ScatterWatch: Subtle Notifications via Indirect Illumination Scattered in the Skin

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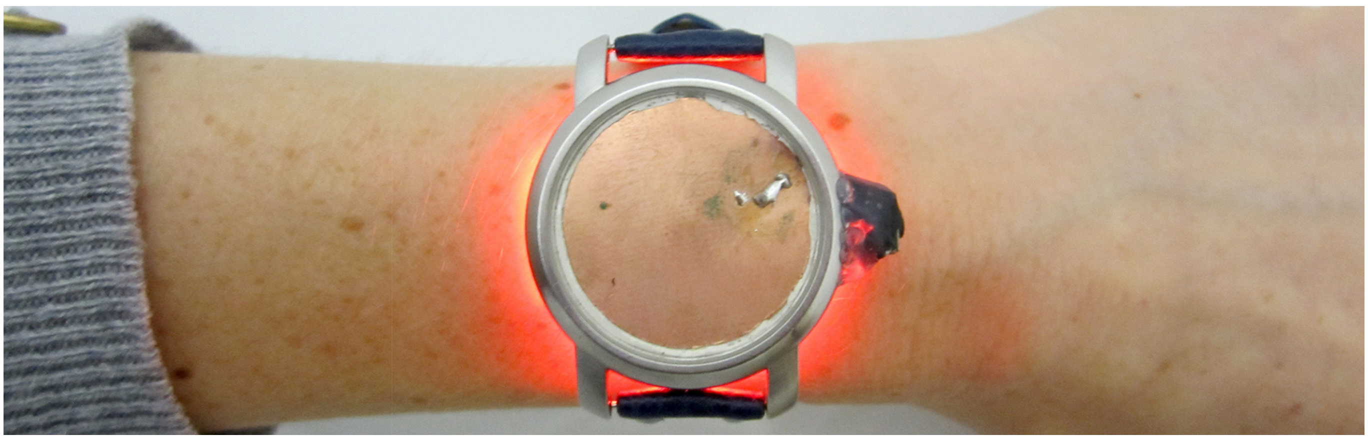

Figure 1. We added LEDs to the bottom of a watch case for use as a notification mechanism. The red light can pass through skin, scatters, and can be observed all around the watch. This enables a more subtle means of feedback—not as disruptive as vibration and more connected to the body than outward-facing illumination. This kind of indirect illumination feedback is still noticeable to users and visible through some clothing.

ABSTRACT

With the increasing popularity of smartwatches over the last years, there has been a substantial interest in novel input methods for such small devices. However, feedback modalities for smartwatches have not seen the same level of interest. This is surprising, as one of the primary function of smartwatches is their use for notifications. It is the interrupting nature of current notifications on smartwatches that has also drawn some of the more critical responses to them. Here, we present a subtle notification mechanism for smartwatches that uses light scattering in a wearer's skin as a feedback modality. This does not disrupt the wearer in the same way as vibration feedback and also connects more naturally with the user's body.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces—*Evaluation/methodology*

Author Keywords

Wearables; notifications; in the wild; indirect illumination

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INTRODUCTION

Apart from telling the time, displaying notifications is the primary function of smartwatches [20]. They fit this role well as the watch form factor is uniquely suited for glanceable, quick, and convenient access [16]. However, interruptions due to many notifications can even induce inattention and hyperactivity in users [12]. But at the very least, undesired interruption is annoying, especially for non-critical notifications. We might be happy with our smartwatch vividly buzzing on our wrist when an important message comes in, yet would be less appreciative when this happens for every *like* on Instagram.

An approach for less disruptive notifications are subtle feedback methods, such as peripheral light indicators mounted to glasses [5]. However, a glass form factor is not suitable for everyone. Instead, we propose embedding LEDs into the back of smartwatches to create subtle light feedback on the wrist. Emitted light scatters in the skin and creates a subtle glow around the smartwatch (see Figure 1). This also keeps the smartwatch screen free for interactions and high-bandwidth feedback, or allows it to be switched off.

Smartwatch aesthetics have been identified as an important factor for their adoption [16]. Indirect light feedback forms an immediate connection between the watch and the arm. On an aesthetic level this extends the design space of future watch designs. But the visible nature of the feature also potentially makes such notifications more socially acceptable, as others can observe them as well [7].

In this paper, we present the concept of indirect light feedback via a prototype contained in a standard watch case. We investigate how well users can detect notifications presented in this way with an in the wild study. During the study, participants wear the prototype for a full day. This allows for a wide range of situations and activities (which participants record in a diary) to impact the results. We find that participants could acknowledge the feedback in all encountered situations. Performance of indirect light feedback is on par with previous direct light feedback methods (when tested in a similar setup).

RELATED WORK

With our exploration of indirect LED feedback, we relate to the larger space of LED feedback. However, we specifically focus on smartwatches and thus the space of novel feedback methods for them. In particular, we tailor indirect light feedback for subtle notifications.

LEDs for Feedback

Almost every piece of consumer electronics contains one or more LEDs. However, their use for feedback is commonly limited to just a binary on/off state indicator. LEDs allow for a much richer output repertoire though, as explored by Harrison et al. [8]. We similarly play back several different patterns, e.g., fading the light intensity in a sinusoidal fashion.

Xu and Lyons explore smartwatch designs that replace the front screen with an LED-based design [26]. Their *Shimmering Smartwatches* show how such low fidelity feedback can still support common smartwatch interactions.

Novel Feedback on the Wrist

Current smartwatches and other wrist-worn wearables commonly include vibration feedback and visual feedback. However, just as we present a new form of visual feedback, several projects have explored feedback modalities beyond those two.

Instead of just one vibration motor, *BuzzWear* arranges three motors on the wrist [14]. Compared to basic vibration feedback, this also allows for playback of tactile patterns. The 24 presented patterns could be well distinguished and were fast to detect even when engaged in a distractor task.

Bauman et al. explore haptic feedback systems that emulate human attention capturing [2]. They mount two different actuators on a *"watchface-like body"*, attached to a wristband: (1) a *squeezing* mechanism to constrict the strap, and (2) a *tapping* mechanism that actuates a foam "finger". Depending on the actuation method, they find that this feedback can elicit relaxing or agitating sensations. Squeezing was also explored by Song et al. [24], who also looked at thermo feedback on the wrist using a pair of peltier elements. However, users had a hard time distinguishing thermal stimuli. Thermal feedback also runs the risk of being uncomfortable, if used outside of a small actuation range [25].

Pasquero et al. investigated haptic feedback on the wrist as well, but fit their actuator into a wristwatch form factor [17]. They embedded a piezoelectric transducer in the bottom of their prototype. When activated it changes to a dome shape and presses against the user's wrist. This can provide a sensation users compared to a *"strong heartbeat pulse"*.

A mechanical feedback mechanism is used in *Skin Drag Displays* [10]. Here, a pin inside a wrist-worn prototype moves over the skin, exerting tangential forces on it. This is used to draw shapes on the skin—a form of gesture output. Compared to vibrotactile arrays, such dragging feedback makes it significantly easier to distinguish different gestures.

Subtle Feedback

Human attention is a limited resource and how to do feedback that takes this into account has been an area of intense research. An early example is the *Reminder Bracelet*, which uses three LEDs on a wristband to enable subtle notifications [6]. Costanza et al.'s *eye-q* is a more refined version of the same principle [5]. Here, four LEDs are placed on the end of both arms of a pair of glasses—sitting in the corners of the lenses. In two studies, they evaluate the factors that influence the perception of these subtle, peripheral stimuli. They find that higher workload, dimmer illumination, and slower animation all lead to less noticeability of the feedback. In *NotifEye*, Lucero and Vetek display virtual butterflies in see-through interactive glasses [15]. While this version makes no attempt to display particularly realistic butterflies, such a system could be extended to have the notifications *blend in* more with the world by rendering more lifelike butterflies.

While the above works used visual subtle notifications, Pielot and de Oliveira instead applied vibrotactile feedback [19]. They set up their prototype to constantly vibrate, but tuned down vibration to be just barely noticeable. Users then had to detect the stimulus being *switched off*. Slow reaction by participants showed that the stimuli did not occupy the focus of attention and that it is a viable form of subtle feedback.

A PROTOTYPE FOR INDIRECT LIGHT FEEDBACK

We designed our prototype to be as similar as possible to a traditional watch. For this purpose, we acquired an empty wrist watch case with attached strap and intact front glass, but without the back of the case, from a flea market. This circular watch case is 7 mm thick and has a diameter of 4 cm. From lug to lug it measures 44 mm. With all internal clock parts removed, this gave us the space to embed custom electronics inside the watch. As the clock face was missing, there is a problem of light leakage out the front of the prototype. We solve this by sealing the front glass with a glued in opaque cutout (made out of a thin copper sheet with plastic backing).

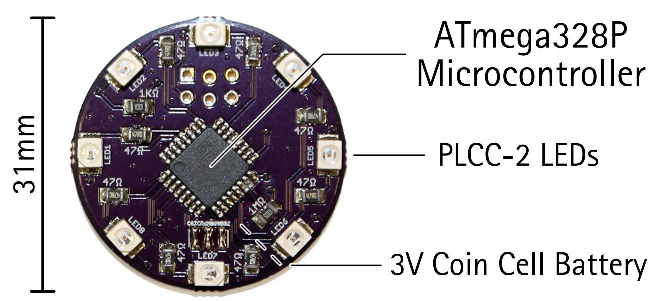

Figure 2. The central part of our prototype is a custom PCB containing 8 LEDs. The LEDs are controlled with a microcontroller and powered from a coin cell battery mounted on the back of the PCB. This board is sized to fit snugly into an empty watch case.

We designed a custom circular PCB to fit inside the watch case (shown in Figure 2). It primarily holds an *ATmega328P* microcontroller, a coin cell battery holder and eight LEDs along the perimeter. For the LEDs, we chose the *ASMT-URB4-YU802* from *Avago Technologies*. These red LEDs measure 2.8×3.2 mm and are 1.9 mm high. When operating at the rated 20 mA, they provide 1.4 cd of luminous intensity. Light is emitted with a viewing angle of 120° and at a dominant wavelength of 623 nm.

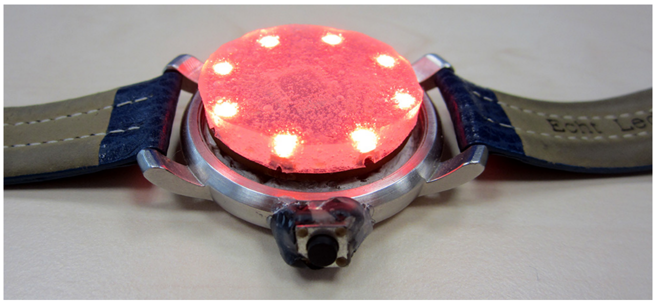

Figure 3. We cover the LEDs in a 4 mm thick layer of clear silicone for added comfort. This prevents the hard edges of the LED housings from irritating the skin, while still allowing light to pass through.

We cover the whole side carrying the LEDs with a 4 mm thick coat of translucent silicone (*SORTA-Clear 37*, see Figure 3). This provides added comfort by padding the sharp edges of the LED cases, while allowing light to pass through. When wearing the prototype, the silicone compresses and the prototype sits just above the wrist. If worn loosely, some light also shines through the lower gap at the side (see Figure 4 for a comparison). This is visually not distinguishable from light scattered in the skin. In future smartwatches, LEDs could instead be put behind a custom glass watch back.

Figure 4. When wearing the watch directly on the arm (left) it sits tighter than when using the silicone padding (right). The slight gap due to the silicone also leads to additional light on top of the scattered one.

In the place reserved for the crown, we instead attach a small push button by gluing it to the frame. This is used for acknowledging any feedback from the watch. To limit the chance of accidental activation, we programmed the button to only trigger an event if held down. When reacting to a stimulus, the button needed to be pressed for 800 ms. When no stimulus is shown, holding down the button for 5 s powers down the watch, the same action starts it again. Both actions are acknowledged with an LED animation. This functionality is used to, e.g., turn off the watch during the night.

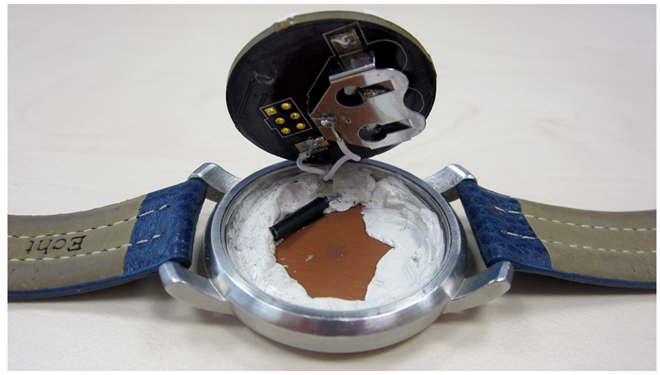

Figure 5. The bottom of the PCB holds a coin cell battery with enough power to run the prototype for a day. We sealed the front of the watch to prevent light leakage to the front. The used putty also holds the PCB in place and prevents damage due to free movement inside the case.

The prototype is powered by a *CR1620* coin cell battery (see Figure 5). We use a lithium battery with 70 mAh capacity, that provides 3 V nominal voltage. As our prototype spends most of the time in power down mode, this battery lasts for more than the required day of operating time. In power down mode, only the watchdog timer remains active and the ATmega328P draws about 4.2 μA. During LED operation, the power draw is much higher. Depending on active mode and PWM settings, the LEDs require 20–160 mA.

Choice of Light Color

Most of the light emitted by our prototype is not observed directly, as the LEDs are directed towards the skin. What is seen instead is the remitted light that passed through the skin. As illustrated in Figure 6, only about 5% of light is directly reflected by the skin. The majority of the light is either absorbed by the skin or scattered inside of it. Such scattering is caused by inhomogeneities inside the skin, which also leads to diffusion of the light as it passes through the skin [1]. This leads to a much larger area remitting light, compared to the area that received light in the first place.

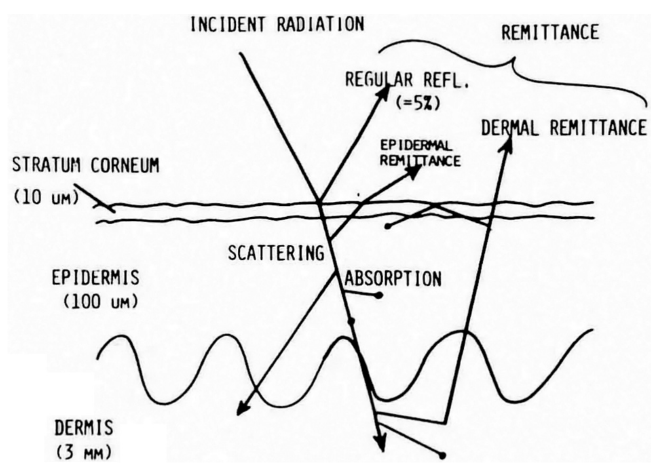

Figure 6. Light can be reflected by or transmitted through the skin in different ways. Reprinted from Journal of Investigative Dermatology 77(1), Anderson and Parrish, The Optics of Human Skin, pp. 13–19, Copyright 1981, with permission from Elsevier.

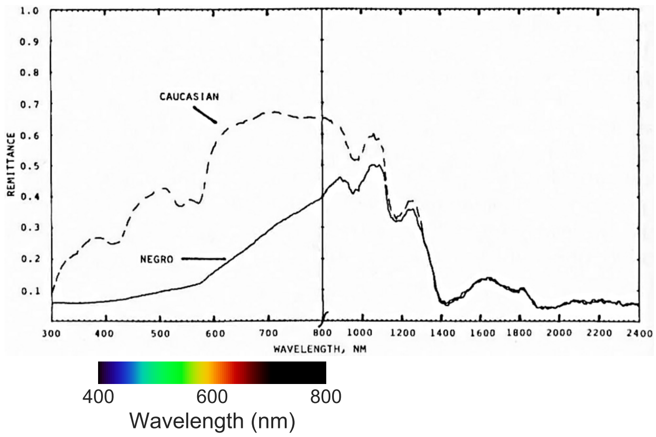

Figure 7. How well light can pass through the skin is dependent in its wavelength. The top plot shows cutaneous spectral remittance curves for light and dark skin. As can be seen, light between 600–1100 nm in wavelength best passes through the skin. Only a small part of this range is inside the visible spectrum (shown below). Accordingly, red light is the clear choice for indirect light feedback. Top plot reprinted from Journal of Investigative Dermatology 77(1), Anderson and Parrish, The Optics of Human Skin, pp. 13–19, Copyright 1981, with permission from Elsevier.

However, light behavior inside the skin varies between absorption and remittance. As shown in Figure 7, the amount of remittance depends on the wavelength of the light. Optimal remittance for fair Caucasian skin is achieved around 700 nm, while remittance for darker skin peaks at about 1100 nm. Unfortunately, this puts the optimal light well into the infrared spectrum—making it invisible to users. We hence settle on light with a slightly lower wavelength, in the red part of the spectrum. The 623 nm LEDs we picked are a compromise between size, wavelength, and luminosity.

While red light performs best for feedback through indirect illumination, this does not mean other light colors are impossible to use. However, the effect is much weaker and thus stronger LEDs need to be used, which comes at a cost to power efficiency. Optimizations to LED placement (more towards the edge) or orientation (angled outwards) could also help, but complicate construction and pose tighter design constraints.

Feedback Modes

Instead of running the LEDs at full power, we implemented several feedback modes. Even with just one LED, the number of possible patterns is large, as demonstrated by Harrison et al. [8]. Having multiple LEDs opens up an even larger design space and allows for rich messages [3]. After piloting, we limited ourselves to seven modes (also see Figure 8):

- Illuminating all LEDs
- Only illuminating the LEDS on the left side of the watch
- Only illuminating the LEDS on the right side of the watch
- Illuminating all LEDs, but reducing the intensity
- Blinking all LEDs at a frequency of about 1 Hz
- Illuminating two LEDs, but moving which ones are lit up clockwise every $1/8$ s. This gives a rotating animation running at about 1 Hz
- Oscillating all LEDs in a sine wave pattern (about $1/2$ Hz) between full and no intensity

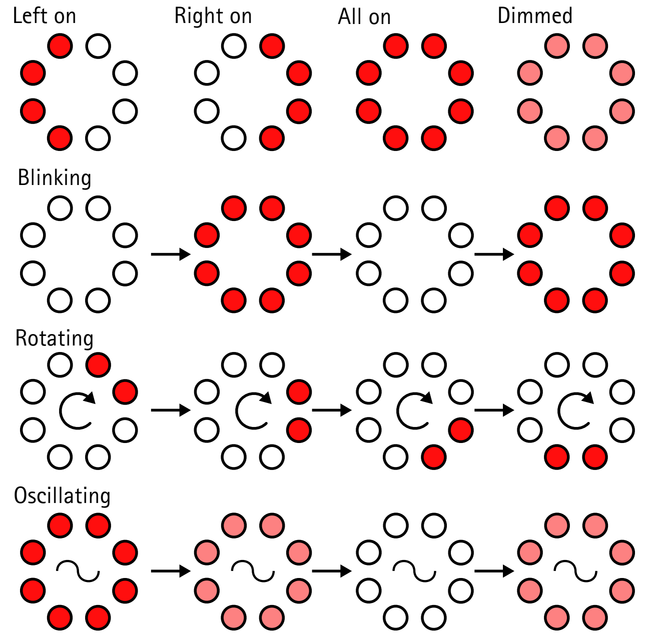

Figure 8. The LEDs in our prototype can display seven different patterns. Four of them are static, while the remaining three are animations.

EVALUATION

While our prototype demonstrates, that indirect light feedback can be implemented in a smartwatch form factor, it is not yet clear whether it is also viable as a feedback mechanism. We thus conducted a user study to determine how well users can perceive such stimuli.

A critical aspect when evaluating notification mechanisms is distraction. If users only need to concentrate on the feedback, reaction times will be very low. Thus, lab studies commonly include distractor tasks to capture participants' attention elsewhere. However, the impact of such measures can vary significantly between different distractor tasks [5]. Another critical aspect with our device is lighting conditions, as the level of ambient light influences how well the feedback can be seen.

We thus opted for an in the wild approach as in [4]. Instead of tightly controlling all factors, we make use of the natural situational diversity (for a discussion of the benefits of field studies see, e.g., [11]). This enables us to gather more realistic data on the feedback and increases ecological validity. Participants wore the prototype for a whole day, going through their normal routine (see Figure 9). In addition to evaluating the performance of the feedback, this also allows us to capture how using this kind of feedback feels to users. For example, one might assume that having a glowing wrist when in public might be uncomfortable for some. They might, e.g., feel that the feedback is drawing unwanted attention to them.

Figure 9. Users in our study wore the prototype for one day while tending to their usual affairs. They recorded their activities in a diary.

There are also drawbacks to our experimental approach. As we have no control over the situations participants encounter, we can not balance conditions. One participant, e.g., might only use the watch at home, while another one goes outside. The way participants report on their day likely also varies. What one considers dim light, the other might rate as regular light. As we depend on self reporting, this can make overall comparisons less clear than if we had accompanied every participant. However, monitoring participants (personally or with a recording device), can induce changes in their behavior.

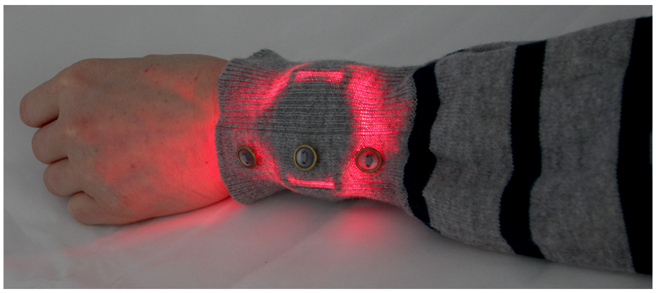

Figure 10. Some clothing (e.g., light sweaters or shirts) allow the light to pass through. However, thicker and/or darker clothing prevents the light from being seen. While this is less of an issue in the summer, winter clothing can prevent the use of this kind of feedback.

The study was conducted in Hannover, Germany in the summer of 2015, between late August and mid September. Hence, many participants spent time outside and the ambient lighting was comparably high. During the days of the study, there were between 0 and 15 mm of rain and 0–11 sunshine hours (6 h of sunshine per day on average). Temperatures averaged a daily low of 12 °C and an average high of 20 °C. We would expect noticeability to increase in the winter, when ambient lighting is reduced. However, more and thicker clothing could also mean that the wrist is less visible and reaction times would go up. Short-sleeved summer clothing does not pose this issue. As can be seen in Figure 10, even light sweaters can allow sufficient light to pass through.

With out study, we set out to determine how well indirect light feedback performs. Taking into account what we expect our participants to encounter, we hypothesize that:

H1 Indirect light feedback is as easy to detect as direct light feedback (as reported in previous work).

H2 How fast users detect feedback is dependent on their current task, with some tasks requiring less intense focus or keeping the watch better in sight.

H3 Indirect light feedback is noticed earlier in darker environment, while it is less noticeable in, e.g., direct sunlight.

Participants

We recruited 13 participants (4 female, age 23–34, $\bar{x} = 27.1$, $\sigma = 3.3$) for the study via social media. Six of those participants regularly wear a watch, two wear one sometimes, while the remaining five never wear a watch. None of the participants owned a smartwatch. All participants were right-handed, and they all wore the prototype on their left wrist.

Procedure

Each participant first signed a consent form and received instructions on how to control the prototype. After putting on and starting the watch, we walked participants through the first two stimuli (not included in the later evaluation). However, this gave us a chance to provide instructions on how to respond to stimuli. Participants were instructed to acknowledge the feedback by pressing the button on the side of the watch.

After each acknowledged stimulus, participants made a diary entry related to this situation either online, via a web form, or on paper. In this diary, we asked them to provide information on (1) which kind of feedback was shown, (2) the brightness of their current surroundings, (3) what they were doing when they noticed the feedback, (4) how comfortable the feedback was, (5) how bright the feedback was, and (6) how fast they think they reacted to the feedback. They could also enter additional remarks if necessary. After wearing the watch for one day, participants returned it and were interviewed by us.

Apparatus

Participants wore the prototype described earlier. We configured the system to display each stimulus for up to two minutes. If not acknowledged by the user by then, the trial is logged as not completed and the stimulus is stopped. We chose this threshold as previous work showed 99% of direct light stimuli on the wrist could be detected within this time [9].

Stimuli order is randomized and a new stimulus is shown every 8–12 minutes. Thus, on average, participants receive six stimuli per hour. While participants wore the watch for a day, we cannot expect data for the full 24 h, as participants were instructed to turn off the watch at night. Instead, we planned for roughly 12×6 h of actual use (participants, e.g., also had to turn off the watch while showering as it is not waterproof).

RESULTS

We logged between 52 and 90 trials per participant (70 trials on average) for 902 trials overall. As shown in Figure 11, the majority of trials occurred between 10:00 and 22:00. Thus, it was still light outside for most trials (in early September astronomical twilight is around 21:00).

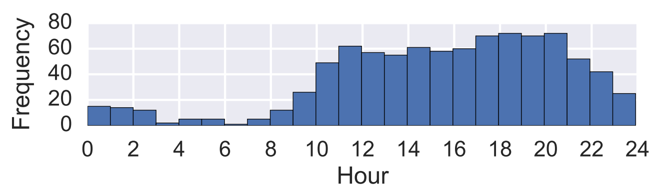

Figure 11. The majority of our trials took place between 10:00 and 22:00. However, some participants stayed up longer or woke up earlier.

One might assume that participants are better at reacting to stimuli during the day and get worse as they are tiring, later in the evening. However, if we take a look at the percentages, there is no such pattern (see Figure 12). There is a small drop-off between 4:00 and 8:00, but we only have 16 samples for this time period. In fact, between 4:00 and 6:59 only one participant was awake—and reacted to 7 of the 11 shown stimuli. Further data is thus needed for conclusive answers on stimulus noticeability at night.

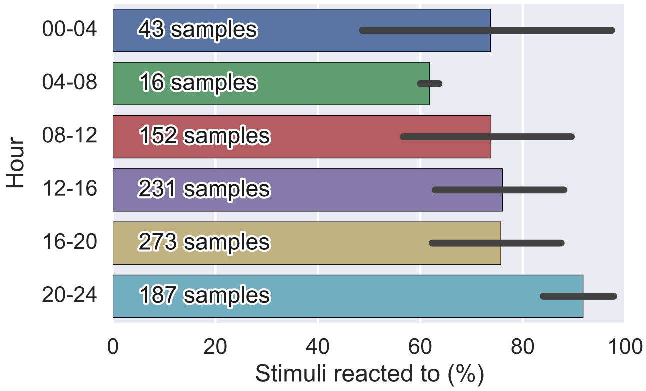

Figure 12. There is no clear pattern for how well participants reacted to stimuli on specific times of day. Error bars show bootstrapped 95 % CI.

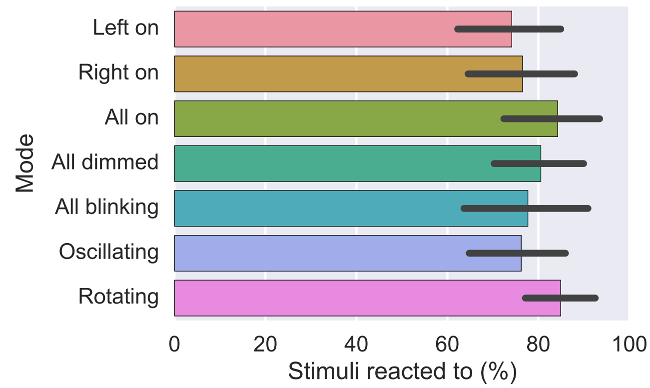

Figure 15. The different modes performed similarly with respect to whether participants reacted. Error bars show bootstrapped 95 % CI.

Overall, participants reacted to 80.3 % of the presented stimuli. As shown in Figure 13, there are large differences between participants. While one participant reacted to all stimuli (78 were presented), another participant only reacted to 42 % of the 73 presented ones.

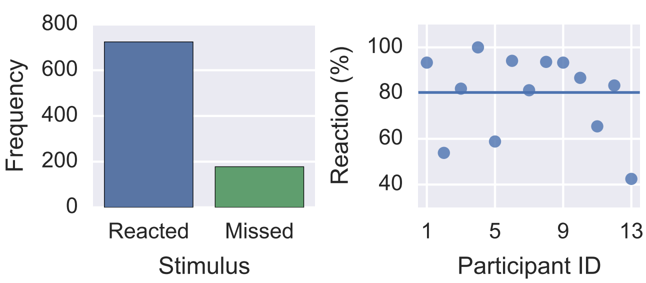

Figure 13. On average, participants reacted to the indirect light feedback in 80.3 % of the trials. However, there was large variation in reaction percentages between different participants.

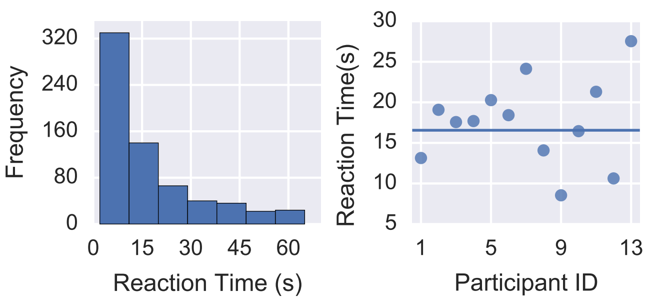

Figure 14. Reaction times follow a power-law distribution. On average, it took participants 16.6 s to react to a stimulus, however there is large variation between different participants.

If we only look at the trials in which participants reacted to the stimulus, we can see that the reaction time follows a power-law distribution (see Figure 14). The average reaction time was 16.6 s (acknowledgement took at least 600 ms as the button had to be pressed long to prevent accidental activation), yet we again see large variation between participants. As before, the same participant performs the worst and took 27.5 s on average to react to a stimulus. With the reaction time distribution this skewed, it is useful to look at the response curve. For example, 50 % of stimuli were acknowledged within 10.5 s. Performance trails off after this: 75 % were acknowledged within 22 s, 90 % within 41 s, and 95 % within 52 s. The two minute window we set for reacting to stimuli was thus much larger than required. Our data shows, that if users do not react within one minute it is very unlikely that they will react at all. For important notifications, systems could then switch to vibration feedback to increase the chance of the user reacting.

Influence of Illumination Mode

Between the different feedback modes, we did not see a difference in whether participants reacted to them (see Figure 15). At the extremes, *Left on* has a 76.0 % reaction rate, while *Rotating* has a 86.0 % one. However, variation between participants is much larger than variation between modes.

Reaction times for the different modes show a similar picture (see Figure 16). Compared to variation in reaction time per participant, variation per mode is much less pronounced. Hence, illumination mode does not seem to make a difference with respect to reaction time. However, different modes are useful to distinguish notification types or for aesthetic reasons.

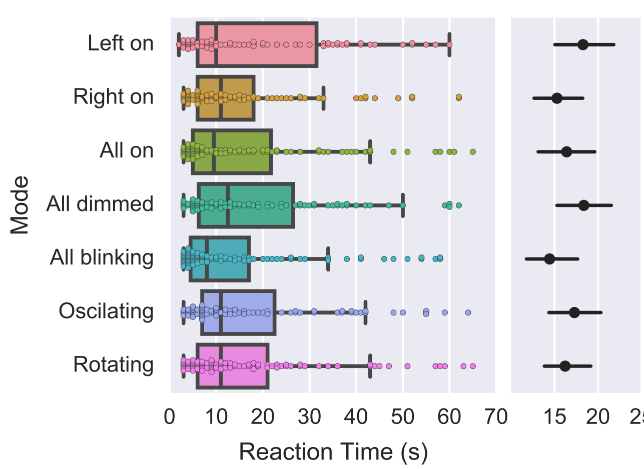

Figure 16. While there is some variation in reaction time for different illumination modes, there is no strong difference. Error bars in the right inset show bootstrapped 95 % CI of the mean.

When using different illumination modes for different notifications, it is important that they are distinguishable. We asked participants to note down the pattern they identified in their diary. To reduce the number of options in the diary we group together the left and right (these depend on watch orientation anyway) and blinking and oscillating stimuli. We can compare this with the actually played back feedback. Figure 17 shows a confusion matrix for each feedback mode. Confusion here could be due to (1) participants not paying much attention to the feedback when reacting, or (2) two modes being visually similar. As can be seen, the rotating feedback was the easiest to tell apart (it is also the most distinct of the set). Confusion arises primarily between muted illumination and full illumination. This is understandable, as there is no reference and external lighting conditions have an impact on how bright the feedback is perceived. There was also some confusion between feedback that was only active on one side (left or right). Sometimes those stimuli were taken for all-around illumination. This is likely due to light leakage. While one side is much brighter when only half the LEDs are on, some light also scatters and shows on the other side.

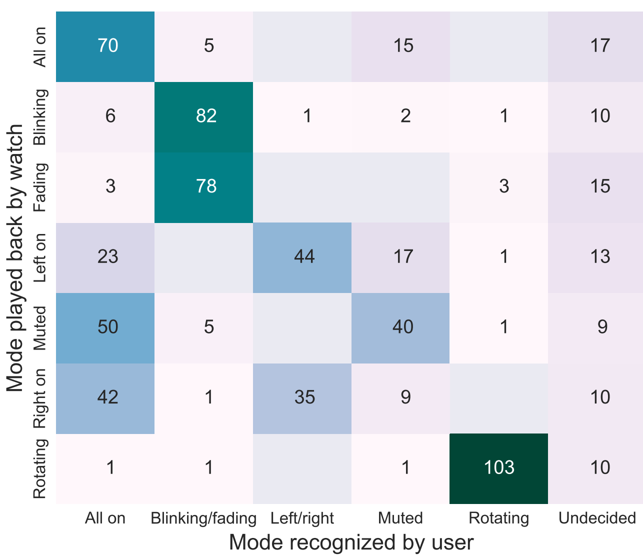

Figure 17. This confusion matrix shows what mode participants noted down in their diary versus which mode was actually played back. While rotating is almost never confused, participants had a harder time distinguishing one-sided apart from all-around and muted from non-muted.

Influence of Activity and Surroundings

We also took a look at how users' activities and surroundings impact their performance. We coded the participants' diary entries and labeled all activities as either (1) *walking*, (2) *waiting or relaxing*, (3) *using a laptop or phone (private)*, (4) *being at work or university*, (5) *driving*, (6) *housework*, or (7) *eating or cooking*. Figure 18 shows reaction time distributions for each of those activities. While the average reaction time when being on the laptop or phone was 11.9 s, it was 18.8 s while at work. However, variance is high in each case. We thus cannot reasonably conclude that any activity enables much better performance than any other. Answering **H2** thus requires additional investigation.

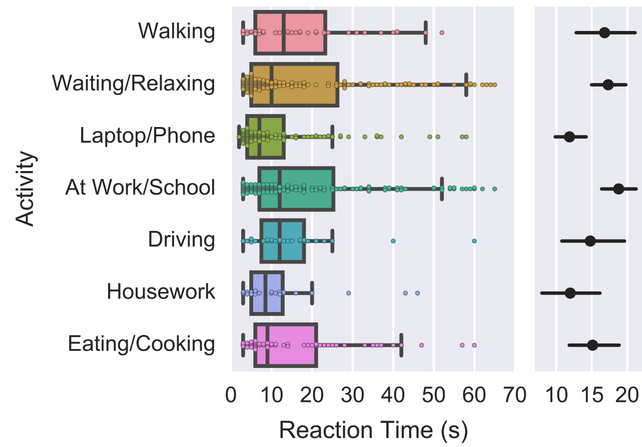

Figure 18. Participants made note of their current activity in their diary, each time they reacted to a stimulus. We categorize activities into six groups. While there are some differences in reaction time per group, there is no activity clearly outperforming others. Error bars in the right inset show bootstrapped 95 % CI of the mean.

Finally, we can compare how fast participants reacted, depending on their current environment. We code their diary entries as either *outdoors*, *indoors + bright*, or *indoors + dim*. Figure 19 shows the response curves for those three conditions. As can be seen, participants tend to react a bit faster in indoor environments. However, this is a subtle difference and there is no large offset between the two conditions. The data is also rather unbalanced—participants spend much more time inside than outside. Hence, even though there is some support for it, we cannot yet give a conclusive answer to **H3**.

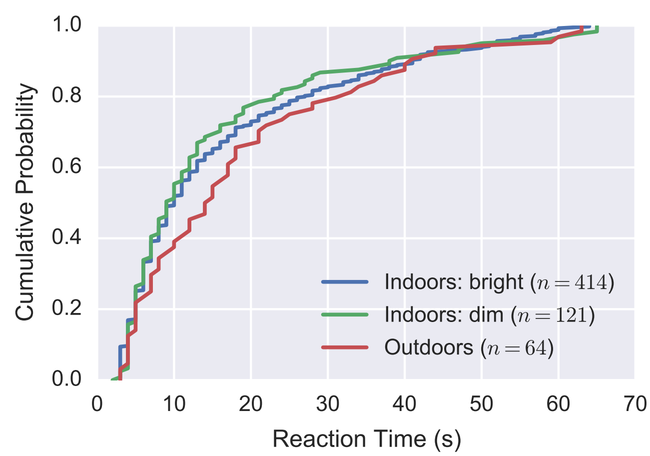

Figure 19. We group participants diary entries on their environment into three categories. The response curve shows that participants tend to react a bit faster when indoors than when outside. However, the difference is small and the share of locations unbalanced. Therefore, we cannot yet be sure that location impacts how fast participants react.

Qualitative Ratings

In addition to measuring participants' reaction to stimuli on the watch prototype, we also asked for their qualitative feedback in an exit poll. For each question, participants indicated their level of agreement on a 5-point Likert scale. An overview of their answers is shown in Figure 20.

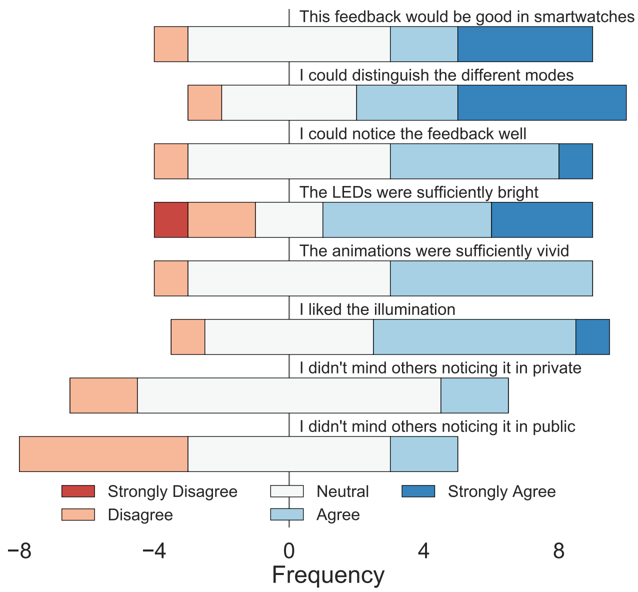

Figure 20. During our exit poll, participants rated several statements on a 5-point Likert scale.

Asked to indicate whether they liked the feedback and whether this would be a good addition to future smartwatches, most participants agreed. We also asked participants how they felt about the feedback when in private or in public. Some participants did not appreciate use in public—likely because the feedback can draw attention to the user. While vibration feedback can generally be received without alerting others, indirect light feedback is equally noticeable to bystanders.

Asked to rate the quality of the feedback, most rated the animations to be sufficiently vivid (e.g., rotating fast enough). While some wished for brighter LEDs, most stated the illumination was also sufficiently bright. We also asked participants which modes they liked/disliked the most. There was no clear consensus, but most liked the *all on* and *rotating* modes, with *fading* a close third. However, *rotating* evoked disagreement and was equally disliked as liked. The most disliked mode was *blinking*, though. This mode was also mentioned by participants when asked for general annoyances during the study.

When asked for specific situations where they liked or disliked the feedback, a general theme emerged. Participants generally appreciated the feedback in private or calm situations, such as at home, when on a laptop, or relaxing. Three participants stated the feedback was basically fine all the time. Several participants indicated a dislike of the feedback in social situations (particularly conversations). One specifically mentioned disliking it when people asked him about the device.

Many participants expressed annoyance by the frequency of the feedback. While we limited stimuli frequency to about six per hour, this might still be too often. This is exacerbated by the fact that the feedback did not actually notify participants of anything. It might hence be a good idea to integrate feedback with each participant's personal notifications, e.g., illuminating the LEDs when an email is received. While this gives less control over the frequency and time of each trial, it could be less annoying for participants.

Discussion

The results show that indirect light feedback works well in a wide range of situations. However, we could not find strong differences for any one feedback mode or activity. We can thus not confidently confirm **H2** or **H3**. This is a drawback of the study design we used. While the good performance under variable conditions shows indirect light feedback is viable, the uncontrolled nature of the in the wild approach makes it hard to compare specific conditions. Hence, it will be necessary to run more constrained evaluations in the future, to investigate the impact of factors such as activity.

Our evaluation showed that participants did not react to 19.7 % of stimuli. We can take a look at those trials where participants did not react. In 56.6 % of the cases, participants only missed one trial before reacting again to the next stimulus. However, we also had one participant miss 10 trials in a row between 13:20 and 15:10. Such longer lapses are likely the result of taking off the watch. The nature of the in the wild study design does not prevent such participant behavior. For short gaps, the diary entries for the preceding and following trial can provide clues regarding the likely setting and activity at the time of the missed trial. In 42 % of such gaps participants likely were indoors with bright lighting. However, this is also the most common setting overall (see Figure 19) and is actually underrepresented in gaps. More interestingly, 25 % of the gaps happen between a trial that occurred indoors and a trial that occurred outdoors (either direction). Stimuli here probably coincided with either arriving or leaving—times of more activity where participants are more likely to miss notifications. If leaving in a rush (e.g., to catch a train), it is also more likely participants ignored a stimuli.

We can compare the reaction times in our study to results from previous work. It took users almost 3 s to react to light stimuli when wearing the *NotiRing* [23]. This is an average over five levels of physical activity (user, e.g., were walking on a treadmill during part of the study). For their glass-mounted light feedback, Costanza et al. report about 1 s reaction times for a study where users were engaged in a reading task [5]. While walking around or editing text, the mean reaction time increases substantially (unfortunately no averages are reported). Those results from the lab are in stark contrast to results from Harrison et al. [9]. During their study participants were left to continue their normal daily routine while wearing a prototype for 2–3 hours. While they mention that almost all that time was spend working while sitting somewhere, this still creates a very different study situation. Correspondingly, reaction time to light stimuli on the wrist was about 19 s. Averaged over all trials, we found a similar reaction time to light stimuli on the wrist of 16.6 s. This shows that study design has a strong impact on measured reaction times. One aspect here is that an in the wild setup provides for a much more diverse and natural set of distractions and primary tasks. But as participants wear a device for a longer period of time, they are also likely getting used to it—*forgetting* it to some extent. A study situation in a lab on the contrary creates artificial focus and hence deceivingly low results for reaction times. However, the similar performance of indirect light feedback and direct light feedback [9] in a similar study setup does support **H1**: that both stimuli are equally hard to detect.

While we look specifically at the use of indirect light feedback for notifications, the subtle feedback capabilities are not the only possible use. As illustrated by Qin et al., LEDs along the perimeter of a device can be used to visualize offscreen content [22]. Correspondingly, the eight LEDs in our prototype could also show navigation directions to the user. This can augment an application running on the screen (e.g., while running a maps application) or display directions while the screen is switched off to reduce power drain. When used as a secondary screen for the smartwatch, the indirect light *screen* is useful for communicating longer running background state. So while users read a text they received on the watch, the illumination could indicate the time left until the next appointment, increasing in intensity as the appointment approaches. But use of the illumination could also be just driven by aesthetic concerns, e.g., pulsating in the beat of the music currently playing.

CONCLUSION

We have shown a prototype implementation of indirect light feedback: a subtle way to, e.g., relay notifications. This kind of feedback can be added to future smartwatches or even analog watches. Compared to vibration feedback, indirect light feedback is less disruptive, yet remains noticeable. The subtle glow around the watch does not preclude other feedback on the watch face. In fact, the low-fidelity nature of indirect light feedback nicely complements high-fidelity information shown on smartwatch displays. By including different levels of feedback, devices could then pick feedback depending on the current engagement of the user, supporting the range from casual to focused interactions [21].

Indirect light feedback is a novel addition to smartwatch feedback methods. But not only does it bring subtle notification capabilities to the form factor, it also opens up a new design space and a venue for aesthetic expression that connects with the wearer's body. The light does not just show on the face of the watch. Instead, the arm around the watch glows and the boundaries between device and body break down to some extent. We believe this is an attractive addition and one participant in fact remarked:

> *I don't own a smartwatch. However, I would buy one if it had this illumination.*

In the future, we also plan to investigate other uses of indirect light feedback. While this paper focuses on notifications, indirect light feedback enables a wider range of offscreen interactions on the wrist when coupled with an appropriate input technology. A similar approach has already been used by *Skin Buttons*, albeit with a top-projection [13]. Where we explore personal use of indirect light feedback, it could also be used as a form of coarse public display [18].

Furthermore, we plan to iterate on the prototype and integrate indirect light feedback directly with a smartwatch. Pebble smartwatches, e.g., allow custom bands to connect with the watch. In such a version, indirect light feedback could also be extended along the strap. While feedback behind the watch face is more public, feedback at the middle of the strap is more private. Integrating with a smartwatch would also allow us to provide indirect light feedback for a user's actual notifications.

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