Hot & Tight: Exploring Thermo and Squeeze Cues Recognition on Wrist Wearables

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ABSTRACT
Wrist worn wearable computing devices are ideally suited for presenting notifications through haptic stimuli as they are always in direct contact with the user's skin. While prior work has explored the feasibility of haptic notifications, we highlight a lack of empirical studies on thermal and pressure feedback in the context of wearable devices. This paper introduces prototypes for thermal and pressure (squeeze) feedback on the wrist. It then presents a study characterizing recognition performance with thermal and pressure cues against baseline performance with vibrations.

Author Keywords
Wrist, notification, haptic, temperature, squeeze.

ACM Classification Keywords
H5.2. User Interfaces: Haptic I/O.

INTRODUCTION
Wrist worn wearable computing devices such as watches [10] and bracelets [4] are ideal devices for delivering haptic notifications to their users. In contrast to more traditional mobile devices such as smartphones, wrist wearables are always in direct contact with a users' skin, a proximity that helps ensure that haptic cues are readily and privately received. The wrist is also a highly accessible location that allows users to rapidly, immediately and unobtrusively follow up on a notification by glancing at the device screen. More generally, research has also suggested that cognitive load can be reduced and attention maintained [8] if notifications are delivered in a modality not involved in a user's primary task. Motivated by these arguments, numerous wrist devices have been created to explore the potential of haptic feedback as an alternative notification modality to audio or visual stimuli.

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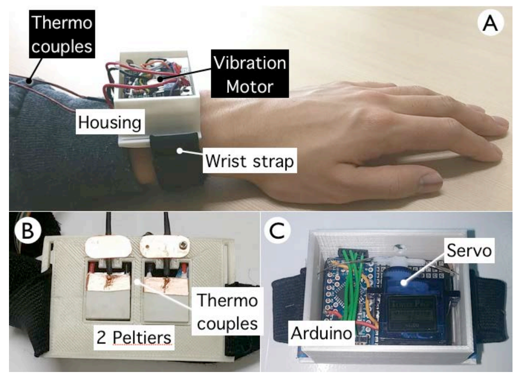

Figure 1. Side (A) and bottom (B) view of the thermal and vibration prototype. Inside view of the squeeze prototype (C).

Specifically, researchers have studied core issues such as the perception of tactons, or structured vibrotactile messages [3], on the wrist [8, 10] and body [6] and made recommendations regarding effective cue design. Others have recorded recognition rates during both cognitive and physical distracter tasks [2, 9] in order to highlight real world situations in which performance degrades. The fundamental results from these studies have been instantiated in application-level prototypes that display haptic notifications [10] as well as convey interpersonal [11] and non-verbal [5] messages.

However, past research has focused almost exclusively on tactons - temporal patterns of tactile feedback. Relatively little work has explored other forms of haptic feedback, such as that based on changes in temperature and pressure cues, in the context of wearable devices. We argue that such cues may be both more pleasant for users [11] and also expand the expressiveness of the haptic channel. In order to explore the potential of these cue types, we constructed two prototype wrist-mounted wearable devices capable of displaying haptic feedback as vibration, temperature and pressure (in the form of squeezes). Using these prototypes, we present the results of a study that characterizes recognition performance with thermal and pressure cues against baseline performance with vibrations. We conclude with recommendations regarding the design and use of temperature and pressure cues for the display of notifications on wearable technologies.

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RELATED WORK

Reflecting the prominence of the notification application scenario, wrist based wearable devices that alert users using visual prompts have attracted substantial research attention. For example, both LED [4] and multiple display [7] systems around the wrist have been proposed to provide rich feedback, mitigate occlusions and leverage peripheral vision. A representative design is the Reminder Bracelet's [4] depiction of the importance of an upcoming event in the blinking pattern of three adjacent LEDs. Expressing urgency has also been explored in the context of audio cockpit alarms [1] with the conclusions that current schemes exhibit low recognition rates. Furthermore, since in many wearable scenarios users' visual and audio senses are engaged with ongoing primary tasks such as work activities or traveling, the delivery of notifications via these sensory channels can contribute to workload and serve as unwanted and potentially disruptive distractions [8].

Accordingly, researchers have also explored the potential of the haptic modality as an alternative to audio and visual notifications. Both Karuei et al. [6] and Oakley and Park [9] demonstrated that people can effectively detect vibration pulses from devices worn on the body while engaging in common physical activities like walking and regardless of visual workload. Moreover, these authors suggest that bands around the wrists and torso may be the most appropriate sites for presentation of haptic cues. Furthermore, Oakley and Park [9] suggest that the cardinal points around the wrist are ideal locations for wrist mounted tactile actuators. These recommendations have been instantiated in prototype devices such as the Haptic Wristwatch [10] and validated by Matscheko et al.'s [8] finding that vibration cues delivered to four tactors positioned around the wrist can be used to convey 2.44 bits of information in contrast to 1.72 bits with a similar set of four tactors located on top of the wrist.

In work closely related to this article, both thermal [11, 12] and kinesthetic feedback in the form of squeezes [2, 5, 11] have been explored as alternative haptic modalities. For example, in a comprehensive study, Wilson et al. [12] describe users' perception of thermal cues and provide guidelines regarding optimal actuator placement and cue temperatures. In design-led research to explore reactions to novel feedback for enhancing interpersonal relationships, Suhonen et al. [11] describe a wearable headband with thermal feedback and a wrist worn squeeze-band for mimicking touch communication among partners. Users considered squeezes as the most pleasant sensation. Similarly, Baumann et al. [2] explore the potential of squeeze-based affective communication with a wrist device and Hoggan et al. [5] presented the ForcePhone - an augmented phone that allows non-verbal communication though force-based input and vibration output. While this work provides valuable design recommendations for these modalities in general, we highlight the fact that the use of these cues as notifications has not been directly explored.

PROTOTYPE

We developed two prototypes in a wrist watch form factor - 67 x 42 x 27 mm 3D printed boxes that enclose an Arduino Pro Mini microprocessor and feature watch style straps. Both are powered externally. One renders vibrotactile and thermal stimuli while the other produces pressure cues in a manner similar to previous work [2] - it squeezes the wrist by tightening the watch strap (Figure 1). The tactile/thermal watch contained a custom PCB connected to a single PWM-controlled 10mm shaft-less vibration motor by Precision Microdrives, and two adjacently positioned 1.5cm square 1A Peltier modules (FALS1-03103T150). One Peltier is configured to cool the skin and the other to warm it. The Peltier modules are driven using a MOSFET connected to a 6V power supply at 1A and their temperature is monitored by two fast-response type K glass braid thermocouples mounted on their surfaces and isolated from the skin with a thin layer of copper. The amplifier circuit for the thermocouples is housed in a separate case that can be strapped to the upper arm. The prototype communicates to a host computer via a wired connection for data logging. The squeeze prototype contains a 22 x 11 x 31 mini-servo motor capable of exerting 1.6kg/cm at 4.8V. To reduce the cables required and increase mobility, communication to the host PC was via a Bluetooth link.

Tactile Stimuli

Five different time-varying cues were designed for the modalities of vibration, temperature and squeeze. Each was stored on the Arduino controller and spanned a four second time window. In cases were presentation of feedback took less than four seconds, cues were right-aligned in this window. This ensured all cue presentation took the same time to complete, irrespective of the length of cue itself.

Vibration cues were derived from prior work [3, 9]. They were: a continuous 2 seconds vibration, a 1s long pulse, two 500ms short pulses, three 300ms short pulses, and a long followed by a short pulse (700ms + 400ms). Temperature cues were based on Wilson et al.'s [12] recommendation to use skin temperature as a baseline and separate cues by 3 degree Celsius absolute differences. We used +6, +3, 0, -3 and -6 degrees from the skin temperature. To display these

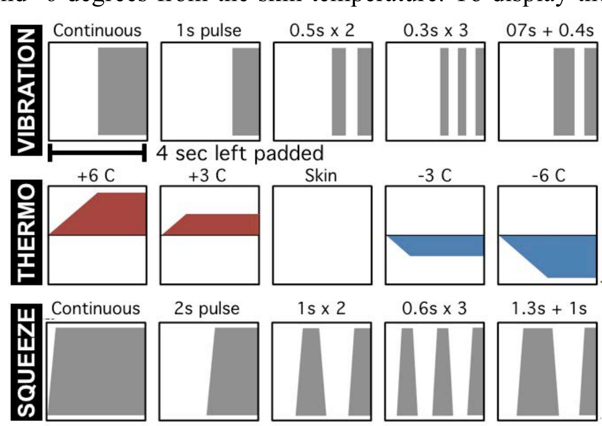

Figure 2. Details of the cues for each condition. All cues had a duration of 4s and were left zero-padded for consistency.

cues, Peltier temperature was sampled at 5Hz and data filtered with a rolling average filter with a window size of 3.2 seconds (16 samples). The system required a maximum of two seconds to reach each target temperature, therefore presenting each final cue for a minimum of 2 seconds. Between presentations power was removed and the Peltier modules returned to skin temperature within 3 seconds. The five levels of squeezing cue were based on Baumann et al.'s [2] notion of motion profiles - patterns of tighter and looser squeezes. We used two levels: loose (motor shaft at 0°) and tight (shaft at 100°), for which the applied force was measured as ~0.24 and ~1.27 Newtons. The five cues we used follow the patterns used in the vibration condition but, due to motor performance, were slower. They were: continuous (4s), single 2s long pulse, two 1s short pulses, three short 600ms pulses, and a long followed by a short pulse (1.3s + 1s).

EVALUATION

We conducted a study to test recognition performance with the vibration, temperature and squeeze cue sets. The goal of this experiment was to determine the suitability of the different cues for displaying notifications in terms of both ease and speed of recognition and subjective experience.

12 participants completed this study (four male), all right-handed. They were a mix of students and professionals aged between 24 and 30 years (μ=25.3, σ=2.2), recruited through word of mouth and public fliers. All stated they were familiar with smart-devices, but not with wearables: only five participants reported prior experience with wearable devices. Eight regularly wore a watch (on their left hand). Participants were compensated with ~10 USD.

The experiment took approximately 45 minutes. First, demographics were collected and participants were introduced to the device prototypes and selected which arm to wear them on. We then measured the temperature (μ=33.6˚C, σ=0.9) and size (μ=15.8cm, σ=1) of the participant's wrist and they donned headphones playing white noise in order to mask sounds from the experimental apparatus. The study then began. Each participant completed all three modality conditions in a fully balanced repeated measures experimental design - two participants completed each of the six possible condition orders. At the end of the study semi-structured interviews were conducted and participants were encouraged to express their opinions about the haptic cues and wearable prototypes.

Each modality condition was presented as follows. First participants donned the relevant prototype and spent five minutes familiarizing themselves with the different haptic cues. These were activated via clicking on iconic buttons in a GUI shown on a PC touch screen that was operated with the participant's un-instrumented hand. Participants then completed a recognition task composed of 25 randomly ordered trials (5 trials x 5 stimuli). Error trials were repeated. The initial ten trials included two presentations of each possible cue and were discarded as training. Each trial started with a ten second countdown, followed by the user pressing a play-cue button to which corresponded the presentation of a single four second cue and the start of the selection time. Participants could use the same iconic GUI to select the cue they had just experienced (end of selection time). Users could also replay the haptic cue by pressing a play button. Logged data included the user's selections, the selection times and the number of play actions initiated. Participants also completed a NASA TLX survey after each modality to test the cognitive workload. The total number of trials analyzed was 540 (12 users x 3 trials x 5 stimuli x 3 conditions).

RESULTS

The average selection time per cue for each modality is reported in Figure 3 and variations were explored using a one-way repeated measures ANOVA and post-hoc tests with Bonferroni CI adjustments. Errors for each condition are reported in confusion matrices (Figure 4) but not statistically tested due to the sparsity of the data.

In the vibration condition, the time resulted in significant differences ($F_{(4,11)}$=15.4 p<0.01, ηp^2 = 0.58). Post hoc tests revealed that the continuous cue was the more rapidly recognized than all others (p<0.01) except the 3-pulse cue. The total number of errors was 13 in 180 trials, and more than half were caused by confusion between the cue with 2 short-pulses and the one with a long followed by a short pulse: the difference of 300ms for the duration between short and long pulse was too small for accurate detection. In the thermal condition, the selection time was not statistically different for different cues. The number of user errors amounted to 110 errors, which were unevenly distributed among participants. As shown in Figure 4-right, a small number of participants generated the majority of the errors. The confusion matrix revealed that participants performed similar mistakes. 48% of errors were caused by interchanging +6C˚ with +3C˚ cues (24%) or -6C˚ with -3C˚ cues (24%). Interestingly, 22% of errors were caused by confusing cold stimuli for hot ones (19%) or hot for cold ones (3%). Finally, 16% of errors were caused by confusing the neutral (skin) temperature with the slightly cold or warm cues (± 3C˚). In the squeeze condition time difference among cues was statistically significant ($F_{(4,11)}$=8.6, p<0.01, ηp^2 = 0.44) and the post-hoc tests showed that the 2s squeeze pulse recognition was significantly longer (p<0.05) than all the other cues but the 2-pulse one. There were 38 errors and, as with the vibration condition, most errors

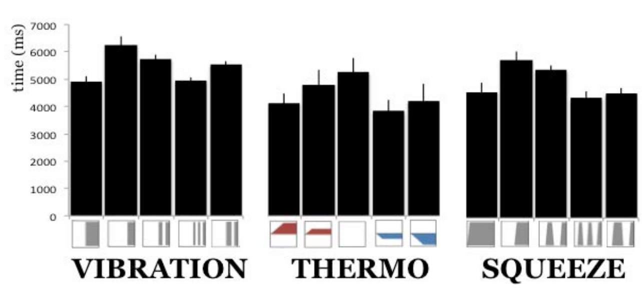

Figure 3. Recognition time for each cue in each modality.

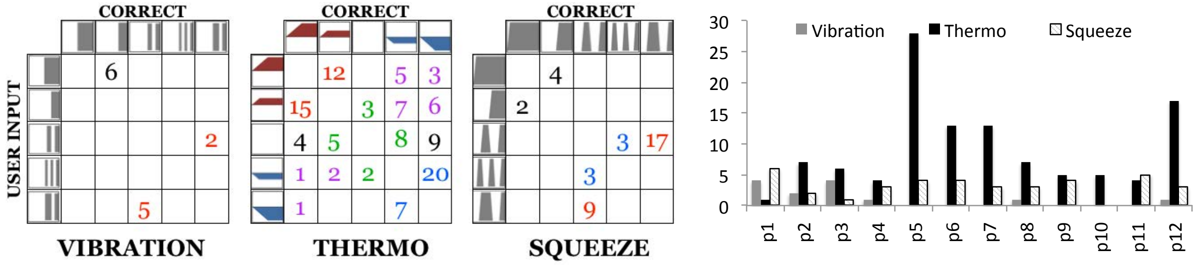

Figure 4. The confusion matrices for each of the three conditions (left): cues are clustered using colors and discussed in the text. On the right, a histogram showing the contribution of errors for each study participant in each condition.

(68%) were caused by confusing the cues with two short pulses with those featuring one-long and one-short pulse. In the squeeze case, the 300ms difference between the two types of pulse was more difficult to recognize. This result highlights the limitations in temporal resolution of the squeeze feedback. Finally, comparing across conditions, the TLX data showed that the user workload was statistically different ($F_{(2,11)}=8.6$, $p<0.01$, $\eta p^2 = 0.56$), with vibration perceived as the easiest among the conditions ($p<0.05$), a result corroborated in the post-hoc interviews. We did not compare time across modalities as the cues are intrinsically different (e.g., time patterns vs temperatures) but the mean recognition times are 5.4s (0.4), 4.4s (1) and 4.2s (0.5) for the vibration, thermal and squeeze conditions.

DISCUSSION AND CONCLUSIONS

This study reveals some of the issues with and potential of thermal and kinesthetic (squeeze) haptic feedback. Clearly, vibration is the least error prone, but the squeeze condition performs almost equally well: the larger number of errors found is mainly due to the confusion between a single pair of cues with pulse durations that differ by only 300ms. This suggests that with squeezing cues, the time resolution of the signal cannot be lower than 13 Hz (4000/300). Discounting this effect, we argue that squeeze performs equally well or better than vibration. The thermal cue, on the other hand, performed relatively poorly. This shows it is not only intrinsically hard to build thermal cues with rapid changes, but also that thermal cues also vary depending on different body locations. Indeed, while previous work [12] indicated that ± 3C° steps should be sufficient to distinguish thermal cues using the palm of the hand, the current results show that, when displaying temperature on the wrist, a more conservative threshold will be required.

In conclusion, this paper suggests that diverse haptic notification cues on wearable devices are feasible but more research is required in order to understand how to best design haptic cues specifically for wrist wearable devices that leverage on thermal or kinesthetic (squeeze) feedback. This initial exploration highlights the potential of these modalities and some of their problems. Future work will attempt to investigate non-temporal cues recognition and perform a direct comparison across modalities.

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