] Mihail Terenti and Radu-Daniel Vatavu. 2023. VIREO: Web-based Graphical Authoring of Vibrotactile Feedback for Interactions with Mobile and Wearable Devices. *International Journal of Human–Computer Interaction* 39, 20 (2023), 4162–4180. https://doi.org/10.1080/10447318.2022.2109584

[32] Radu-Daniel Vatavu. 2017. Visual Impairments and Mobile Touchscreen Interaction: State-of-the-Art, Causes of Visual Impairment, and Design Guidelines. *International Journal of Human-Computer Interaction* 33, 6 (2017), 486–509. https://doi.org/10.1080/10447318.2017.1279827

[33] Radu-Daniel Vatavu, Annette Mossel, and Christian Schönauer. 2016. Digital Vibrons: Understanding Users' Perceptions of Interacting with Invisible, Zero-Weight Matter. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '16)*. ACM, New York, NY, USA, 217–226. https://doi.org/10.1145/2935334.2935364

[34] Dong-Bach Vo and Stephen Brewster. 2020. Investigating the Effect of Tactile Input and Output Locations for Drivers' Hands on In-Car Tasks Performance. In *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '20)*. ACM, New York, NY, USA, 1–8. https://doi.org/10.1145/3409120.3410656

[35] Rand Wilcox. 2017. *Modern Statistics for the Social and Behavioral Sciences: A Practical Introduction* (2nd ed.). Chapman and Hall/CRC, New York, NY, USA. https://doi.org/10.1201/9781315154480