Peripheral Vibro-Tactile Displays

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ABSTRACT

We report from a study exploring the boundaries of the peripheral perception of vibro-tactile stimuli. For three days, we exposed 15 subjects to a continual vibration pattern that was created by a mobile device worn in their trouser pocket. In order to guarantee that the stimuli would not require the subjects focal attention, the vibration pattern was tested and refined to minimise its obtrusiveness, and during the study, the participants adjusted its intensity to just above their personal detection threshold. At random times, the vibration stopped and participants had to acknowledge these events as soon as they noticed them. Only 6.5% of the events were acknowledged fast enough to assume that the cue had been on the focus of the participants' attention. The majority of events were answered between 1 and 10 minutes, which indicates that the participants were aware of the cue without focussing on it. In addition, participants reported not to be annoyed by the signal in 94.4% of the events. These results provide evidence that vibration patterns can form non-annoying, lightweight information displays, which can be consumed at the periphery of a users attention.

Author Keywords

Peripheral Displays; Ambient Displays; Haptics; Tactile UIs; Ubiquitous Computing / Smart Environments

ACM Classification Keywords

H.5.2 User Interfaces: Haptic I/O

General Terms

Human Factors

INTRODUCTION

Peripheral display (or *ambient display*) is an important approach to realise the goal of calm technology. It refers to an information display designed to convey information in the periphery of its user's attention. Such displays can be used to keep people aware about important but non-critical status information (*e.g.*, weather, amount of unread messages) concurrent to a focal, primary task on which the user needs to

focus (*e.g.*, reading a paper, composing an email). Ideally, information can bypass focal attention altogether, so users will even not notice the peripheral display consciously, but at the same time stay aware about the information it conveys.

Connected, intelligent computing devices have become ubiquitous and we find them in all parts of our daily life. Weiser [29] has foreseen this ubiquity and envisioned *calm technology*, *i.e.* technology that acts as *quiet and invisible servant*. The reality is that many of these devices are salient and not calm at all. They interrupt us at inconvenient times and demand our attention when it should be focussed elsewhere [5, 10, 12].

Most of the research on peripheral and ambient displays focusses on visual and auditory information presentation [11, 23, 7, 18]. However, since visual and auditory interfaces are public, they may violate the user's privacy and add more noise to our surroundings. Consequently, MacLean has suggested *putting haptics into the ambience* [14]. Previous work [8] has evaluated exposing people to continuous vibration as peripheral awareness cue, but many of the participants reported to be annoyed, which indicates that the stimuli frequently were in their focussed attention.

In this paper, we present a field study with 15 participants, in which we explore the boundaries of the peripheral perception of vibro-tactile stimuli. For up to three days, our participants were exposed to a continually repeating, gentle and steady vibration pattern. To ensure that the signal would not attract their focussed attention, the participants adjusted the vibration intensity before and during the study so that it would just be above their perception threshold. The signal stopped at random times to probe whether the subjects were still aware of the stimuli in the periphery of their attention. Ideally participants would eventually "forget" the stimuli and focus on their daily routines, but also be able to realise its absence after a reasonable amount of time.

Our results reveal that the majority of events were acknowledged within 1 to 10 minutes, a time span which lets us conclude that the participants were still aware about the cue but not focussing on it. In addition, participants reported not to be annoyed by the continuous stimulus in 94.4% of the cases. Prior to 6.5% of the events only, the vibration appeared to have attracted focussed attention – given that they were acknowledged "too fast". These findings provide evidence that vibro-tactile stimuli can be perceived in the periphery of users' attention.

Use Case Scenarios

Katie is giving an important talk to a large audience. Occasionally she notices that the attendants are spending more time looking at their phones and laptop screens rather than looking at her. She gets anxious and starts to wonder if she is losing the audience. However, Katie is wearing an electronic bracelet that emits a soothing vibration pattern indicating the activity level in social networks with positive posts related to her talk. Peripherally she can notice in real-time that her talk is being successfully advertised online, which then relieves her stress on stage.

Paul is a big fan of the Pomodoro time management technique[a]. To increase work efficiency, this method structures work into 25-minute slots, followed by 5-min breaks. Very gentle vibration pulses emitted by his smart watch peripherally conveys the time left until the next break, which doesn't disturb Paul from his main task while helping him to bring tasks to an end in time (inspired by the *Ambient Timer* Project [19]).

Matheo is a project manager with about 20 engineers reporting to him. Today he is taking the day off. Nevertheless, he usually checks his phone for urgent emails every 10 minutes to make sure everything is going well at work in his absence. This generates a lot of anxiety and prevents him from relaxing during his vacation. In order to address the problem, he started to use a mobile device in his pocket that emits a *soothing and mild* vibration pattern every once in a while *only* when multiple emails flagged as urgent arrive in his inbox in a short period of time. Hence, Matheo doesn't have to constantly check his phone, while still peripherally perceiving information without being abruptly disturbed during vacation.

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[a]`http://www.pomodorotechnique.com/`

RELATED WORK

Peripheral Displays

Peripheral displays can be defined as displays that are out of a person's focus [25] and only minimally attended [16], *i.e.* its user is aware of the display but not focussed on it. They are primarily perceived from outside of a person's focus of attention [6, 7]. The term *ambient display* is often used interchangeably. However, Pousman and Stasko [23] suggest to treat them as a sub-class of peripheral displays, where information is conveyed through subtle changes in the physical environment [11] (*e.g.* by altering the ambient lighting conditions), and where emphasis is put on the aesthetic value of the display [15, 23].

Attention describes a persons intent and expectation towards a stimulus [13]. According to Matthews *et al.* [17], there are four levels of attention, which are relevant to the design of peripheral displays:

- *preattention*: no conscious perception, information is not available for later processing,

- *inattention*: no conscious perception, but information may affect behaviour,

- *divided attention*: conscious perception, but attention is split amongst different stimuli, and

- *focussed attention*: conscious perception, focussing perception on one stimulus.

Peripheral displays are designed to make people *aware* about a status via inattention or divided attention. *Saliency* describes how much attention a peripheral display draws to it. By increasing or decreasing its saliency, peripheral displays can target different levels of attention.

Mobile Peripheral Interfaces

In previous research, mobile and wearable computers have been proposed to create peripheral displays. Schmidt *et al.* [24] suggested to use mobile phones as personal, always-on peripheral displays. They explored to convey information via screen savers in an ambient way.

Electronic garments have also been explored as mobile peripheral interfaces. For instance, Williams *et al.* [30] proposed a bracelet which consists of six LEDs: five of them indicating a friend's activity level (sent text messages) and one LED indicating the activity level of the whole group. They found conflicting opinions about the LEDs being visible to the public, thus revealing specific contexts in which visual peripheral displays are undesirable.

Costanza *et al.* [4] tested peripheral perception via glasses with arrays of green and red LEDs attached to the frame in the periphery of the field of vision. In an experiment with ten participants, they tested how well people perceive cues from these LEDs under different levels of cognitive load. Their findings suggest that high cognitive load degrades the perception of peripheral cues.

Haptic Peripheral Interfaces

MacLean [14] argues that *"the haptic sense is well posed to present background, ambient information"*, as most haptic information is already processed peripherally. Vibro-tactile displays are a subtype of haptic displays, which stimuli the skin via vibration. The advantage of vibro-tactile displays over other forms of haptic actuators is that they can be found in virtually every mobile phone today. Poupyrev *et al.* [22] found that when augmenting the interaction with a mobile phone by using peripheral vibro-tactile feedback, the efficiency of the interaction improves significantly. A different example is *Shoogle* by Williamson *et al.* [31]. When shaking the mobile phone, it creates vibro-tactile feedback to convey the amount of resources that are in use by the phone. Both examples show that vibro-tactile feedback can be used in the background of attention to convey information. However, both of these examples involve proactive interaction by the user, so that they are expecting the vibro-tactile stimuli.

For peripheral, device-initiated information presentation, vibro-tactile stimuli have been largely overlooked. One of the reasons is that – if not expected – tactile cues can capture and direct a person's focal attention [9]. Yet, there is research

indicating that continuous stimuli may eventually become peripheral. Nagel *et al.* [20] used a belt-shaped tactile display to continuously create vibration on the side of the torso that faced North, hence providing its wearer with a sixth sense of orientation. Tam *et al.* [26] used vibro-tactile pulses as timing cues during oral presentations. Another examples include to remotely connect people through vibro-tactile displays to create a sense of connectedness [1, 2, 28]. Nevertheless, neither of these reports provide the data to conclude that the stimuli were processed in the periphery of attention.

Another challenge is that continuous sensory stimuli may cause *adaptation* and *habituation*. Adaptation refers to the loss of sensitiveness. Adaptation to vibro-tactile stimuli can be countered, by using on-off instead of continuous stimuli [27]. Habituation refers to the human ability to getting used to certain stimuli, such as the ticking of a clock. According to van Erp [27], "*it is difficult to predict to what extend the tactile modality shows habituation*". For a peripheral vibro-tactile display, it is important to avoid adaptation, since it then would enter the *preattention* stage.

A work very close to ours is the *Ambient Life* Project by Hemmert [8]. He suggested the use of continual vibration as a means to make phones convey an "I am here, and everything is fine" status message. Hemmert conducted study, in which six people were asked to carry a mobile phone in the pocket, which continuously created heartbeat-like vibration pulses. A timer was set to turn off the vibration every 10-15 minutes. In almost half of the time, participants acknowledged the absence of the vibration within less than only 30 seconds. Since acknowledging the absence of the vibration required to detect and confirm its absence, take the phone out of the pocket, unlock the screen, and press the right button, these results indicate that the author's heartbeat approach was too salient and attracting the participants' focussed attention rather than their peripheral attention. This is supported by the fact that, according to Hemmert, "many users in our test group were quickly annoyed by the pulse, only few got used to it".

What is missing is a study approach, where the salience of the vibration is kept as low as possible, to provide solid evidence about whether vibration can enter the periphery of attention.

Evaluating Peripheral Displays

Evaluating ambient and peripheral displays is challenging, since these interfaces are highly subtle and indirect [7]. According to MacLean [14], to show the effectiveness of a peripheral display, *two things must be true: 1) the interface is communicative, at least some of the time, and 2) it is not in the center of the users attention, most of the time.* One of the main challenges is to design a study in a way that it will not push the display into the focus of attention, and hence violate the idea of a peripheral display through the researchers' intervention [6].

Traditional methods of evaluating user interfaces, such as the usability heuristics by Nielsen and Molich [21], are not applicable to evaluate peripheral displays. In particular, since peripheral displays are passive, all usability aspects related to the interaction with a user interface do not apply [15]. As

a consequence, Mankoff *et al.* [15] proposed an advanced set of heuristics tailored to the evaluation of ambient displays. In two case studies, which compared these heuristics to Nielsen's traditional heuristics, evaluators identified significantly more usability weaknesses, in particular the more severe ones of the studied ambient display.

Consolvo and Towle [3] applied these heuristics alongside an in-situ evaluation and found them to be effective. However, the most severe usability problems were only found in the in-situ evaluation. Since these severe problems actually violated the heuristics, Consolvo and Towle conclude that the general lack of experience with evaluating ambient displays makes in-situ evaluations necessary. Similarly, Messeter and Molenaar [18] highlight that evaluating ambient displays has to be done in-situ to appropriately consider its context of use. In their study on an ambient bus schedule in a public bus stop, travellers made each other aware of the ambient display, directing their focal attention towards it.

Hence, to explore the boundaries of vibro-tactile stimuli for peripheral information presentation, a study has to last sufficiently long enough so that the stimulus can enter the background of attention [14] and the study has to take place in-situ in the daily life of people to appropriately study the effect of the context of use [3, 18].

HYPOTHESES

The main goal of this research is to explore whether vibro-tactile cues can be consumed in the periphery of a person's attention. Therefore, we opted for using constant vibration pulses – similar to [8] – and tested whether these vibration cues would eventually move from the focus into the periphery of a user's attention. If the vibration is still minimally attended, users should, however, remain aware of the status of the cue. Therefore, whenever they notice the absence of the vibration, they should promptly inform it. If participants react some time after the vibration stopped, we can conclude that they are minimally attending the display. Conversely, if they react too fast – *e.g.* in less than 30 seconds for 44% of the cases reported in [8], they are focusing their attention in the vibration stimulus, thus contradicting the hypothesis that vibro-tactile actuators allow to create peripheral displays. In a nutshell, we want to validate the following three hypothesis:

- H1: participants will not be annoyed by the vibration stimulus (*i.e.*, the stimulus does not act on focused attention)

- H2: participants will not immediately notice the absence of the vibration (*i.e.*, the stimulus does not act on focused attention).

- H3: participants will notice the absence of the vibration in a reasonable amount of time (*i.e.*, the stimulus does not act on preattention)
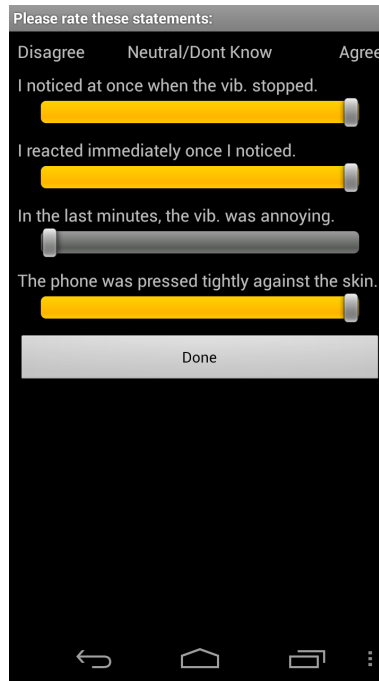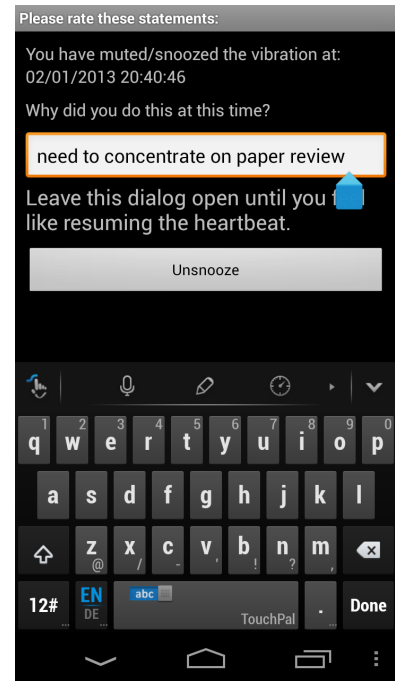
METHODOLOGY

Apparatus

To create the vibro-tactile stimuli, we used standard smartphones, since they provide the necessary actuator, as well as the sensors and the capabilities to capture data and collect
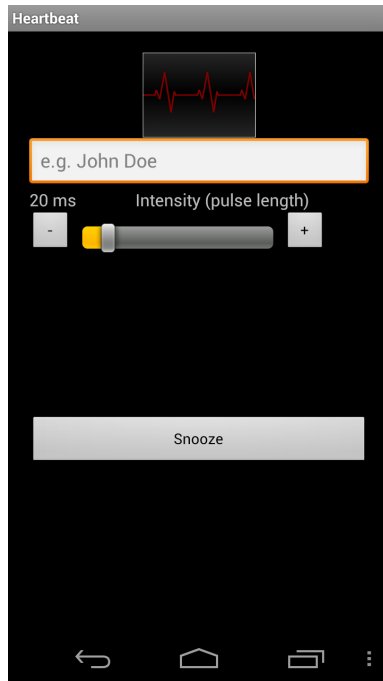
(a) Main view.

(b) Questionnaire following the acknowledgement of a Death Event.

(c) View shown when user pressed the Snooze Button.

Figure 1. Screenshots of the application.

in-situ feedback from the participants. We tested the battery consumption of our setup and found that it reduces the battery life by 2.4-5.0%[1] compared to normal use. Hence, the apparatus can be run for a full day without requiring extra recharging cycles. The phone models used in this study were Nexus One (119.0 x 59.8 x 11.5 mm, 130 g) and Nexus S (123.9 x 63 x 10.8 mm, 129 g). The smartphones were intended to be carried in addition to each participants' personal mobile phone, and not to be used for anything else besides the study.

Design

Similarly to Hemmert's work [8], we used the phone's built-in vibration motors to create a heartbeat-like vibration pattern. Nevertheless, our study design has a number of methodological differences compared to [8], which we explain in the following paragraphs.

First, we fine-tuned the "heart beat" pattern during a series of pilot tests. Initially, we used patterns with fast repetitions of the vibration pulse, however, our pilot study participants found this to make them nervous. The final pattern, which is the result of iterative adjustments, consists of two short pulses separated by a 500 ms pause. A 5-second pause separates two "heart beats". Participants of the pilot test considered this to be a calm and soothing pattern. The pilot test also confirmed that the pause between the pulses prevented quick adaptation, because between each pulse the skin has sufficient time to regain sensitiveness.
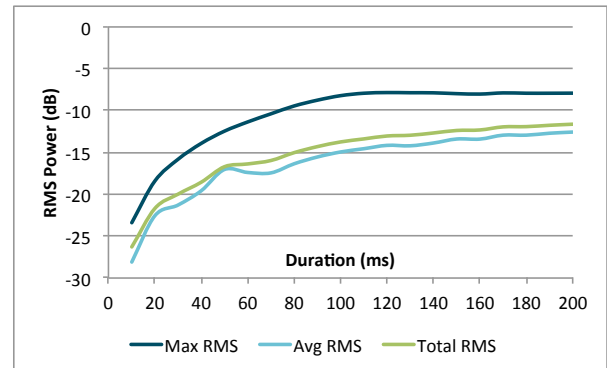

Figure 2. Objective vibration intensity (RMS dB) resulting from different vibration motor driving times (ms).

Second, another key difference in our study is the participants' proactive role in adjusting the vibration intensity according to their personal perception threshold, initially as well as throughout the study. By driving the motors for a few ms only, vibrations with lower-than-maximum time, different levels of intensity were created. As illustrated in Figure 2, the intensity grows logarithmically with increasing driving time of the vibration motor. The frequency remains stable around $208 Hz$. By operating a graphical slider on the phone screen (see Figure 1a), the participants could manually specify the vibration motor's driving time, and hence, the vibration intensity. We asked participants to keep the intensity at a level where they just barely perceive the vibration when sitting still.

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[1]see **http://pielot.org/?p=1178** for the test description

The third significant difference in our study is related to the detection of whether the vibration is perceived in the periphery of the user's attention. Hence, our aim was to alter the vibration pattern and probe if this alteration was perceived. In order to avoid attracting the user's attention due to changes in the vibration pattern, we chose the least salient change: stopping the vibration. By taking the stimulus away – from hereon called *Death Event* – participants could only notice its absence if it already was in their (peripheral or focal) attention. However, in contrast to [8], we opted for a longer time range of 15-60 minutes instead of 10-15 minutes for the Death Events to occur, in order to give the participants time to forget the vibration and avoid generating anxiety and expectation.

Forth, in the case of a Death Event, a button with the label "revive" became visible and participants were asked to acknowledge the event by pressing the button (see Figure 1 a). Conversely to [8], in our study the revive button triggered a short questionnaire, which allowed us to collect contextual factors via subjective feedback (see Figure 1 b). This step itself requires focal attention, but only after participants already became aware of the Death Event. Participants only reach this point when they are above the *preattention* level, which is required to consider the display to be acting on the periphery of attention. Hence, it is an opportunistic moment to collect qualitative information about participants' perception of the vibration without biasing their behaviour.

Fifth, as further means to investigate when the vibration becomes obtrusive, we introduced a snooze function. Whenever the participants pressed the Snooze Button on the main screen, the vibration paused for 30 minutes. The application then switched to the view shown in Figure 1 c, where the participants could voluntarily provide the reason for snoozing the vibration. In addition, the view offered a button to re-activate the vibration early if desired.

Finally, we used the phone sensors to log additional contextual factors. Our pilot tests showed that the perception of the vibration is strongly impeded by movement and the social context. As soon as our pilot testers started moving, the vibration was not perceptible anymore, and, in social situations, *e.g.* at lunch, the perception degraded as well. Hence, for each Death Event, we used the phone's sensors to record measures, such as the level of activity, that allow to make estimations about the context of use.

Measures

The activation of the Revive Button was used to measure how long it takes each participant to acknowledge each Death Event. *Revive Time* denotes the time span between a Death Event and the moment the Revive Button is pressed. If participants press the Revive Button immediately after a Death Event, we conclude that the vibration was on their focussed attention. On the other hand, if they press the button after a while, we conclude that the vibration was rather on their periphery of attention. We considered the following phases prior to pressing the Revive Button:

- *Inattention phase:* Ideally participants will "forget" the vibration stimuli, transitioning this perception to their peripheral attention. We expect this phase to take at least a couple of "heart beats". Given that every pair of pulses are separated by five seconds, we estimate a minimum of 10 seconds for this phase.

- *Suspicion phase:* In order to suspect a Death Event, one must wait at least more than five seconds without feeling the vibration.

- *Confirmation phase:* In order to confirm a suspicion of Death Event, one must wait at least another five seconds without feeling any vibration.

- *Reaction phase:* Finally the participant must take the phone out of his/her pocket, turn the screen on, switch to the vibration app, identify that a Death Event occurred, and press the "revive" button. In our pilot tests, subjects took between 5 seconds and 15 seconds to perform all of these actions.

Considering these phases, we estimate a minimum of 30 seconds between any Death Event and its detection by the participants in order to consider that the vibration was on the user's peripheral attention.

After pressing the Revive Button in the case of a Death Event, participants were asked to rate the agreement to the following statements in a three-point Likert scale (see Figure 1b):

- *I noticed at once when the vibration stopped*

- *I reacted immediately once I noticed*

- *In the last minutes, the vibration was annoying*

- *The device was pressed tightly against the skin*

In the pilot tests, we were using five-point scales for expressing the level of agreement to these statements. However, our testers did not find the extra-granularity useful and considered it to add extra complexity. Thus, in the presented study, we opted for simpler three-point scales.

Beyond the reaction times and the subjective feedback, we also collected the context of use through the phone's sensors. In particular, we used acceleration sensors to estimate the level of activity, the proximity sensor to detect when the phone's screen was covered, and we used the built-in microphone to collect the average noise level. To save battery power, these measures were only taken when a Death Event occurred. Thus, our measures reflect the participants' context of use when the Death Event was triggered.

Participants

We recruited 15 people (5 female) with an average age of 26.9 ($s = 4.1$) years who were willing to voluntarily participate in our study. They all worked with information technology in a multinational company and used to carry a smartphone on a daily basis. These people were all office workers, hence spending most of their time on a work desk or in meetings. To avoid biased feedback, we told them that we were revisiting a previous experiment and neither had personal feelings nor any assumptions about the study's outcome.

Procedure

We briefed each participant individually. First, we informed them that we were trying to investigate whether vibration can be perceived peripherally. Then, we handed them the phone with the vibration application installed. We asked participants to carry this device in addition to their regular phone, *i.e.,* to not consider it as a phone but as a "study apparatus". We allowed them to test different vibration intensity settings and to identify the intensity that they just barely could perceive when they were sitting still. Afterwards, we demonstrated a Death Event and a Snooze Event, and walked them through the corresponding questionnaires. Finally, we advised participants to continually keep the phone in their trouser pocket; whenever necessary (*e.g.,* when going to bed), they could simply take it off and shut down the vibration application (developed for the study). Participants were encouraged to contact us and give us feedback at any point during the study. By the end of the third day, we conducted an open interview to collect their impressions and thoughts.

RESULTS

We collected an initial pool of 370 Death Events and 53 Snooze Events. However, we could not consider all of the Death Events in the analysis. Some (N = 78) occurred when participants did not have the phone in their trouser pocket – and hence could not feel the vibration. Others (N = 134) occurred when they could not react immediately after noticing the event. Note that these reasons are not exclusive and can occur at the same time.

These events were considered invalid to analyse whether the vibration cue was perceived in the periphery of attention. Both situations, not having the phone in the pocket and not being able to respond right-away (*e.g.,* driving a car), led to prolonged response times even though the corresponding Death Events could have been noticed early on.

The valid dataset included therefore only the 195 Death Events in which participants agreed to the statements *"I reacted immediately once I noticed [that the vibration stopped]"*, and *"The device was pressed tightly against the skin"*. In the following, we describe the analysis of these 195 Death Events, the 53 Snooze Events, and the qualitative feedback we received from our participants.

Vibration Intensity

The participants set a wide range of vibration intensities during the study. Figure 3 shows the histograms of vibration frequencies as recorded right before each Death Event. Intensities ranged from 10 to 200 ms, with an average of 56.5 ms ($s = 39.8$, $\tilde{x} = 40$ ms). We found a wide spread of vibration intensities used by the participants. The highest peaks can be found around 30 ms and 80 ms. At the same time, the wide range of intensities can be explained by the fact that the perception depends a lot on how the phone is worn.

Death Events

Participants did not feel annoyed by the vibration. According to the subjective responses collected with the "revive" questionnaire, participants disagreed with the statement *"In the*

last minutes, the vibration was annoying" in 184 (94.4%) of the valid Death Events (see Figure 4).

In terms of subjectively being aware of the vibration, participants in most cases did not agree to the statement *"I noticed at once when the vibration stopped"*: 67.7% disagree, 14.4% neutral, 17.9% agree (see Figure 4).
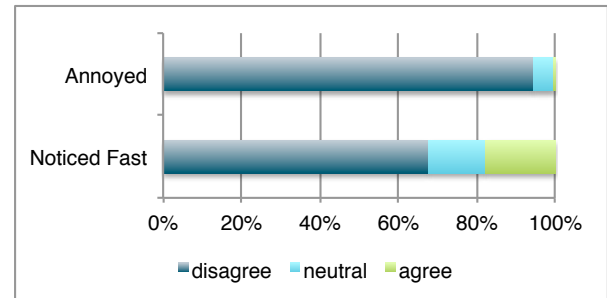

Figure 4. Responses to the questions Annoyed – *"In the last minutes, the vibration was annoying"* – and Noticed Fast – *"I reacted immediately once I noticed"* ($N = 195$ Death Events).

Finally, our analysis of participants' reaction time indicates that the vibration was indeed actuating on the periphery of users' attention. Figure 5 shows how fast participants acknowledged Death Events. Overall, participants did not acknowledge these events immediately – as if vibration was on their focussed attention –, but rather in 15.2 minutes in average ($\tilde{x} = 8.3$ min, $s = 19.6$). More precisely, in only 12 events (6.19%) participants responded within 30 seconds, which means that in the majority of the cases vibration was on the periphery of the users' attention. Moreover, 13.4% and 56.2% of events were acknowledged by our participants within 1 minute and 10 minutes, respectively. All but five (97.4%) events were acknowledged within 1 hour.
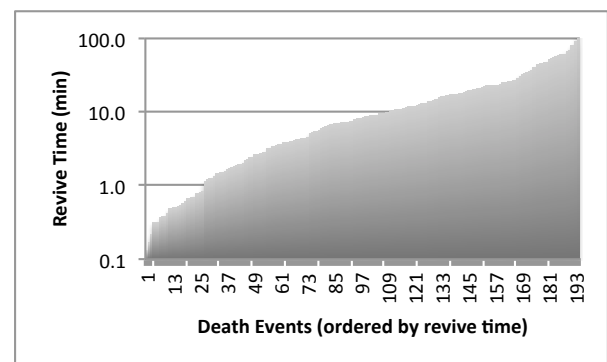

Figure 5. *Revive Time*: time span between Death Event and its acknowledgment by the participants (Y-axis in logarithmic scale).

Snooze Events

We recorded 52 Snooze Events, which equals 3.47 snoozes per participants or a little more than one occurrence per day per participant. Out off these events, participants annotated 24 with a reason for snoozing the vibration. Usually, the annotation consisted of a single word. Below, we list topics and frequencies of the annotations:
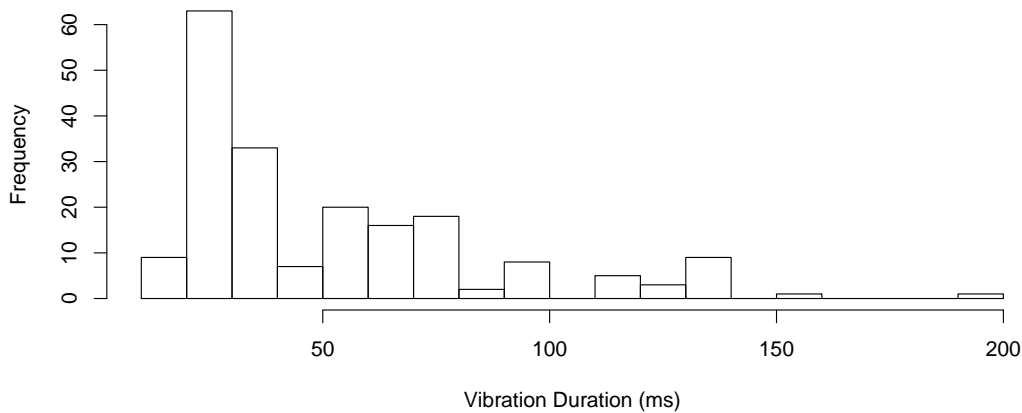
Figure 3. Histogram of the used vibration durations (ms) before each Death Event.

- Seven comments indicated *accidental use* of the snooze function (*e.g., testing*).

- Five comments indicated the *need* to concentrate on other activities (*e.g., could not concentrate*)

- In five comments, *other activities* such as *dinner, concert, drunk, hug boyfriend, and play with cat* were named as the reason for snoozing the vibration.

- Four times, the participants commented with the word *annoyed*, indicating that the vibration was considered obtrusive.

- In three of the snooze events, the participants put getting *nervous* as reason.

Except for *accidental use*, all other 17 annotations may seen as indicators that the vibration was in the focal attention of the user. Assuming that the non-annotated snooze events have similar reasons, each participant, in average, may have snoozed up to two times because of the vibration being in the focus of attention.

Contextual Factors
Figure 6 shows the table of correlations between the measures. Since most of our data was not normally distributed, the correlations are given in Spearman's ρ. On the following, we only discuss the statistically significant correlations.

The time the participants were exposed to this vibration stimuli was one of the most significant contextual factors. We found a medium correlation ($\rho = .44$) between the up-time, *i.e.* the time the application was running during the day, and the vibration intensity. This means that the longer the app was running during each day, the higher the participants set the vibration intensity. Similarly, we also found a strong correlation ($\rho = .63$) between the number of the Death Event a participant experienced, and the vibration intensity. These

findings indicate that the more time the participants were exposed to the vibration stimulus, the higher they adjusted its intensity. (see Figure 7). While at first glance this may appear to be a result of adaptation, adaptation typically happens within seconds or minutes. Here, we are observing a continuous increase even over days, including the nighttimes without stimuli, which should have been sufficient to reverse all adaptation effects.
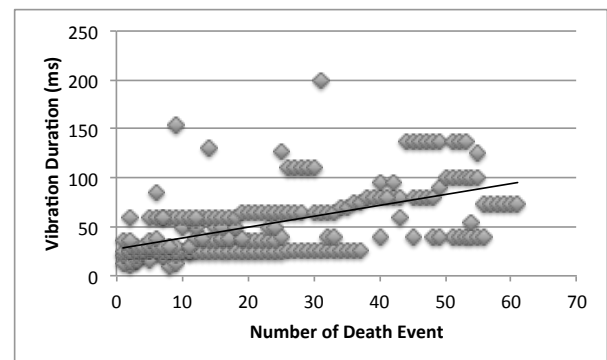

Figure 7. There was a strong correlation between the number of Death Event and the vibration intensity. Apparently, the longer a participant took part in the study, the higher s/he sets the vibration intensity.

Also, the (negative) correlations between exposure time and the subjective ratings of being *annoyed* ($\rho = -.29$) and quickly *noticing* Death Events ($\rho = -.31$) indicate that with time the stimuli were moving further into the periphery of attention.

We found a strong correlation between how fast subjects objectively and subjectively acknowledged Death Events ($\rho = -.50$). The faster the subjects responded, the more sure they were that they actually had responded fast. This is an indicator of the awareness of the absence or presence of the stimulus.

	Vib. Intensity (ms)	Revive Event (#)	Time 'til Death (min)	Revive Time (ms)	Noticed	Annoyed	Activity (m/s2)	Proximity (cm)	Noise Level (dB)
Uptime (ms)	**0.44**	**0.57**	0.03	-0.11	-0.02	**-0.28**	**0.20**	0.10	-0.12
Vib. Intensity (ms)		**0.63**	0.05	0.04	**-0.14**	**-0.25**	0.06	-0.10	0.03
Revive Event (#)			0.04	0.04	**-0.31**	**-0.29**	0.08	0.04	0.03
Time 'til Death (min)				-0.04	-0.03	-0.09	0.02	-0.12	-0.04
Revive Time (ms)					**-0.50**	0.13	-0.02	0.10	0.11
Noticed (3-point scale)						0.07	0.06	-0.02	-0.03
Annoyed (3-point scale)							0.12	**0.20**	0.05
Activity (m/s2)								**0.58**	**0.29**
Proximity (cm)									**0.16**

Figure 6. Correlation Table: *uptime (ms)* = the time that the application was running since start in the morning, *vib intensity (ms)* = the vibration intensity, *revive event #* = number of revive event (per user), *time til death (min)* = time the vibration is active until a Death Event occurs, *revive time (min)* = time it took the participant to react to a Death Event and press the Revive Button, *noticed (3-point scale)* = how fast user subjectively noticed the last Death Event, *annoyed (3-point scale)* = how annoyed the user is about the vibration, *average activity* (m/s^2) = acceleration indicating the level of activity, *average proximity (cm)* = output of the phone's proximity sensor, *average noise level (dB)* = noise level in dB. Correlations were calculated using Spearman's Rho due to the presence of ordinal variables (*i.e.* noticed, annoyed) and interval variables that did not follow the normal distribution. Bold coefficients are statistically significant at $p < .05$. Background colour visually illustrates the strength of correlations.

There was a small correlation between *proximity* and *annoyed* ($\rho = .20$), *i.e.*, the more annoyed the participants were, the more likely it is that the display was not completely covered. We also found correlations between the contextual factors themselves: the more active the users were, the more tight the phone was stored in the pocket, and the higher the recorded noise level was (see lower right corner of Table 6). This may be an indicator that the tighter the phone is stored in the pocket, the more its sensors become sensitive to activity and noise. However, we could not identify significant correlations between contextual factors and the perception of the vibration stimulus.

Participants' Comments
Since the participants were encouraged to provide comments at any time, we collected qualitative feedback as well. Below, we summarise the topics that were brought up by more than one participant in these interview.

First day stress
7 participants stated that initially they found the vibration annoying, but that this feeling disappeared over time. The explanation given is that people initially felt the urge to comply to the study, *i.e.* react fast to the phone's death. Once this feeling had been overcome, the stress disappeared as well.

Users get used to vibration over time
7 participants reported that their perception of the vibration decreases over time. They had to increase the vibration intensity to still be able to perceive the vibration signals.

Mental focus reduces vibration sensing
5 participants added that focussing on other things, such as reading or writing, made them more likely to forget about the vibration.

Physical activity impairs perception
5 participants noted that the perception of the vibration strongly depends on the level of activity. The more active they are (walking, running) the less likely they are to perceive the vibration.

Vibration can be tiring
2 participants stated that they found the vibration tiring for the initial time where they felt that they had to actively pay attention to it.

Triggers old usage patterns
2 participants usually carried their phone in their pocket and used the vibration alarm to keep aware of incoming messages. These two stated that the vibration triggered their habit of checking for such incoming messages.

False positives
2 participants reported from instances, where they thought the vibration was off, when in fact it was still running.

DISCUSSION
We collected 370 Death Events of which 195 were used for analysis. Our participants used a wide range of vibration intensities, and tended to increase the intensity over time. Of the analysed Death Events, *i.e.* the random stop of the vibration, the majority were acknowledged between 1 minute and 10 minutes. Participants hardly reported to be annoyed by the vibration and mostly felt that they did not notice Death Events immediately. Snoozing the vibration for 30 minutes was used 53 times, mostly because participants wanted to fully focus on other tasks. There were no statistically significant correlations between the logged contextual factors and how fast participants acknowledged events. Qualitative feedback indicates that after a short adjustment period the participants

were not annoyed by the continual vibration stimulus, and that physical and mental activities decrease the awareness of the cue.

Our study findings support **H1** (*participants will not be annoyed by the vibration stimulus*). In the subjective feedback, participants disagreed with being annoyed with the vibration in the majority of cases (94.4%). This is strong evidence that the vibration stimulus was not in the focus of the participants' attention. Further, participants in average only triggered two snooze events (= 60 minutes of muting the vibration) during three days of participation each. This shows that, in general, the vibration was not distracting (bear in mind that even the ticking of a clock can sometimes be annoying to a person trying to concentrate when reading in an otherwise quiet room). The qualitative feedback indicates that primarily in the beginning the vibration cue tended to be annoying. However, after a while this feeling disappeared, indicating that with time the cue was not in the subjects' focussed attention anymore.

Our results also confirm **H2** (*participants will not immediately notice the absence of the vibration*). Participants acknowledged only 6.19% of Death Events within 30 seconds and 13.4% events within one minute. Assuming that participants would have to acknowledge a Death Event within the first 30 seconds in order to consider that the vibration cue was in their focal attention, we conclude that hardly any of the Death Events was noticed immediately.

H3 (*participants will notice the absence of the vibration in a reasonable amount of time*) is also confirmed by the results. The majority of the Death Events was acknowledged within 10 minutes. At the same time, only a few events were acknowledged so fast that the reaction time would indicate focused attention. These findings are inline with the definition of peripheral displays *two things must be true: 1) the interface is communicative, at least some of the time, and 2) it is not in the centre of the users attention, most of the time* [14]. Therefore, in the majority of the events, participants' response times were long enough to let us conclude that the participants were aware of the vibration cue, and that it was perceived in the periphery of their attention.

Our findings are in contrast with those reported by Hemmert [8], since in his work 44% and 55.9% of the Death Events were acknowledged within 30 seconds and 1 minute, respectively. This indicates that in [8], the vibration cues were mostly in the subjects' focussed attention. This is supported by the fact that most of the participants reported to be annoyed by the cue. A couple of reasons could explain these contrasting results. First, [8] did not disclose the methodology to adjust the vibration intensity according to each subject's personal detection threshold. Presumably, the vibration intensity was too high so that the vibration kept attracting focussed attention. In our case, participants set the vibration themselves before and during the study, aiming to adjust the cue intensity to their own sensitivity levels. And second, since in [8] the Death Events occurred in a more predictable pattern (every 10 to 15 minutes), their participants may have stayed alert throughout the study. In our design however, Death Events followed a "more random" pattern, given the longer

time interval in which these events occurred (every 15 to 60 minutes). We expect that these design details played an important role in letting our participants eventually forget about the vibration stimulus, thus allowing it to enter their peripheral attention.

Regarding the context of use, we could not identify objectively measurable factors that influence the perception of the vibration stimulus. However, participants' subjective feedback during the post-study interviews indicate that the main contextual factor was related to the different levels of concentration demanded by various tasks performed during the day. This is in accordance with Constanza *et al.* [4], who argue that focussing attention on one task means that there are less attentional resources towards environmental, ambient cues. Hence, even a peripheral display actuating on divided attention may be too demanding if a person's full, undivided attention is required elsewhere.

A general limitation of research on peripheral interfaces is the complexity to reliably measure when a display conveys information via inattention or divided attention, *i.e.,* when the display is attended subconsciously versus being glanced at in regular intervals. In our study, four participants reported that, at times, they mentally "glanced" at the vibration cue. Nevertheless, the vibration cues were mostly not in the centre of the users' attention most of the time, which is in accordance with MacLean's definition [14] and the idea of a minimally attended display [16].

Our findings corroborate that vibro-tactile stimuli can be consumed in the periphery of attention. The main implication is to explore real-time vibration-based peripheral displays, exemplified by the use case scenarios in the introduction of this paper (i.e. feedback on audience engagement, work intervals, activity while out-of-office, etc.). Yet, the continual "heart beat" approach presented in our study should be considered as a means to investigate the feasibility of vibro-tactile peripheral displays, rather than a final design for an application of that kind. We hope this initial step motivates the scientific community to further study the boundaries of people's peripheral attention, propose novel ways to convey information requiring minimal focal attention, identify compelling use cases, and reveal the best contexts and design settings to apply peripheral vibro-tactile cues.

CONCLUSIONS

The study we have presented provides evidence that vibro-tactile cues can be consumed in the humans periphery of attention. For several days, we exposed people to continual vibration stimuli and studied how they reacted to the disappearance of this cue at random times. The reaction times and the participants' subjective feedback indicate that the stimuli were perceived in the periphery of their attention, while the subjects remained aware of it.

Consequently, we have shown that vibro-tactile stimuli have the potential to create private peripheral user interfaces. Hence, wearable tactile displays or mobile phones can be used to continually convey non-critical status information in a private, minimally-attended way.

Future research will explore potential use-case scenarios to leverage the implications of this study, in particular, which kinds of information to present, and how to be best convey it without requiring focal attention. Further, a deeper understanding on what contextual factors influence the perception of the cue is needed, so that eventually vibro-tactile peripheral displays can automatically adapt their saliency to the context of use.

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