A Haptic Wristwatch for Eyes-Free Interactions

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ABSTRACT
We present a haptic wristwatch prototype that makes it possible to acquire information from a companion mobile device through simple eyes-free gestures. The wristwatch we have built uses a custom-made piezoelectric actuator combined with sensors to create a natural, inconspicuous, gesture-based interface. Feedback is returned to the user in the form of haptic stimuli that are delivered to the wrist. We evaluated the capabilities and limitations of our prototype through two user experiments. One experiment verified that the apparatus could be used as a tactile notification mechanism. The other experiment assessed the feasibility of using a cover-and-hold gesture on the wristwatch to obtain numerical data tactually. Results from the numerosity experiment and feedback from participants prompted us to redesign the cover-and-hold gesture to provide users with additional control over the interaction. We qualitatively evaluated the redesigned interaction by handing the prototype to users so that they could use it in a realistic work environment. Taken together, results from the experiments and the validation process indicate that a wrist accessory can be effectively used to perform discreet, closed-loop, eyes-free interactions with a mobile device.

Author Keywords
Eyes-free interaction, non-visual gestures, wearable computing, haptic interface.

ACM Classification Keywords
H5.2 [User Interfaces]: Haptic I/O, Input devices and strategies, Prototyping.

General Terms: Human Factors

INTRODUCTION
Many of the interactions we have with our environment are predominantly non-visual in nature. We turn door knobs without looking at them; we flick light switches in the dark; and we shake hands without breaking eye contact. These examples, drawn from everyday activities, illustrate the role played by the physical interactions we have with the material world that do not rely significantly on our sense of sight. These interactions, however, are often overlooked when designing novel interactions for mobile devices.

Figure 1: The haptic wristwatch communicates with a mobile device through Bluetooth®.

In this paper, we introduce a custom-made haptic wristwatch that we have built. The peripheral is paired wirelessly through Bluetooth® with a mobile device capable of advanced functionalities such as email (see Figure 1). The watch makes it possible to, among other things, tactually acquire numerical information from the paired mobile device by performing simple eyes-free gestures. Our goal is to explore new and expanded mobile device experiences through the use of wearable tactile interactions.

Motivation
Typically, acquiring information from a mobile device, or configuring a device's settings, requires users to retrieve their device from a pocket, purse, or holster and turn on the display. These actions are obtrusive and relatively time-consuming. A wearable peripheral paired with a mobile device can provide simple, reliable and discreet methods to interact with the device through eyes-free gestures and tactile feedback. Consider the following scenarios illustrating some applications of such a peripheral:

Interpreting Many Notifications
Gerry, a very successful businessman, gets in excess of 100 emails a day that vary in level of importance. The result is

that his mobile device, which he has set to notify him of incoming emails tactually, is constantly vibrating to the point that he doesn't really pay attention to it anymore. A wearable peripheral could be configured to add a second layer of tactile notification, informing him only when an incoming e-mail is from a short list of contacts.

Changing a Ringing Profile

Wendy is presenting her research at a meeting when she suddenly realizes that she left her device, configured with a ringing profile, at her seat at the table. She wants to be able to ensure that the device will not disturb the meeting attendees with its notifications, but also does not want to disrupt the meeting by returning to her seat to change her settings. A wearable peripheral would be available to Wendy when the mobile device is not, and if it can respond to subtle tactile input, will allow her to change the profile discretely without interrupting the presentation.

Consulting a Schedule

Patricia, a real-estate agent, is giving her clients the tour of a property when she starts wondering about her appointment with her next clients. Retrieving her mobile device from her purse to check her calendar would be awkward and may appear rude. If she had a wearable peripheral to provide sophisticated non-visual numerical information, she could use it to determine her schedule without undue effort, and without being too inattentive to her current clients.

Wearable Tactile Interactions

Existing implementations of wearable interactions that make use of tactile feedback can be categorized according to where they fall on a continuum of user control. At one end of the continuum, users passively consume tactile notifications that are delivered to them. They have no control over when and how the stimulation is delivered. This type of interaction is exemplified in the first scenario above and is the subject of most research exploring tactual interactions with a user [2,18,25]. The other end of the continuum is composed of those active interactions that leave users in complete control. The last two scenarios are examples that fit closer to this active end of the continuum.

The device we introduce in this paper can play a range of roles that span over the entire continuum of wearable tactile interactions. However, we focused our efforts on the design of active interactions that provide the user with significant control. Specifically, we designed an interaction that embeds the delivery of the tactile signal within an eyes-free query gesture in order to communicate numerical data. We propose this as an alternative to the current model where users react to notifications. Instead, they actively query a device for relevant numerical information at their convenience, giving them full control. Because passive and reactive notification capabilities are still useful, they are also discussed and validated when appropriate.

RELATED WORK

The recent emergence of miniature sensors that are increasingly affordable and less power-hungry has enabled new ways to interface with mobile technology. Murray-Smith et al. introduced the idea of using a scratch-based gesture to control the basic features of a music player [19]. Their system is capable of distinguishing between scratch gestures, classifying them according to the sounds they generate on different surfaces. The audio is captured by a piezo contact microphone and processed through a digital signal processor. Skinput, a system designed by Harrison et al., also takes advantage of acoustic transmission, but this time through the human body [7]. Blasko and Feiner demonstrated how a pressure-sensor pad made of independent and reconfigurable logical strips could be used to control more than a dozen widget parameters with a single hand [4]. Their system supported interactions with minimum requirement for visual feedback, such as the dynamic resizing of buttons.

The development of more sophisticated sensors also enables the exploration of new eyes-free interaction metaphors. Brown and Williamson designed the Shake2Talk mobile device by which users can create non-visual messages through simple gestures such as flicking the device or stroking one of its capacitive sensors [5]. The audio-tactile messages are then sent to other Shake2Talk users. Williamson et al. designed a feedback metaphor that simulates the bouncing of balls inside a mobile device, providing messages in the form of audio and vibrotactile stimulation [27]. The clatter of the virtual balls inside the device indicates pertinent contextual information such as remaining battery life.

The wrist is a natural candidate for an anchor region where gestural interactions can take place. Clothing accessories that are worn on the wrist, such as watches, can be easily embedded with electronics to provide input capabilities [6,15,17]. Bauman et al. built a series of electromechanical wristbands of various haptic expressive capabilities to study means to grab a user's attention through touch [1]. Blasko and Feiner proposed the use of a capacitive sensor on a watch with tactile landmarks to indicate a region that supports eye-free stroke interaction [3]. They demonstrated that multi-stroke gestures could be used efficiently to traverse a menu hierarchy. Others have suggested the use of a capacitive bezel or an infrared proximity sensors to recognize hand gestures made over the wrist [1,12,13].

DESIGN

The potential benefits of eyes-free gesture interactions for mobile devices are apparent, but their design remains a challenge. First, the sensors that these interactions require vary greatly in their degrees of precision and repeatability because they must remain inexpensive, small and power-efficient. While the recent market availability of miniature off-the-shelf sensors of all types (e.g., Hall-effect sensors, accelerometers, etc.) has enabled the design of input interactions that do not require the use of a display, the reliable capture and interpretation of gestural inputs is an issue [11,20,28,29]. Second, technological means for communicating through touch, such as miniature actuators, remain very limited when compared to display technology, mostly due to the fact that tactile stimulation requires miniature moving parts that are complicated to build. Third, designers of eyes-free interactions are confronted with the challenge of developing new means to notify users that the device has properly registered their input gesture. By definition, the feedback that is provided in response to eyes-free interactions cannot take the form of visual information, and therefore it must be delivered either through an audio signal or tactually. Unfortunately, audio feedback can be disruptive in a mobile environment and the sense of touch offers an information channel that is limited in transmission throughput when compared to the visual channel [9]. Finally, the use of wearable eyes-free technology offers potential benefits in terms of convenience and accessibility, but this often comes at the cost of an increased social weight. The responsibility to balance the benefits of a given eyes-free interaction and its social impact falls partially on the designer [26].

Gestures Study

We chose to design a wristwatch that acts as a proxy interface between users and their mobile device. With a watch that is fastened properly, contact between a tactile actuator located in the watch and the user's skin can be guaranteed at all time, and therefore, tactile communication is possible. Furthermore, the wrist is one of the most accessible body sites for natural gestures and using a wristwatch leaves both hands free. In an effort to explore the best affordances suggested by a wristwatch, we identified, filmed, and classified over 40 different gestures that involved an interaction with a watch.

We limited our exploration to natural gestures that were short (under 5 seconds), spontaneous and not exaggerated in their execution. We then invited a dozen expert users of mobile devices to a brainstorming session during which we introduced the gestures. For each gesture presented, participants were asked to write down a potential function that the gesture could play in communicating non-visually with a mobile device. They were also instructed to ignore technological feasibility. Each gesture collected - a sample of which is shown in Table 1 - fell into one of three main categories according to the function it performs:

- *Reactive* gestures denote actions that are taken in response to an event or notification initiated by the device. Figure 2(a) illustrates covering the face of the watch, which can be used as a reactive gesture to mute a ringing mobile device.
- *Control* gestures are initiated by the user and are typically used to change the state of the mobile device or to adjust a setting. Figure 2(b) shows a user turning the watch bezel, which can be used as a control motion to set a ringing profile mode.
- *Query* gestures refer to the act of requesting information from the mobile device. For instance, touching and holding the watch face with two fingers, as in Figure 2(c), can be used as a query gesture to check for the presence of any new unchecked notification, such as an unread text message.

Gesture	Function	Type	Sensor	Feedback
Cover the watch face	Mute a phone call	Reactive	Capacitive sensor	The phone stops vibrating
Turn the watch bezel	Set a ringing profile mode	Control	Hall-effect sensors	Haptic confirmation on the watch
Swipe a finger over the watch face	Navigate through a music play list	Control	Capacitive sensor	A new music track starts playing
Shake the hand in a dismissive manner	Snooze a calendar reminder notification	Reactive	Accelero-meter	Haptic confirmation on the watch
Touch and hold the watch face	Sense the number of unread emails in inbox	Query	Capacitive sensor	Haptic confirmation on the watch

Table 1: List of most popular gesture/function combinations collected during the gesture study session.

(a)

(b)

(c)

Figure 2: Samples of non-visual gestures that take advantage of the accessibility of a wristwatch.

Design Objectives

We set out to design the watch to support eyes-free user interactions such as the one collected during the gesture study. While the end goal was to develop tactile sensations in response to a deliberate action from users, we did not want to lose the functionality of being able to grab users' attention with tactile feedback. To meet these requirements, the watch needed to be capable of generating at least two types of perceptually different tactile sensations: a rich and pleasant sensation used for communicating data and an intrusive easily detectable tactile notification signal.

HARDWARE

We built a wireless watch capable of providing rich haptic feedback on the wrist in a limited volume, according to the requirements listed above. The resulting prototype is a 14-mm-thick watch that bears a 40-mm-diameter round face (see Figure 3). The face of the watch supports capacitive sensing and its back holds a custom-made piezoelectric transducer that is used for the generation of the tactile stimulation. The prototype also embodies a force sensor that makes it possible to monitor the amount of vertical force the user is applying against the watch face. The watch supports the Bluetooth® standard which means it can wirelessly exchange data with a paired mobile device over short distances.

Tactile Feedback

We experimented with different types of miniature actuation mechanisms that are capable of providing tactile feedback. These mechanisms needed to be small enough to fit in a watch prototype and to consume a realistic amount of power for consumer mobile devices. We revisited the usual candidates: the off-centered vibration motor; the C2 tactor [8]; miniature linear motors; and even refreshable Braille cells. To assess the value of a particular mechanism, we strapped it to a tester's wrist and operated it with driving electronics that were controlled from a personal computer with a Digital Acquisition Card. The intent was to find a mechanism that could provide rich and expressive tactile stimulation that felt natural to users. By our judgment, however, none of the mechanisms tested were practical and expressive enough for the gestural metaphors in which we were interested.

Miniature vibration motors constitute proven and inexpensive means to provide simple tactile confirmation feedback, but they fall short in communicating rich and natural tactile stimulation that recalls real-life sensations. They are characterized by drawbacks such as a slow rising time and a limited dynamic range; this makes them difficult to use for applications where refreshable continuous tactile feedback is required. We, therefore, opted to develop our own haptic actuator that can generate tactile sensations that work in synergy with the gestures.

Haptic Piezoelectric Mechanism

The transducer is a 30-mm-radius piezoelectric disc that, when activated, takes on a dome shape and makes hard contact against a thin plastic membrane (refer to Figure 4). The actuation mechanism is at the bottom of the watch, where the membrane is in direct contact with the user's wrist. The use of piezoelectric material, which is capable of large signal bandwidth, allows for the programming of a wide variety of activation waveforms for the transducer.

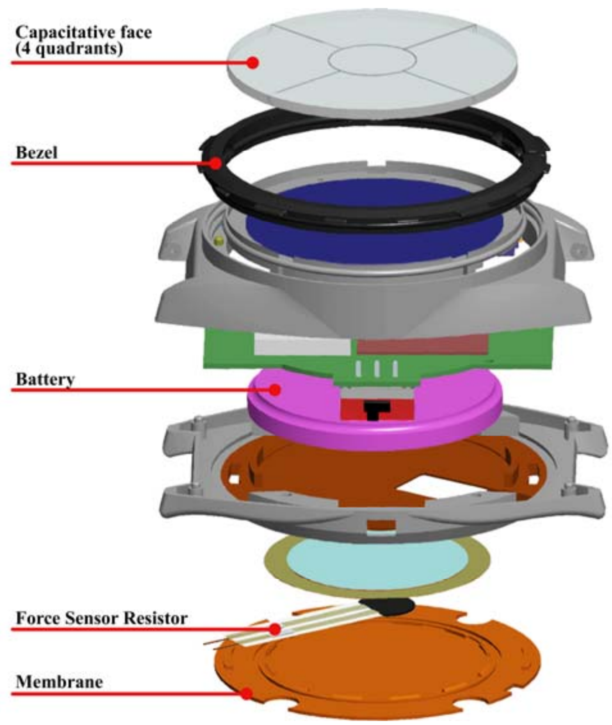

Figure 3: Exploded view of the watch.

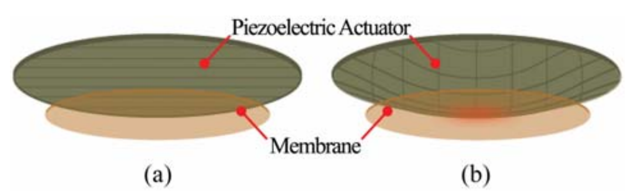

Figure 4: Illustration of a piezoelectric disc shown (a) in its neutral state and (b) hitting a membrane when activated.

Capacitive Sensing

The face of the watch was manufactured with a milling machine by cutting a transparent touch-sensing lens taken from a mobile device. Then, by laser etching the lens' top Indium Tin Oxide (ITO) layer – the layer that is responsible for its electrical conductivity and capacity – the face was divided into four independent capacitive regions and one neutral inactive central region. The result is a transparent watch face with equal active quadrants that can be used to monitor simple finger gestures.

Force Sensing Resistor

We placed a Force Sensing Resistor (FSR) on top of the piezo-actuated mechanism. Because they don't require much power to operate and are relatively thin, FSRs make for a practical and inexpensive input interface. On the downside, FSRs tend to return values that drift with time, so they need to be calibrated on a regular basis.

Rotating Bezel

Our design intent was to take advantage of the natural coupling that exists between sensory functions and motor functions. Figure 5 shows a mechanism developed to exploit muscle memory. It consists of a rotating bezel that can be set to any of 5 discrete positions around the watch face. An array of Hall-effect sensors inside the watch follows the configuration of five miniature magnets inside the bezel, providing a way to monitor the bezel position electronically. When the bezel clicks into one of the five positions, a mechanical detent is felt.


(a) (b)

Figure 5: Bezel mechanism (a) with magnets shown. (b) When the tactile landmark (orange) on the bezel is aligned with one of the five mode indicators (blue), the bezel clicks into place.

Electronics

All electronics are embedded within the watch, which runs a PIC24FJ64GA002 microcontroller from Microchip® as the main processing unit. A PSoC® controller (CY8C21434-24LFXI) from Cypress Semiconductor Corporation takes care of capturing and integrating the capacitive touch data from the watch face. An isolated fly-back power supply and an optical-isolator provide the means to control the piezoelectric disc at the high operating voltage (160 V) that it requires. Activation waveforms are generated through a charge and discharge cycle that is modulated via Pulse Width Modulation (PWM). A cylindrical rechargeable Li-ion battery with a nominal capacity over 300 mAh provides power for over 10 hours. The watch also bears a Bluetooth® Module from Roving Networks Inc. (RN-41) that allows it to communicate wirelessly with a BlackBerry® device.

VIBROTACTILE NOTIFICATIONS

Delivering the tactile stimuli on a wearable wrist peripheral offers multiple potential benefits. For one, certain users are not in constant physical contact with their mobile device, making them prone to miss a vibrotactile notification. A stimulus emanating from a watch is likely to be missed less often because the watch is unlikely to leave the user's wrist during the day. Also, stimulating two different body sites in order to communicate more detailed information is possible by adding a second dimension to the notification. For any such case, however, the notifications generated by the watch must be recognized by the user with high levels of accuracy in order to provide added value.

Reactive Gesture Experiment

We conducted a targeted experiment to gain insight on the feasibility of using the watch in a reactive interaction with the user. The objective of the experiment was to ensure the stimulus would be detected in a typical office environment, and to have the user interact with the peripheral in response to that stimulus.

Procedure

Eight volunteers (4 males and 4 females) were recruited for this study. All were right-handed and ranged in age between 22 and 42 years old (mean 30). They all wore the watch on the left hand. Participants were handed the watch and were asked to wear it for a period of 2 hours, carrying out their usual work tasks, and acknowledging any vibration felt on the wrist. Participants acknowledged a notification by covering the watch face with their hand.

Over the 2-hour period, the watch generated 20 notifications, separated by random intervals between 1 and 17 minutes. Four different types of notifications were used, each a sequence of very fast vibration (at a rate of 97.7 cycles/sec) differing in the number of cycles generated. The four cycle counts of 25 cycles, 75 cycles, 125 cycles and 175 cycles corresponded to stimulus lengths of 256 ms, 768 ms, 1280 ms and 1792 ms respectively. The 20 notifications, 5 of each type, were presented in pseudo-random order. Comments from the participants were collected once the experiment was over.

Results

Results are shown in Figure 6. Half of the participants acknowledged all of the notifications to which they were exposed (20/20). The remaining 4 missed a total of 5 notifications (3 for the 768-ms stimulus length, 1 for the 256-ms stimulus, and 1 for 1280-ms stimulus). This means that 97% of all notifications were detected. All participants were very confident that they hadn't missed more than a single notification; two had at least one false positive.

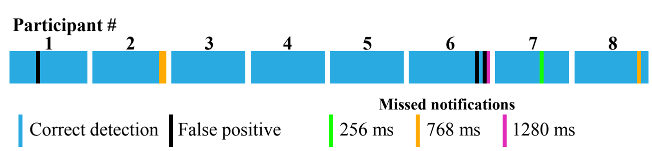

Figure 6: Results from the reactive gesture experiment.

A few participants commented that the long vibrating alerts could be irritating. This is in accordance with our findings and has also been reported by others [10]. Because all but one of the 256-ms notifications were detected, we conclude that there isn't any significant performance decline in detection rates, or reaction effectiveness, for the shortest stimulus tested. A shorter stimulus length offers the benefit of reduced power consumption without significantly affecting the rate of detection.

QUERY INTERACTION

The reactive gesture experiment had users interacting with the peripheral in response to an external trigger and the gestural acknowledgement of a notification provided the user with some control. To demonstrate the capabilities of the watch as a platform that gives users even more control, we also designed an eyes-free gesture that makes it possible for users to feel numerical information through a query interaction.

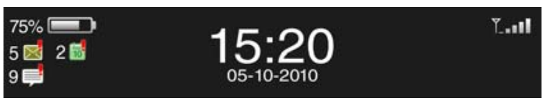

Figure 7: Example of a typical notification banner.

Problem Statement

Figure 7 illustrates an example of a notification banner found on the home screen of most commercially-available mobile devices. While they vary in their detailed implementation, these banners typically display miniature icons that provide valuable and easily accessible information about the state of the device. Information such as the presence of unread messages, missed calls, calendar notifications, and wireless connectivity is typically displayed this way. Numerical data, such as the number of new notifications or the remaining battery life is also often presented. Notification banners provide a useful interface to users for keeping track of the level of activity on their device. However, acquiring this information remains a multi-step and time-consuming operation because the device usually first needs to be pulled out from a holster or purse. Often a key press is also required to light up the screen that has automatically been turned off to conserve power. We set out to design an eyes-free query interaction that is less disruptive in nature.

Gesture Design Objectives

Generally speaking, we adhered to key principles for designing ambient haptics [16]. However, we designed our interaction for deliberate user action rather than having the movement between the periphery to the center of attention dictated by context. In that sense, our design intent was to construct physical metaphors for which continuous haptic feedback is mediated by user control [24]. We set the goal of designing for a gesture that is barely noticeable by an interlocutor with whom the user is engaged in conversation. This means that the entire communication, from the input gesture to the tactile response to the user, needs to take place quickly (less than 5 seconds), without requiring too much cognitive effort from the user.

Cover-and-Hold Gesture

The resulting query gesture is initiated by covering the watch face with the palm of the opposite hand. The watch responds by emitting a sequence of tactile pulses where each pulse represents a discrete element of a whole value that the watch is communicating. For example, each pulse can correspond to a single unread email present in an inbox.

We designed the metaphor to keep users in continuous, active control of this information exchange. As soon as the palm breaks contact with the watch face, the tactile feedback is terminated. Users are not forced to receive or feel any unsent pulses; they can break communication with their device at any time.

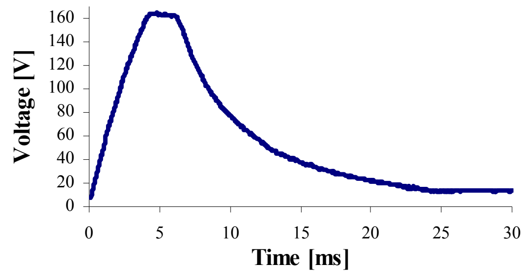

Figure 8: Voltage waveform applied to the piezoelectric disc to generate a single pulse.

Figure 8 shows the voltage waveform applied to the piezoelectric disc, which makes hard contact with the membrane. This generates a distinct beat on the user's wrist under the watch and results in a localized sensation that users often compare to a strong heartbeat pulse.

Preliminary tests with this cover-and-hold query gesture demonstrated that these tactile sensations are easily detectable by the user. Contact between the haptic actuator and the skin is improved when users are pressing down on the watch, and the sensation is felt at two body locations - the wrist and the palm - rather than a single one, making the pulse easy to sense by the watch wearer. Moreover, the gesture does not require finger movement, and thus is discreet by nature and much less likely to attract attention.

Query Gesture Experiment

We conducted an experiment to determine if the user could reliably obtain detailed numerical data from the peripheral with the query gesture. The intention was to evaluate a fully user-controlled gesture interaction, and also to determine the relationship between reading accuracy and delivery rate of the pulses.

Procedure

Twelve participants (7 males and 5 females) were recruited for this study. They ranged in age between 22 and 53 years old (mean 31.5). All but one were right-handed. They made queries with their preferred hand and therefore wore the watch on their other hand. Participants were first given a short instructional session to familiarize themselves with the device and its haptic capabilities. The study was conducted in a realistic environment with the examiner meeting the participants in their respective work cubicles or offices rather than in a usability laboratory. While participants were never interrupted directly, ambient noise (e.g., telephones ringing, people walking by,) was a desired and integral part of the experiment.

Task

Participants were instructed to cover the watch with their free hand, count the number of pulses and report this number by typing it in a spreadsheet. The experiment was divided into four series of 20 trials each, and lasted approximately 30 minutes. Four pulse delivery rates were used (9.1 pulses/s, 4.8 pulses/s, 2.8 pulses/s and 1.6 pulses/s), with the rate kept constant for an entire series. Each trial within a series delivered a number of pulses that ranged between 1 and 9, or a very rapid sequence of pulses representing the digit zero. In order to distinguish an absence of pulse from a gesture not registered properly by the device, it was necessary to display a stimulus for the digit zero. Zero was represented by a 27-Hz vibration with 360-ms duration. During the short instructional session that preceded the experiment, all four delivery rates were demonstrated for the participants, as well as the sequence of pulses representing zero. The four series took place in pseudo-random order. Each series had every digit (0-9) shown twice, also in pseudo-random order, for a total of 80 trials per participant. After each series, participants were asked to rate from 0 to 10 their confidence level in accuracy for the entire series.

Results

Table 2-5 show confusion matrices for all four delivery rates. Overall accuracy was 73.6%, with most errors made at the fastest delivery rate. Repeated-measures ANOVA analysis using the Bonferroni method for controlling Type 1 error rates for multiple comparison, shows significant difference between the 4 delivery rates for accuracy ($F(3,33)=96.634$, $p<0.01$), error ($F(3,33)=21.484$, $p<0.01$), and maximum error ($F(3,33)=25.672$, $p<0.01$). Post-hoc Bonferroni-corrected pairwise comparisons provide additional insight as to where these significant differences lie. These are summarized in Table 6.

Mean error, that we define as the mean of the absolute nonzero differences between the number of pulses displayed and reported, seems to increase linearly as a function of rate, though only the differences between the fastest delivery rate (9.1 Pulses/s) and the two slowest delivery rates (2.8 and 1.6 Pulses/s) were statistically significant. Maximum error reached 3.67 at the fastest delivery rate. Figure 9 shows cumulative accuracies for the delivery rates. In each case, accuracy rates remain over 80% for digits 0 to 3 but start dropping rapidly thereafter.

stimulus \ response	0	1	2	3	4	5	6	7	8	9
0	22			1			1			
1		23	1							
2		2	22							
3			14	10						
4			4	18	2					
5			1	11	11	1				
6				3	13	8	0			
7				2	4	12	6	0		
8				2	2	7	12	1	0	
9					3	2	16	1	2	0

Table 2: Confusion matrix (9.1 pulses/s). Accuracy 33.3% (σ: 6.2%)

stimulus \ response	0	1	2	3	4	5	6	7	8	9
0	23						1			
1		23	1							
2			24	1						
3			4	20						
4				6	18					
5					8	14	1	1		
6				1	1	8	14			
7					2		9	11	2	
8						2	4	5	12	1
9							1	3	8	12

Table 3: Confusion matrix (4.8 pulses/s). Accuracy 70.8% (σ: 21.9%)

stimulus \ response	0	1	2	3	4	5	6	7	8	9
0	24									
1		24								
2			24							
3				23				1		
4			1	2	20	1				
5					1	23				
6						1	23			
7							1	21	2	
8							1	4	19	
9									2	22

Table 4:Confusion matrix (2.8 pulses/s). Accuracy 92.9% (σ: 9.4%)

stimulus \ response	0	1	2	3	4	5	6	7	8	9
0	24									
1		24								
2			24							
3		1		23						
4				2	21	1				
5						24				
6						2	22			
7								24		
8									24	
9										24

Table 5: Confusion matrix (1.6 pulses/s). Accuracy 97.5% (σ: 3.4%)

[pulses\s]	accuracy [%]	mean error [pulses]	max error [pulses]
9.1	33.3	1.98	3.67
4.8	71.3	1.13	1.83
2.8	92.9	0.53	0.92
1.6	97.5	0.50	0.50

Table 6: Post-hoc Bonferroni-corrected pairwise comparisons. Statistically significant differences are linked (p<0.01).

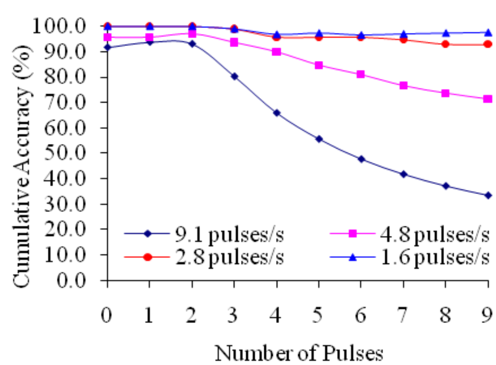

Figure 9: Cumulative percentage of correct answers in function of the number of pulses for all 4 delivery rates.

Discussion

The results show that delivery rate influences the ability for participants to accurately count the number of pulses displayed; participants' responses were less accurate when higher rates were delivered. It is interesting to note that participants tend to underestimate the number of pulses. The majority of errors made by participants were underestimates (93.7%), an effect even more pronounced at faster delivery rates. Such a bias towards underestimating the number of tactile signals displayed, especially for a large numerosity, has also been observed by others, though for different types of tactile stimuli [14,21]. This is an undesired effect, particularly when taken in the context of a query interaction, but results suggest that it can be minimized by slowing down the delivery rate when a large number of pulses are presented.

The digit zero, which was represented by a distinct high-frequency vibration rather than a sequence of discrete pulses, was identified with 96.9% accuracy. This provides partial evidence of the expressive capabilities of the tactile actuator and suggests that the actuator can generate many more perceptually differentiable tactile stimuli.

Results show that using a delivery rate faster than 4.8 pulses/s for the query interaction would generate a large number of errors for digits over 3. At the end of the study, participants were asked which of the delivery rates they would find more useful if the number of pulses delivered represented unread emails in their inbox. A large majority of participants (10/12) reported that they found the 2.8-pulses/s-delivery rate to be the most appropriate and all found the slowest delivery rate to be too slow. However, many participants also pointed out that there are many real-life situations for which they would only be interested in getting a sense for how busy their inbox is rather than trying to get an exact email count number. In these situations, a fast delivery rate of about 9 pulses/s would be valuable, as it would provide this information quickly.

A Pearson correlation analysis shows a positive correlation between accuracy levels and reported confidence levels ($r=0.776$, $n=48$, $p<0.01$). This implies that participants are good at judging how accurately they can count the number of pulses. Taken together with the observation that a faster rate would be useful in certain contexts, these results suggest that the query interaction should provide more user control flexibility than what is available with a single pulse delivery rate. In light of this, we adjusted the control metaphor to support multiple levels of delivery rates.

REDESIGN OF THE CONTROL METAPHOR

We modified the control metaphor to take advantage of the human capability to precisely modulate pressure [22]. The FSR present in the watch provided the means for force input. The new control metaphor allows users to modulate the pulse delivery rate by exerting force on the watch face. A higher force increases the frequency at which the tactile pulses are generated, and a lower force decreases the frequency. The choice of the delivery rates supported for this relationship was informed by the results of the query gesture experiment. Ideally, and in its purest form, the delivery rate would be directly proportional to the force applied. However, because they are largely dependent on environmental conditions, FSRs can be difficult to calibrate, and the force values they return can drift with time. In addition, different users will fasten their watch on their wrist at different resting forces, which cannot be accommodated for in design. To solve these problems, the watch supports only 2 delivery rates, and the initial force recorded when the watch face is first touched is always used as a reference. When the user first presses on the watch, the force exerted is recorded and the delivery rate is always the slowest by default (3 pulses/s). To accelerate the delivery of the sequence of pulses to the faster speed of 9 pulses/s, users need to press 1.5 times harder than the initial reference value recorded. This method avoids the need for calibration of the FSR and provides users with means to modulate the pulse rate independently of any absolute reading from the FSR.

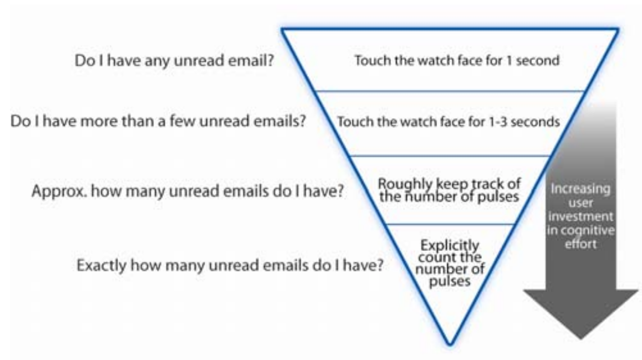

Figure 10: An inverted pyramid as a model for providing users with maximum control and flexibility. Users can make the delivery of tactile pulses stop when desired by removing their hand from the watch face.

Information Granularity

The modified control metaphor provides users with information that is encoded with hierarchical levels of granularity, accessible through deliberate user effort. The model is one of an inverted pyramid where the information is presented to users in descending order of importance, and increasing order of required user cognitive effort (see Figure 10). The gesture lets users decide how much cognitive effort they want to allocate to the interaction, with the amount of information they get in return being proportional to that investment. For instance, briefly touching the watch face tells them whether or not there are any new unread emails present. However, explicitly counting the number of pulses provides them with an exact count. The latter operation is far more demanding cognitively than the former, but provides more detailed information. The new control metaphor offers another potential benefit: because users can modulate the pulse delivery rate with the amount of force they exert, novice and expert users alike are given the means to conduct the query interaction at a speed that is appropriate for them.

QUALITATIVE VALIDATION

In order to qualitatively evaluate the added value of using the haptic watch in a realistic mobile environment, we handed the watch to a small number of participants. The watch was linked to a mobile device and programmed to provide the user with information about their e-mail inbox. The redesigned query metaphor described above was used to inform the user of the unread count, and the notification functionality was enabled to alert them of new incoming messages. Participants were not given any specific instruction other than a short explanation on how to perform the query gesture. They were free to interact with the watch to check the level of inbox activity at their discretion. No data was collected other than their comments on their experience of using the prototype.

All participants found the gesture to be very intuitive. Some users, however, reported that they had, at times, instinctively carried out the gesture over the sleeve of their shirt; this operation fails because the capacitive touch sensor cannot be activated through fabric. This identifies a limitation of our implementation, but it was not found to affect the overall experience; participants quickly realized the source of the problem.

All participants spontaneously commented that the tactile feedback was unique and pleasant. They considered it far more natural than the stimulation generated by a vibration motor, with the exception of one participant who found the tactile feedback to be “slightly irritating” because it reminded him of the pulse of his own heart beat, something with which he wasn’t very comfortable.

One participant who had used the device in his closed office commented that the noise made by the actuator hitting the membrane could be perceived in a quiet environment. None of the other participants, who mostly tried the device in their working cubicles, mentioned the faint noise to be a problem, most likely because they never noticed it.

Two participants reported attempting, as a challenge, to count the number of emails in their inbox while carrying a face-to-face conversation with a colleague. Details on whether they were successful or not in counting the exact numbers of emails were not provided but their attempts illustrate how such a scenario is not unrealistic.

All participants reported that they appreciated the convenience of having a smart accessory that is easily accessible. This seemed to be particularly true of a female power user who typically gets in excess of 50 emails a day and does not like to carry her device in a holster or pocket.

Some participants commented that they would have liked the notification feature to be disabled. They appreciated the freedom to query their device at their leisure, and found the nature of the notification feature conflicted with this philosophy. One commented that disabling the notifications would allow him to “regain partial control over his inbox”. This illustrates the value to the user of interactions that grant them more control.

One participant, who was handed the watch for an extended period of time, mentioned he would have welcomed a third level of force input that would deliver tactile pulses faster, allowing more control over the delivery rate. This suggests that the combination of the watch and the interaction could support different levels of expertise. It also hints at the fact that the rate of the tactile signal could also be used directly as an effective encoding scheme to communicate information that is not numerical [23].

CONCLUSION AND FUTURE WORK

We have built a haptic-enabled wristwatch to support eyes-free communication with a mobile device. The watch makes use of a custom-made haptic actuator that is capable of rich tactile feedback.

Wearable and mobile interactions that are tactile-enabled extend over a continuum defined by how much control the users have. At one extreme, users are at the mercy of disruptive tactile alerts over which they have no immediate control. Tactile notifications, however, do play a valuable role in eyes-free mobile communication, since it is frequently crucial to be able to grab a user’s attention. We conducted an experiment to validate that users could register the tactile notifications generated by the novel actuation mechanism. Results showed a high registration rate of 97%. We also ensured that the interaction was not entirely passive in nature; participants had reactive control over the notification, enabling them to acknowledge and mute it with a simple gesture upon delivery.

The other end of the continuum is populated with gestures that are supported by tactile feedback. In this space, users have more control over when and how the tactile interaction will take place. We introduced a query gesture that makes it possible to acquire numerical data tactually. A user experiment was conducted in realistic work office environment to evaluate the feasibility of the proposed query interactions and to uncover the best possible parameters to reduce it to practice. It was found that a delivery rate of around 3 pulses/s offers the best compromise between identification accuracy (93%) and overall duration. Nevertheless, participants commented that a faster delivery rate of around 9 pulses/s would still be useful when they only wanted to get a sense the inbox’s activity level. This triggered a redesign of the interaction to support force control as a means to shift between two delivery rates (3 and 9 pulses/s).

Users were handed out the watch to use in a work environment; they commented positively. The new gesture metaphor granted them continuous control and provided them with the means to dynamically modify the parameters of the interaction as it was occurring. This work suggests how to design for eyes-free tactile interactions that take place with a wearable accessory. It is part of a larger effort to develop ways to communicate with mobile devices without the visual channel and, therefore, create interactions that have the potential to be more convenient and less intrusive than existing vision-dependent ones.

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