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

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A Masters Thesis Submitted to the Department of Human ICT Convergence
and the Graduate School of Sungkyunkwan University
in partial fulfillment of the requirements
for the degree of Master of Science in Human ICT Convergence

January 2016

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January 2016
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Abstract

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Wrist worn wearable computing devices are well suited for presenting notifications through haptic stimuli since they are in direct contact with the user’s skin. While previous work has explored the feasibility of haptic notifications, we highlight a lack of empirical studies on thermal and pressure haptic feedback in the context of wearable devices. Accordingly, this work introduces two prototypes for thermal and pressure (squeeze) feedback on the wrist. It also presents a study to characterise recognition performance with thermal and pressure haptic cues against baseline performance with vibrations.

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

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 pulses duration differing by only 300ms. This suggests that with squeezing cues, the time resolution of the signal cannot be under 13 Hz (4000/300).

**Keywords**: Wrist, notification, haptic, temperature, squeeze
I. Introduction

1. Background

Wrist worn wearable computing devices such as watches [Pasquero, J., Stobbe, S.J., Stonehouse, N., 2011] and bracelets [Hansson, R., Ljungstrand, P., 2000] 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 [Matscheko, M et al., 2010] if notifications are delivered in a modality not involved in a user’s primary task. Motivated by these arguments, numerous wearable wrist devices have been created to explore the potential of haptic feedback as an alternative notification modality to audio or visual stimuli.
Specifically, researchers have studied core issues such as the perception of tactons, or structured vibrotactile messages [Brown, L.M., Brewster, S.A., Purchase, H.C., 2006], on the wrist [Matscheko, M et al., 2010, Pasquero, J., Stobbe, S.J., Stonehouse, N., 2011] and body [Karuei, I et al., 2012] and made recommendations regarding effective cue design. Others have recorded recognition rates during both cognitive and physical distracter tasks [Baumann, M.A et al., 2010, Oakley, I., Park, J., 2008] 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 [Pasquero, J., Stobbe, S.J., Stonehouse, N., 2011] as well as convey interpersonal [Suhonen, K et al., 2012] and non-verbal [Hoggan, E et al., 2012] messages.

2. Expressiveness of the haptic channel

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 [Suhonen, K et al., 2012] and also expand the expressiveness of the haptic channel. In order to explore the potential of these cue types, we constructed two prototype wrist wearable devices capable of displaying haptic feedback as vibration, temperature and pressure (in the form of squeezing the wrist). Using these prototypes, we present the results of a study that characterises 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 wearables.

II. Related Work

1. Visual stimuli for wearables

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 [Hansson, R., Ljungstrand, P., 2000] and multiple display [Lyons, K., Nguyen, D., Ashbrook, D., White, S., 2012] 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 [Hansson, R., Ljungstrand, P., 2000] 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 [Arrabito, G.R., Mondor, T.A., Kent K.J, 2014] 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 [Matscheko, M et al., 2010].

2. Vibration pulses from devices

Accordingly, researchers have also explored the potential of the haptic modality as an alternative to audio and visual notifications. Both Karuei et al. [Karuei, I et al., 2012] and Oakley and Park [Oakley, I., Park, J., 2008] 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 [Oakley, I., Park, J., 2008]
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 [Pasquero, J., Stobbe, S.J., Stonehouse, N., 2011] and validated by Matscheko et al.’s [Matscheko, M et al., 2010] 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.

3. Temperature / Squeezing for wearables

In work closely related to this article, both thermal [Suhonen, K et al., 2012, 12] and kinesthetic feedback in the form of squeezes [Baumann, M.A et al., 2010, Hoggan, E et al., 2012, Suhonen, K et al., 2012] have been explored as alternative haptic modalities. For example, in a comprehensive study, Wilson et al. [Wilson, G et al., 2012] 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. [Suhonen, K et al., 2012] 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.
[Baumann, M.A et al., 2010] explore the potential of squeeze-based affective communication with a wrist device and Hoggan et al. [Hoggan, E et al., 2012] presented the ForcePhone – an augmented phone that allows non-verbal communication through 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.

III. Prototype

1. Hardware Prototyping

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 [Baumann, M.A et al., 2010] – it squeezes the wrist by tightening the watch strap (Figure 1,2).
Figure 1. View of the thermal and vibration prototype

The squeeze prototype (Figure 2) 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.
2. Software Prototyping

The tactile/thermal watch (Figure 1) contained a custom PCB connected to a single PWM-controlled pancake-style vibration motor (5Ø) and two adjacently positioned 1.5cm square 1A Peltier modules. 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 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
A. Temperature

1. MCU gets temperature from sensor per 0.2 second.
   - Rising time: around 2 seconds
   - Staying time: 2 seconds.

2. Total operating time for each stimulus is around 4 seconds
   - Peltier's 5 states
   1). Very hot: +6 degrees from avg. skin temp
   2) Little hot: +3 degrees from avg. skin temp
   3) Normal: nothing
   4) Little cool: -3 degrees from avg. skin temp
   5) Very cool: -6 degrees from avg. skin temp
   - To get avg. skin temp, we use moving average filter and filter size is 16

B. Vibration

- Use PWM for control
- Proto has 2 seconds for rest when signal received.
- After 2 seconds break, five vibration feedbacks will occurred for 2 seconds
- Total duration: 2 seconds (for 4 seconds comparison, we can just plus 2 seconds in front of each states)
- 5 states (n: nothing, v: vibe)
  1) 2 sec v
  2) 1 sec n + 1 sec v
  3) 0.5 sec n + 0.5 sec v + 0.5 sec n + 0.5 sec v
  4) 0.5 sec n + 0.3 sec v + 0.3 sec n + 0.3 sec v + 0.3 sec n + 0.3 sec v
  5) 0.5 sec n + 0.7 sec v + 0.4 sec n + 0.4 sec v
C. Squeeze

- Use 100 degree for squeezing. 0 degree is basis.
- Total duration: 4 seconds
- 5 states (n: nothing, t: tightening)
  1) 4 sec t
  2) 2 sec n + 2 sec t
  3) 1 sec n + 1 sec t + 1 sec n + 1 sec t
  4) 0.4 sec n + 0.8 sec t + 0.6 sec n + 0.8 sec t + 0.6 sec n + 0.8 sec t
  5) 0.9 sec n + 1.3 sec t + 0.8 sec n + 1.0 sec t

Table 1. Detailed prototype design information

3. Tactile Stimuli

Five different time-varying cues were designed for the modalities of vibration, temperature and squeeze (Figure 3). Each was stored on the Arduino controller and spanned a four second time window. In cases where 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 [Brown, L.M., Brewster, S.A.,
Purchase, H.C., 2006, Oakley, I., Park, J., 2008]. 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 [Wilson, G et al., 2012] 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 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 [Baumann, M.A et al., 2010] 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).
IV. Evaluation

1. Purpose of Experiment

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.

2. Participants

12 participants completed this study (four male), all right-handed. Gender was recruited by 4 men and 8 women. They were a mix of students and professionals aged between 24 and 30 years ($\mu=25.3, \sigma=2.2$), recruited through word of mouth and public fliers. Their Wrist had a mean size of 16cm and Body temperature had a mean 33.8°C. All stated they were familiar with smart-devices, but not with wearables: only five participants reported prior experience with wearable devices. However, 7 participants had never worn smart wearables. More than half of the participants were wearing watches and all on their left wrist except one. Participants were compensated with ~10 USD.

Figure 4. Study process images
3. Method

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 ($\mu = 33.6^\circ$C, $\sigma = 0.9$) and size ($\mu = 15.8\text{cm}$, $\sigma = 1$) of the participant’s wrist and they donned headphones playing white noise in order to mask sounds from the experimental apparatus. We tried to minimize the noises from the hardwear by having participants sit on tables with headsets volumed with white noises during the test.

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 encouraged to express their opinions about the haptic cues and wearable prototypes.
4. The study tested on 3 notification

The study tested on 3 notifications: Vibration, temperature, and clasp. Experiment was processed where participants selected five different patterns of modality tasks from three different notifications. We randomized the three task notifications for each participants. Participants were asked to click on the "Play" button on the laptop's screen. After they had received the modality feedback, they were asked to select one of five choices that they thought was correct. Each modality condition was presented as follows. First participants donned the relevant prototype and spent five minutes familiarising themselves with the different haptic cues. These were activated via clicking on iconic buttons in a GUI shown on a PC (Figure 6) 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.

![Figure 6. GUI shown on a PC](image)
5. TLX / Interview

Participants also completed a NASA TLX survey after each modality condition. The total number of trials analysed was 180 (12 users x 3 trials x 5 stimuli). Lastly, they participated in an interview concerning the experiment's difficulty and other opinions (5 minutes). We focused in Interview question for each modality.

- Could user well distinguish the stimuli in this modality?
- Was there any particularly easy or particularly hard stimuli to recognise?
- Any other comment?

At the end of the question, we asked user about experiment.

- Was the watch comfortable to use?
- Do you prefer any of the modalities we presented?
V. Results

The average selection time per cue for each modality is reported in Figure 7. For vibration, the average recognition time was 5.4 seconds. We found statistical differences and the continuous vibration was the fastest. For temperature, the average was 4.4 seconds, there were no differences. For squeeze, the average was 4.2 seconds, there was statistical difference and this cue one was the slowest.

![Figure 7. Recognition time for each cue in each modality](image)

We use the anova to check different condition. Variations were explored using a one-way repeated measures ANOVA and post-hoc tests with Bonferroni CI adjustments. Errors for each conditions are reported in confusion.
matrices (Figure 8,9,10 left) but not statistically tested, due to the sparsity of the data.

1. Vibration condition

Figure 8. The confusion matrices for vibration condition (left): cues are clustered using colors and discussed in the text. On the right, an histogram showing the contribution of errors

In the vibration condition, the time resulted in significant differences ($F(4,11)=15.4 \ p<0.01, \ \eta^2_p = 0.58$). Post hoc tests revealed that the continuous cue was the more rapidly recognised 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.
2. Thermal condition

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 9-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 +6°C with +3°C cues (24%) or −6°C with −3°C 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 (± 3°C).

Figure 9. The confusion matrices for thermal condition (left): cues are clustered using colors and discussed in the text. On the right, an histogram showing the contribution of errors.
3. Squeeze condition

![Confusion Matrix for Squeeze Condition](image)

**Figure 10.** The confusion matrices for squeeze condition (left): cues are clustered using colors and discussed in the text. On the right, an histogram showing the contribution of errors.

In the squeeze condition time difference among cues was statistically significant (F(4,11)=8.6, p<0.01, \( \eta^2 = 0.44 \)) 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 (68%) were caused by confusing between the cues with two short pulses vs one-long-one-short pulse. In the squeeze case, the 300ms difference between the two types of pulse was more difficult to recognise. This result highlights some of the limitations for the time resolution of the squeeze feedback. Squeeze condition was very similar to vibration. However, there were many errors with short pulses. These two short cues are different by only 300 milliseconds.
4. Cognitive workload

Finally, comparing across conditions, the TLX data showed that the user workload was statistically different ($F(2,11)=8.6$, $p<0.01$, $\eta^2 = 0.56$), with vibration perceived as the easiest among the conditions ($p<0.05$), a result corroborated in the post-hoc interviews. We found that vibration was perceived as the most easy condition. We did not compare time across modalities as the cues are intrinsically different (e.g., time patterns vs temperatures) but the average recognitions times are 5.4s (0.4), 4.4s (1) and 4.2s (0.5) for the vibration, thermal and squeeze conditions.
VI. Discussion

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 pulses duration differing by only 300ms. This suggests that with squeezing cues, the time resolution of the signal cannot be under 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 [Wilson, G et al., 2012] indicated that ± 3°C 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.

Upon perspectives of various responses in relation with stimuli to be easily or hardly recognized among user interviews, the vibration stimulus in overall has been relatively easy to be recognized in comparison with other stimuli since
it is already familiar stimulus. Squeeze had been responded as it had been easier to feel the strength due to the strong stimulus in comparison with other two stimuli. On the other hand, thermal had been responded highly as it had been confused to differentiate each of thermal difference stimulus. Opinions of majority had been obtained through the interview that it might be better to maximize the thermal difference and to have an alarm through Squeeze.

VII. Conclusion

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.

The homogeneity of each stimulus has not been obtained in the experiment, so the standardization between the level of each stimulus has to be tried in advance. According to this experiment analysis result, the vibration has not experienced any difficulties in relation with the recognition because it has been a stimulus already familiar to users, and on the other hand, it has been found that the recognition of difference in temperature of thermal stimulus within a short period time can be difficult. Based on these findings, it seems that the design which leads to the security, usability, and convenience of
system with stimuli used for feedback shall be additionally necessary. This initial exploration highlights the potential of these modalities and some of their problems.
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Supplements 1. The resulting data of errors
Supplementary 2: The resulting data of Recognition time
논문요약

온도와 압력 : 손목 착용형 디바이스 인식 관련

열과 압력신호 탐구

손목형 웨어러블 컴퓨팅 장치들은 사용자 피부와 직접적인 접촉에서부터 촉각적 요소를 통한 알림을 보여주는데 매우 적합하다. 이전 작업이 촉각적 알림의 실행 가능성을 탐구하였다면, 저자는 웨어러블 장치의 맥락에서 열과 압력에 의한 촉각적 피드백의 경험적 연구의 결과를 강조하고자 한다. 따라서 본 연구는 손목에 전달되는 열과 압력(압축:Squeeze) 피드백을 위한 두 가지 원형을 소개한다. 또한, 본 연구는 진동을 동반한 기초선(baseline) 성능 대비 열/압력 촉각 신호의 인식 성능을 구별한다.

본 실험의 목적은 인식 속도 및 용이성과 주관적 경험의 측면에서 알림을 나타내기 위한 다양한 큐의 적합성을 판단하기 위함으로 진동, 온도, 압력 큐와 함께 인식 성능을 시험하는 연구를 진행하였다. 각 양상별로 큐 당 평균 선택 시간을 종합하였고, 단일 방향 반복 측정 방식인 ANOVA 와 Bonferroni CI 조정 방식인 사후 검점을 통해 변형 모델을 탐구하였다. 조건별 오차는 오차행렬에서 나타났지만, 자료 결합으로 인해 통계학적 검증은 이루지지 않았다.
본 연구는 열과 운동 감각적(압력) 촉각 피드백의 잠재성과 관련한 다양한 문제를 밝혀낸다. 확실한 것은, 전동은 오차에 대한 관련성이 가장 적으나, 압축 조건은 동일하게 큰 역할을 한다. 발견된 더욱 큰 오차는 300ms 차이에 불과한 맥박 지속시간 및 단일 큐 사이의 오차 때문이다. 이는 압축 큐와 함께 신호의 시간해상도(Time resolution)가 13Hz 미만(4000/300)일 수 없다는 것을 방증한다.