A Wrist-Worn Thermohaptic Device for Graceful Interruption

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Abstract. Thermal haptics is a potential system output modality for wearable devices that promises to function at the periphery of human attention. When adequately combined with existing attention-governing mechanisms of the human mind, it could be used for interrupting the human agent at a time when the negative influence on the ongoing activity is minimal. In this article we present our self-mitigated interruption concept (essentially a symbiosis of artificial external stimuli tuned to existing human attention management mechanisms) and perform a pilot study laying the ground for using a wrist-worn thermohaptic actuator for self-mitigating interruption. We then develope a prototype and perform an insightful pilot study.

We frame our empirical thermohaptic experimental work in terms of Peripheral Interaction concepts and show how this new approach to Human-Computer Interaction relates to the Context-Aware-systems-inspired approach “Egocentric Interaction” aimed at supporting the design of envisioned Wearable Personal Assistants intended to, among other things, help human perception and cognition with the management of interruptions.

Keywords. Thermal Haptics, peripheral interaction, notification, interruption.

1 Introduction

Historically, access to information beyond what you can see and hear, here and now, has been something only for the privileged. The printing press, diffusion of literacy and increased level of general education has together with information technology (e.g. mass produced books, TV, computers, smartphones) almost reversed the situation, leading to increasing situations of “information overload” where access to information hampers our actions and decision-making rather than simplifying it. Today, knowledge and resources are needed *to keep information out.* The conscious human mind is not made for concurrent tasks and generally works best when focus can be maintained on one thing at a time. A possibility increasingly diminishing because while the recent advent of mobile and wearable tools for communication has boosted the possibility of sharing information independently from place, it has also brought with it an increased risk for users to be interrupted at a bad moment such as when carefully prepared or focused work is being done.

The work presented in this article belongs to the set of efforts that aim at reducing unwanted interruptions by making the mobile/wearable devices that cause the interruptions “smarter”. Inspired by recent work in peripheral interaction, our approach to graceful interruption management is based on the idea of a carefully designed symbiotic interplay between the existing interruption management infrastructure in our brains, and the digital devices that want to draw our attention. The rational behind this approach is that by partially offloading interruptability decision making to biology (the part of our brains that has evolved to do exactly that), the need for sensing and modelling the situational context of the human agent (e.g. ongoing and recently performed activities, nearby entities, nearby other human agents) would be reduced. While this implicit user interface design approach certainly faces its particular challenges due to how volatile, multimodal, and sensitive human attention is, the classical context-awareness approach e.g. to determine interruptability based on tracking and modelling physical phenomena in the vicinity of human agents have also proven to be very hard indeed. While the two approaches obviously complement each other, we do in this article focus on the challenge of interfacing to the human attention system and this through an as of yet very unexplored modality within Human-Computer Interaction: thermohaptics.

The haptic modality has some properties that makes it particularly interesting for graceful interruption and peripheral interaction in general, including the minimal interference with potentially ongoing everyday tasks (perceptionally, cognitively, socially) and the relative ease in which haptic information can be generated by wearable and mobile devices. We present a pilot experiment in which we investigated the feasibility of thermohaptics for graceful interruption, using a wrist-worn thermohaptic actuator through which stimuli with varying intensity were generated.

2 Interruptions

The term “interruption” has received various definitions. In this article, we adhere to Boehm-Davis and Remington’s who define an interruption to be “the suspension of one stream of work prior to completion, with the intent of returning to and completing the original stream of work” (p. 1125) [1]. The link between peripheral interaction and interruptions caused by digital devices is strong. We find it reasonable that if the information associated with a specific notification is important and urgent, the interrupting notification should demand focused attention whereas a notification that represents an equally important but not urgent message should be delivered using a method that targets the periphery of attention. In the remaining parts of this section, we will highlight some effects that external interruptions from mobile and wearable devices can have in everyday life as well as the role modality, intensity, and timing of the interruptive stimuli plays.

2.1 An Increasing Problem

While interruptions caused by body-external events can be regarded as natural and unavoidable in a world were human agents switch between individual and collaborative activities as part of everyday life, there is no shortage in research identifying the negative side effects that interruptions can have. These include the negative effects interruptions have on a person's rate of performing tasks [2], their impact on the ability to drive safely [3], and an increase in associated accidents by healthcare providers [4,5]. Mark et al. found that workers compensate for interruptions by increasing work rate and maintaining work quality but experiencing an increase in stress, frustration, time pressure and increase in effort [6]. Much of this research findings stem from investigating subjects performing a focused activity, often with high risk of failure. In more open-ended settings, the findings of interruption studies are less clear. O'Conaill and Frohlich found that the interruptee benefits in some way from most interruptions and that the benefits offered are not balanced between interrupter and interruptee and are not consistent [7].

As mentioned in the introduction section, we believe that the increased use of mobile and wearable communication devices, apart from all the obvious positive effects, potentially threatens the well-being of people by the increased exposure to unwanted interruptions, resulting in for instance increased stress and stress-related diseases.

2.2 Social aspects of interruption

Audio-based mobile device interruptions can have a negative impact on the social context of the person receiving the interruption. Kern and Schiele use the concept of social interruptibility and give the following reasoning, "A notification does not necessarily reach the user only. An audio alarm can also be perceived by the environment; a potentially embarrassing situation, e.g in a lecture." (p. 3) [8] From Hansonn et al. we can see that "Auditory cues for mobile devices are typically designed to attract maximum attention to be able to penetrate even a very noisy sound environment. The notification in itself requires the recipient to, more or less instantly, direct her attention towards it. " (p. 2) [9].

Exteroceptic (body-external) haptic notification stimuli such as vibration or heat changes caused by devices in direct or indirect contact with the skin have clear social advantages over audio for notifications directed to single individuals by being perceivable only by the intended recipient.

2.3 Time

Interruptions (whether triggered internally or as in the case of our experiment, externally generated) can occur more or less frequently, resulting in "concurrent" multitasking when task switches are forced to occur every other second and "sequential multitasking" when task switching happens with hours in between [10].

Our approach to interruption management on envisioned future wearable devices is in practice an indirect manipulation of the point in time when the interruption stimuli is consciously noticed and causes a task switch. The point in time when an interruptive stimuli is noticed is hypothetically to be determined by on the one hand the thermohaptic stimuli intensity controlled by the notification system and on the other hand the human attention management system embedded in our brains which filters out unimportant stimuli.

While cognitive psychologists are still debating the exact inner workings of human attention, as designers of interactive systems we allow ourselves to treat it very much as a black box. In this article, we present our initial attempts in determining how this black box responds to variations in stimuli intensity and cognitive load and whether we can successfully incorporate its behaviour in future design of interactive systems.

3 Talking to human attention

It is clear that graceful interruption demands a more careful approach to human attention than the brute force override taken by most mobile systems to day (e.g. the loud audio-based ringing tone of cellular phones). As designers of interaction systems that perform interruptions, we need to take the human attention system more seriously.

Although our brain, body, and perception system operates in a highly parallel fashion, we consciously attend to only a very limited set of these processes. Much control of body and thought is automated and thus escapes our conscious mind. Human attention is indeed very much a "one thing at a time" phenomenon. However, since different body functions (e.g. the perception of different sensory modalities) are handled by different relatively independent parts of our brains, psychologists have found that perception, cognition, and action involving mutually independent control centres (cognitive resources) can indeed be successfully monitored and controlled by our brains in the grey-area between conscious and unconscious attention. Hausen shows a simplified model of human attention [11] based on divided attention theory [12], illustrating how various factors (including the availability of cognitive resources) influence whether human attention is directed towards a given stimuli or not.

Our sensory system seems to have a modality-based distribution over centres in our brain which allows for multitasking without reduced cognitive performance as long as, put simply, modalities (e.g. touch, vision) used in the different activities do not overlap [13]. Bakker illustrates our ability to distribute attentional resources over more than one task in parallel as long as none of them are too demanding [14]. Most attentional resources are allocated to the primary (center) task of preparing dinner but some are also devoted to secondary (peripheral) tasks: listening to the radio and monitoring the dishwasher; cognitive resource allocation.

3.1 Potato peeling + radio = true

Cognitive resource allocation is very dynamic and changes instantly as a result of for instance external stimuli changes. For instance, if the hypothetical preparing dinner task enters into a habituated/automated phase (e.g. peeling potatoes) the radio the radio program is more likely to substitute the dinner preparation as primary task. If the two tasks are swapped again at a later stage (the dinner preparation task becomes central and the radio listening task becomes peripheral), without negative impact on neither tasks, we have a win-win situation where the dinner both tastes great and was fun to prepare. The radio “interruption” was graceful by adding value without negatively impacting the primary task. It worked, in part, and according to Multiple Resource Theory [13], because the sound modality is not very important as feedback when peeling potatoes and (we assume) our protagonist to be a fairly avid and experienced potato peeler.

Peripheral interaction as proposed by Edge [15] and further developed by Bakker [14] and Hausen [11], is a design approach aimed at allowing for peripheral perception and/or manipulation of artefacts without significantly drawing attention from another primary task. As such, the peripheral interaction design approach is a promising and fresh take on the design of interactive systems that integrate themselves into everyday real world activities. Drawing from the interaction design discipline which traditionally tend to emphasise the shape and behaviour of single artefacts, most existing prototype designs are however limited to HCI dialogues based one a *single* (potentially multimodal) system that interacts with a user.

Coming from the Ubiquitous Computing discipline ourselves, and envisioning an increasing amount of digital services (from different manufacturers and service providers) that call for our attention, we have found it necessary to conceptualise future HCI as an interaction paradigm consisting of *many* artefacts (including everyday objects, digital devices, and services). This is the situation our “users” are facing and we might as well aim at modelling this somewhat chaotic situation also as system designers. The case for interruption management is a good example of an interaction design challenge that calls for this kind of holistic perspective.

4 Wearable Personal Assistants

Any interruption management mechanism that is implemented in a mobile or wearable system will be effective only to the degree it is aware of, and can control, the sources of interruptions affecting the person carrying/wearing the device. Just like today’s mobile phones are used as central portal to sources of information on the Internet to provide various services, we envision Wearable Personal Assistants (WPAs) [16] to act as a central bottleneck through which the majority of digital services need to push any potentially interrupting notifications. In fact, modern smartphones can be considered to be early instances of WPAs, having started to offer certain explicit control to their users with respect to which digital services that should be allowed to make use of what notification modality and under which circumstance. We think that this is just the beginning of the development of future more advanced interruption management mechanisms.

4.1 A filter and a torch

Our long term goal is to build Wearable Personal Assistants (WPAs) that facilitate, for a given human agent, performing the activities s/he wants to perform in short and long term by suppressing currently irrelevant information from perception/cognition and by highlighting the relevant. Thus the WPA would need to be somewhat aware of and capable of influencing processes taking place both in the local physical (real environment) and in the digital domain on the Internet or local computing devices. Apart from this need to sense external context, it is clear that a good interface towards human attention processes is necessary as well. We think peripheral interaction theory and our own work on egocentric interaction are good conceptual stepping stones towards framing this kind of human-computer interaction dialogue that partially will take place without the “user” being consciously aware of it.

4.2 Perception-Cognition-Action Loop

To design wearable personal assistants (WPAs, to be discussed in detail in the next section) we developed a simple interaction flow model in the spirit of classical HCI dialogue models but with emphasis on the interplay between human perception, cognition and action on the one hand and the environment and the wearable assistant on the other (Figure 1) [16].

Unconscious Perception By and large, our perception of the world (pathway 2-4) and our perception of body state (arrow 5) is beyond our conscious control. The filters in Hausen’s model are some of the mechanisms, symbolized by arrow 12 in the figure, that are at work. However, conscious cognitive processes influence unconscious processes (arrow 7), as in the case when we deliberately address our attention to a certain speaker in a crowd and we automatically (thanks to subconscious processing), to some degree, can single out the voice we are interested in. We can also consciously and indirectly affect unconscious processing by orienting our body sensors (e.g. vision) towards phenomena of interest (pathway 8-10-2-4).

Unconscious Cognition Human cognition is divided into unconscious and conscious processing (arrows 12 and 13 respectively in Figure 1), receiving input from sensors capturing in-body phenomena (e.g. proprioceptive information about limb positions; information for maintaining homeostasis) and from sensors capturing information from the external world. No world phenomena or in-body phenomena is subjected to conscious cognitive processing before having been unconsciously processed (pathways 2-4-6 and 5-6 respectively).

Action Human action is initiated and controlled by a mix of conscious and unconscious cognitive processes. An example of an activity mostly driven by an *unconscious* perception-cognition-action loop could be “walking” along a well-known road with no exposure to obstacles (pathway 2-4-9-10 & 11).

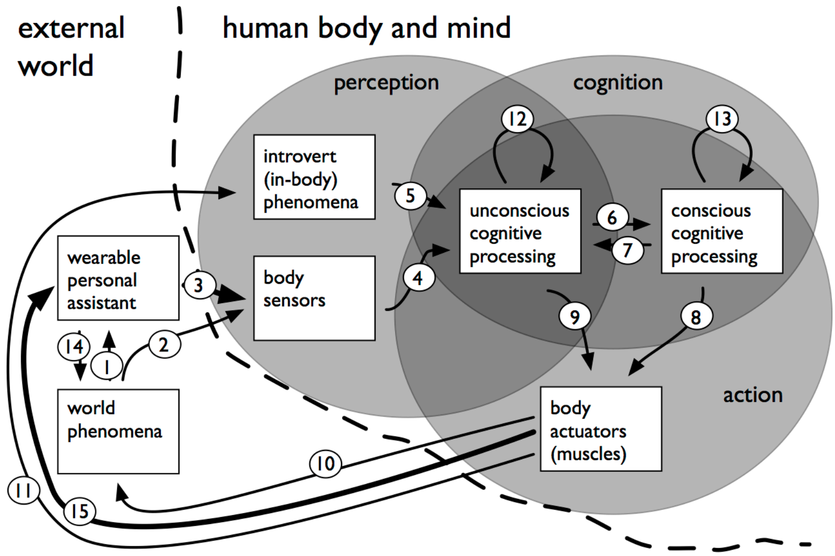

Fig. 1 A simple model of information flows occurring as result of a human agent acting in the world, partially supported by a wearable personal assistant. [16]

4.3 Self-mitigated interruption

There are many ways in which interruption management could be implemented in a wearable personal device such as a WPA. In this article we present our first investigation into using the thermohaptic modality for perceptually and cognitively graceful integration of notifications originating from digital services with ongoing tasks that the human agent is performing. The main idea behind the mechanism which we call "self-mitigated interruption" (see Figure 2) is to let the existing supervisory attentional system [17] play an important part in deciding whether a notification is to interrupt the current primary task or not, instead of primarily let the WPA rely on sensing and interpreting the context and then rather brutally call for attention. Note that we still treat the actual inner workings of the supervisory attentional system as a "black box" (see the discussion in section 2.3) and expect to learn a little bit about its behaviour as part of our experiment.

Of course, the self-mitigated interruption approach is modality agnostic. Our interest in the thermal modality is motivated by the fact that it is a modality rarely explicitly used in everyday activities and thus a potentially very useful information channel for interruption by not intruding directly into modalities that might already "be in use" [13].

4.4 Human haptic perception

Richter [18] distinguishes among three kinds of haptic perception: interoception, proprioception and exteroception. Interoception handles the state of the internal organs which we are most of the time not consciously aware of, driving for instance the feeling of hunger and pain [11]. Proprioception deals with the limb and digit joint position as well as the balance and orientation sense provided by the inner ear. Both interoception and proprioception are represented as “introvert in-body phenomena” in Figure 1. Finally, and of most relevance to us in this article, exteroception relates to stimuli coming from outside of the body and includes the sense of touch, vibration, and temperature differences. Haptic exteroceptic information is acquired by the human sensory system through perceptors sensitive to pressure and temperature changes occurring for instance when we manipulate objects with our hands [19].

4.5 Thermal haptics

Thermal haptics ties together psychophysics (the branch of psychology concerned with the perception of stimuli), engineering and Human Computer Interaction. This subsection introduces psychophysics, prior work in thermal haptics and a motivation for using thermal haptics in a wrist watch type device.

Early psychophysics research showed that human bodies do not sense temperature as thermometers do, but rather sense the change from neutral skin temperature [20]. The slightest change that a person performing a psychophysics experiment reports is called the just noticeable difference (JND).

Temperature changes are perceived by cold receptors and warm receptors. Cold receptors are more numerous than warm receptors by a ratio of up to 30:1, and respond to decreases in temperature over a temperature range of 5-43°C [21]. Warm receptors discharge with increases in skin temperature reaching a maximum at temperatures of around 45°C [22].

The JND changes as a function of rate of stimulus change [23] and with spatial summation [24]. A faster rate of change or a larger surface area allows for a smaller temperature difference to be sensed. JND also depends on the position of stimulation on the body with hairless skin (e.g fingertips and palms) being less sensitive than hairy skin, and areas on or near the trunk more sensitive than the extremities [25].

Psychophysics experiments are normally performed in a controlled setting with the participant dedicating time and attention to the experiment, this is unlike the highly variable set of contexts in which pervasive computing takes place. A factor largely ignored in thermal haptic notification research thus far is the level of cognitive when a thermal stimulus is generated. Arroyo and Selker used heat and light based ambient displays for providing interruptions. They found that heat was slower to sense but harder to ignore once sensed than light, that heat was more disruptive than light, and that heat could be perceived than invasive to private space but was able to communicate to a person privately [32].

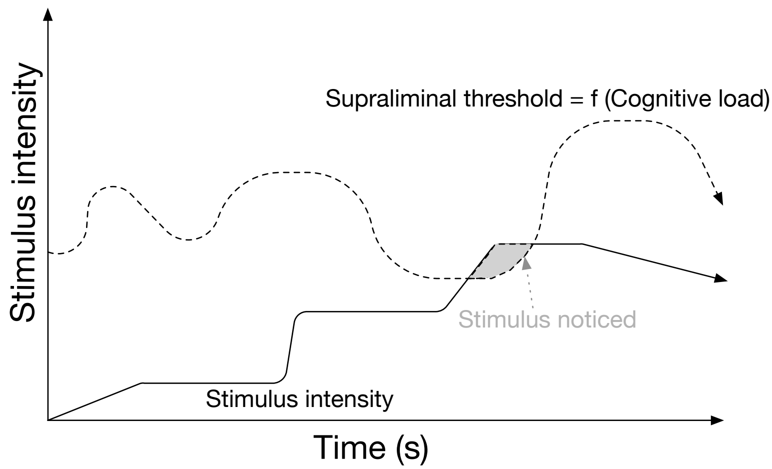

Fig. 2 Principle of self-mitigated interruption: The intensity of the stimulus (represented by the solid line) and the supraliminal threshold (represented by the dashed line), which is dependent on level of cognitive load, determines whether the stimulus gets consciously noticed. By increasing the stimulus intensity level, the likelihood of the stimulus being noticed increases.

5 Why a Wrist-Worn Thermohaptic Device?

While the haptic modality is abundantly used as part of explicit input to interactive computer systems (e.g. we *grab* the computer mouse and we *click* its buttons), haptics is less frequetly used in the other direction. Currently the most common use as a system output is probably as “silent ring tone” vibration on phones.

As pointed out by both Bakker [14] and Hausen [11], wearable interactive computer devices constitute a very interesting hardware platform for investigating peripheral interaction. While opening up the design space for graceful interruption mechanisms, wearable and mobile devices at the same time also contribute themselves to increase the risks for their carriers to become involuntarily interrupted due to the simple fact that these wearable devices are always there.

Wettach explored the use of thermal haptics for navigation and notifications, employing a resistive actuator that could only warm. The notifications worked well but navigation proved problematic [21]. Wilson et al. [25–28] and Halvey et al. [29–31] performed several studies using thermoelectric cooler based thermal haptic devices. Much of their work followed a psychophysics research approach (identifying level of detection, level of discrimination, etc) and they also included realistic device ecology considerations (how does it work while wearing clothing, outdoors, etc). Casio released a series of databank watches starting in 1980 with a wrist worn calculator, a dictionary and later with the 1984 release of a databank watch. The pebble smart watches broke new ground in 2012 when they introduced a consumer grade smartwatch to the market. This device connected to a smartphone and run host stand alone applications or act as a remote interface for applications that ran on the mobile phone. Various Android manufacturers (e.g. Samsung and LG) and Apple have also introduced smartwatches to their product lines. The history and the state of the art are evidence that the wrist is a most viable “home” for wearable computing.

Thermal stimulus was chosen for the prototype as it is a modality which allows for very subtle gradual changes (temperature takes time to change which makes it less startling than other modalities). Thermal stimuli are also completely private as it cannot be heard by somebody nearby the wearer (as is often the case with vibrotactile notifications).

Realistic scenarios where a wrist worn thermal notification could be valuable are for discrete notifications where the importance of the message is non-zero but also not very urgent or very critical (for instance, emails received during a lecture).

6 Experiment design

To investigate the feasibility of using a wrist-worn thermal haptic actuator for notifications, we produced a prototype and performed a pilot study where participants were also asked to respond to occasionally occurring thermohaptic stimuli.

The independent variables are: stimulus intensity, which is function of amount and rate of temperature change and direction (heating or cooling). In total, we have 18 different stimulus intensity for 2 directions (cooling and heating) × 3 change rates controlled by changing the fraction of time that the current is flowing (slow, medium, fast) × 3 temperature change amounts (0.5°C, 1.0°C and 1.5°C). The dependent variable is a binary variable indicating whether a particular stimulus was perceived.

To validate the prototype the following well-established psychophysics behaviours were tested: people are more sensitive to cooling than warming, people are more sensitive to high rate of temperature change than a low rate of temperature change, and lastly, that people are more sensitive to a higher overall temperature change than a low overall temperature change.

We recruited 15 volunteer participants (2 females) among local university students to participate in the experiment. All of the participants were right hand dominant. All of the participants completed the task within approximately 45 minutes.

6.1 Apparatus: wearable wrist worn thermal haptic prototype

We developed and evaluated a prototype wrist-worn thermal haptic system able to provide notifications to the person carrying it. The system consists of several components explained in this section, the wearable wristwatch device (Figure 3-B), the power controller (right hand side of Figure 3-A), and experiment software running on a computer.

Temperature differences are produced by the Peltier principle by passing electrical current through a Thermoelectric cooler (TEC).

Detailed system architecture for our system is shown in Figure 4 showing the components of the wearable device, the power controller and the computer. The power controller and wearable device are both connected to the computer.

Wearable wristwatch component The objective of this prototype was to realise wearable thermal haptic notifications whilst maintaining a somewhat realistic wearable device weight. The wrist device holds a microcontroller (Arduino ® Nano) and four thermistors (to measure the hot and cold sides of the TEC, the skin temperature of the person wearing the device, and the room temperature). Electronics are shown exposed in Figure 3-B and were covered with insulating tape for the experiment (Figure 3-A). Thermal contact with the skin is made by an anodised aluminium heat spreader. Residual heat is dissipated with a heat sink fitted to the back side of the Peltier. The microcontroller is programmed to be inherently safe with a safety feature to turn off the power if a thermistor wire break occurs or if the temperature exceeds 50°C or gets below 5°C.

We tried to minimise the size of the thermal haptic device to fit into a watch form factor; however, due to the physical limitations of the Peltier device and the power electronics, a large heatsink was required on the exposed side of the wearable device (black square in Figure 3-B).

Power electronics The temperature changes are produced using a thermoelectric cooler (described in Section 6.1). The amount heat flow is dependent on the magnitude of the current applied, to drive this a bidirectional current source is needed, this can be achieved using the H-bridge which is a switching device that allows a single power supply to drive an electrical load in both directions. To vary heat transfer rates, pulse width modulation (PWM) is used to control the magnitude of the current. PWM works by a switch being turned on and off, the ratio of time that the switch is closed (current flows) in a given period is varied to control the current to the load. The prototype power controller is shown on the right hand side of Figure 3-A.

Thermal Stimulus selection As explained in Section 4.5, a person's sensitivity to temperature change is a function of more than just the maximum or minimum temperature reached as. It is also a function of rate of temperature change, whether heating or cooling is performed, and the surface area of stimulation. In practice, the sensitivity to stimuli also depends on the contact pressure of the haptic device with the skin. It is also well known that there is between-subject variability in temperature sensitivity.

Initial device testing was using previously used values [25] to warm, and cool the skin temperature by 1°C, 3°C and 6°C, at two rates (3°C per second and 6°C per second).

During lab testing of the thermal haptic device the intensities were reduced to be appropriate to our wearable device (0.5°C, 1.0°C and 1.5°C). Additionally, it proved difficult to have a closed loop controller manipulate the temperature to have a consistent rate of temperature change as there was some heat transfer delay in the system. We decided rather to implement three fixed temperature change rates referred to in the rest of the paper as the heating rates "slow", "medium" and "fast", by manipulating the Duty Ratios for the heating and cooling (i.e. 38%, 50% and 77%), illustrated in the "power controller" in Figure 4.

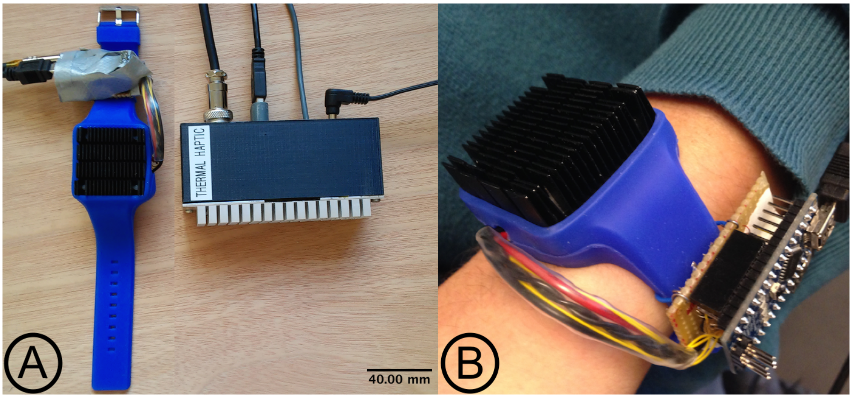

Fig. 3 A: Wearable thermal haptic notifier system. The wearable component is on the left and the power controller component is on the right, B: Thermal haptic notifier being worn.

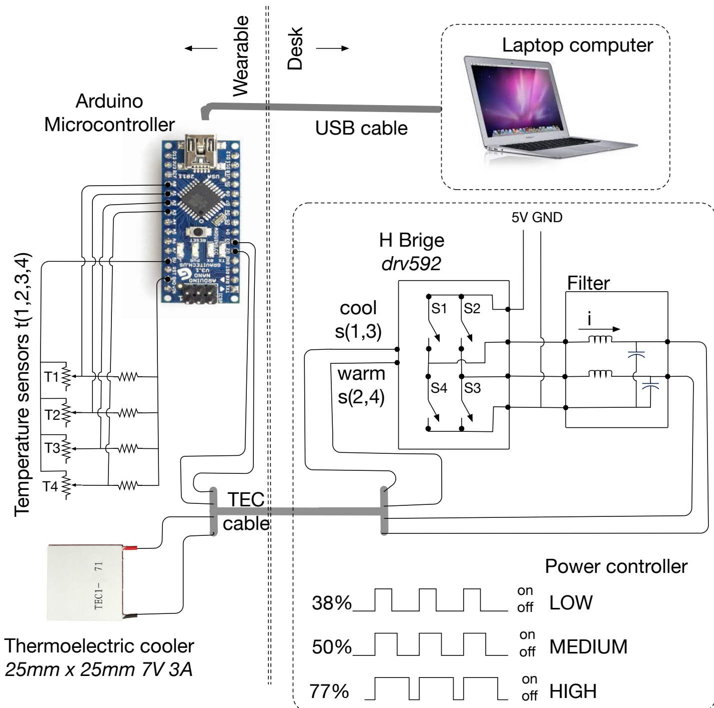

Fig. 4 System architecture diagram. The components of the wearable device are on the left side (Thermoelectric cooler, Arduino Nano, and 4 thermistor based temperature measurements. A simplified h-bridge is shown in the power controller block.

An Apple Macbook Air (2GHz i7, 8GB RAM, OS X 10.9.4) was used for the experiment. A Processing program generates thermal stimuli and logs keystrokes and temperature data.

6.2 Procedure

The experiment started with a short introduction to the task and to the use of the apparatus, but the main purpose of the experiment was not explained to avoid biasing the participants. The participants were told that they are participating in an experiment evaluating the thermal haptic wristband for notification purposes. After introduction the participants signed the consent form.

The experiment comprised three different sessions. The first session was training the participant to experience the thermal haptic stimuli. They were asked to wear the thermal haptic wristband on the non-dominant hand. This was a 5-minute training session where warming and cooling stimuli of different intensities were given along with a spoken cue from experimenter when the stimulus was presented. The objective of this is that the participant begins to understand the magnitude of the different stimulus types such that they are not startled or left unsure when sensing something during the experiment. After training session, they performed two 10-minute experimental blocks in which they were asked to respond to the thermal stimuli by pressing the space key. Only the findings from one of the experimental blocks is included in this article. The second experimental block contained a snake game and verbal communication with the participant for manipulation of cognitive load but was omitted from the study as this method was deemed inappropriate for our research questions after the experiment was concluded.

6.3 Design

The pilot experiment has a within-subjects design, each participant completed all conditions in one experimental session that lasted for approximately 45 minutes. In each condition, 18 stimuli were presented to the participants. The stimuli were presented in two different modes (cooling and heating), with 9 different intensities. The intensity of the stimuli was adjusted by 3 heating/cooling rates (slow, medium and fast), and 3 temperature changes (0.5°C, 1°C and 1.5°C).

7 Results

The data recorded in the experiment was in the form of a log file, every stimulus and keystroke was recorded. Post processing consisted of separating the stimuli and space-bar presses (participant senses thermal stimulus) from the rest of the data. If a participant pressed the space-bar within 10 seconds of the start of the stimulus, the stimulus was labeled as detected and as missed if no space-bar pressed occurred. Figure 5 shows the detection data for all of the participants. The variables are: direction (warm vs cool, between top and bottom sections), heating rates (left, middle and right plots) and temperature change (the vertical levels).

A repeated measure ANOVA is used to investigate the effect of each factor on number of detections. Post-hoc paired samples t-tests with a Bonferroni correction were used for pairwise comparisons ($\alpha = 0.05$).

Temperature changes: the number of detected notifications significantly varies with amount of temperature changes: $F(2, 14) = 5.354$, $p < .012$. The post-hoc analysis revealed that notifications with higher temperature change were detected more than notifications with lower temperature change.

Heating rates: the number of detected notifications significantly varies with the rate of temperature changes: $F(2,14) = 34.551$, $p < .0001$. The post-hoc analysis revealed that participants detected more notifications with faster changing rate compared to slower ones.

Direction: the number of detected notifications significantly varies with the direction: $F(1,14) = 146.689$, $p < .0001$. The post-hoc analysis revealed that participants detected more cooling notifications than heating notifications.

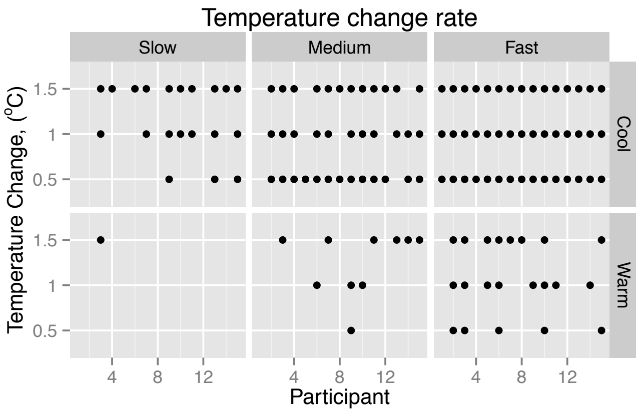

Fig. 5 Notification detection

8 Discussion & Conclusions

Trends were observed (Figure 5) where participants acknowledge more of the higher intensity stimuli than the lower intensity stimuli, and that cold stimuli were more effective than warming stimuli.

The results from our study indicate that for certain systems that generate potentially interruptive information, it might not be necessary to sense and process a large amount of contextual factors local to the receiver of a notification (the classical Context-Aware system design approach to graceful interruption) but rather to rely on previous knowledge about the specific wearers personal threshold for when a thermal stimuli transcends from being unconsciously perceived to consciously perceived (paths 3-4-9-10 and 3-4-6-8-10 in Fig. 1 respectively). In future studies, we will empirically investigate if sensitivity of human subjects to thermal stimuli varies with cognitive load. If we can find a sensitivity threshold for different cognitive load conditions, a context aware wearable device could rather rely on the human natural ability to discriminate between what is important and what is not, resulting in a mitigation of unwanted interruption.

In this article, we have presented the design and a first pilot experiment exploring the use of wrist-worn thermohaptic devices as mediators for graceful interruptions. We have grounded the proposed "self-mitigated interruption" approach in peripheral interaction theory and motivated it by the need to improve the situation for human agents in the emerging egocentric interaction paradigm where multiple devices (wearable, mobile, stationary) threatens to increasingly call for attention, on top of the focus demanded by current real world tasks. We have argued for why interrupting notifications from services should be handled in a centralised manner and exemplified a possible solution based on the concept of Wearable Personal Assistants. Further, we have argued for the use of wearable haptic actuators for notifications, in particular thermohaptic ones.

With respect to our empirical work, we can conclude that this initial exploratory experiment has validated our experimental setup and motivates us to perform a more focused experiment using our wrist-worn thermohaptic device in the future where we will reduce the number of factors to investigate, increase the number of participants, and calibrate for individual differences in stimuli sensitivity among participants.

With respect to theory development, we hope to have shown how existing peripheral interaction concepts resonate well with our own egocentric interaction vision, and that these conceptual frameworks have a huge potential in bringing (wearable) context-aware system developers and interaction designers together based on the huge overlap in interests.

Acknowledgements This work was supported by the EU Marie Curie Network iCareNet under grant number 264738.

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