Tactor placement in wrist worn wearables

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Tactor Placement in Wrist Worn Wearables

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Abstract

Vibro-tactile stimulation has been revealed as a potentially effective means to deliver spontaneous notifications like alerts to recipients that are focused on other tasks (although only at very low bit rates, and depending on the place at which the tactors are placed). This work addresses the issue of the amount of information that can be perceived via stimuli coming from wrist worn tactors, given the recipient is not expecting or attentive to the potential occurrence of an alert. Assuming apparel like wrist watches with embedded tactors to represent the alert delivery platform, we investigate - respecting physiognomical properties of tactile perception- the effectiveness of different tactor placements. We compare the case of embedding 4 tactors underneath the "face" of the wrist watch, against the case of embedding it into the wristband ("wrist"). A user study of 1,823 trials has been conducted involving recipients exposed to different levels of engagement in a certain activity. The experiments show, that the amount of information perceived via spontaneous tactile alerts ranges from 1.90–2.49 bits at low, to 1.59–2.41 bits at high levels of engagement. The "wrist" tactor placement achieves a 41.6 % higher perception bit rate than the "face" tactor placement.

Keywords. *Vibro-tactile Stimulation, Subliminal Perception, Tactile Display, Perception Performance*

1. Introduction

Delivering information at the periphery of human attention is considered as a potentially effective way to notify individuals engaged in an attentive activity ("primary task") in a non disruptive way. We refer to an individual being attentive whenever the human mind takes possession of one out of several simultaneously possible objects of engagement or trains of thought. Certain channels of perception (e. g. visual and/or auditory) are involved to sustain this possession, while the occurrence of out of context signals along those channels causes interrupt or loss of attention.

Recent literature [1], [2] delivers support for the hypothesis, that using channels of perception not engaged in the primary task appears to be attention preserving. Notifying, thus, without compromising attention, might have a solution with a careful design of information delivery systems addressing the "secondary channels". Since many (primary) tasks of everyday life (e. g. work, sports, leisure), but also in exceptional situations (e. g. evacuations) engage the visual and auditory channels, the consideration of other –like the tactile [3] and olfactory [4]– channels appear worthwhile for attention preserving communication systems.

With this work we address the challenging issue of delivering information to individuals while being engaged in tasks that occupy the visual, and possibly also auditory channel of perception. Particularly, the tactile channel of perception is addressed to deliver information, but with as few as possible disruption of the primary engagement. In order to investigate on the effectiveness of nondisruptive vibro-tactile information delivery, we propose a wearable (wrist worn) tactile stimulation system, and assess it wrt. to the amount of information possibly perceived through it. Formally, the research question addressed here asks for the amount of information that could be delivered to an engaged individual in a non-interruptive, yet perceivable and memorable way in a tactile modality. The approach to answer this research question is constructive and experimental. First, restricting to wrist worn wearables, we propose two referential systems designs of integrating tactors into appliances like wrist watches. Second, we set up experiments of dual-task stimulus-response (S-R) modalities. In order to represent a typical engagement of an individual in an everyday work or leisure situation, we introduce a visual-motor modality load (referred to as "primary task"), and test for the efficiency of a simultaneous tactile-vocal modality load.

Figure 1: Watch as a wrist worn tactile display in "primary task" engagements like typing, driving, carrying or opening doors.

To empirically investigate on non-disruptive, attention preserving communication systems we here restrict to wrist worn wearables like wrist watches or tightly worn bracelets (see Figure 1). Appliances of the kind have a habitual scheme of everyday use, and therefore appear promising to embedded wearable computing technology. Here we are interested in embedding a vibro-tactile notification system into such wrist worn wearables, with tactor elements invisibly integrated into the fabric of the wearable, "displaying" information received through a wireless data channel via patterns of tactile stimulation (we therefore also refer to it as a a "tactile display").

Wrist worn wearables have a long tradition in the wearable computing literature (see e.g. systems like the Zypad, "WatchPad", etc. to name a few [5], [6], [7], [8]), but have not addressed vibro-tactile stimulation for non-disruptive communication up until now. [9] generally addresses user distraction as a factor which may mask or obscure vibro-tactile perception. Their studies compare recognition performance on nine tactile icons, with results indicating that perception performance significantly drops if stimuli are delivered in situations of distraction from the primary task. In [10] a multimodal interaction with feedback through different output mediators is proposed, using the vibration facilities of mobile phones (Nokia E70 worn on the wrist) as one output mediator. The humans ability to localize tactile stimulation on the dorsal wrist is studied in [11]. Both the volar and the dorsal sides of the forearm near the wrist were tested for stimuli localization. [12] uses vibro-tactile together with audio actuators mounted at a swimmers left wrist, to be used as non-interruptive user interfaces for swimmers. Coincidentally to our work, a very recent research result based on the "BuzzWear" system [2] shows, that the application of tactile displays on the wrist is suitable for alert perception. Finally, [13] investigates on the possible improvements in the form factor of a wrist-based mobile gesture interface based on limitations discovered from the BuzzWear prototype.

Figure 2: The design space for wrist watch tactor placement: (i) "face", underneath the watch face, (ii) "wrist", along the band (upper part).

As far as the wearable tactile notification system is concerned, this paper aims for a systematic investigation of the design space for integrating tactile elements into a common wrist worn wearable, considering tactor placement (i) underneath the watch's face (indicated by the grey circle in Figure 2), or along the (ii) band (indicated by the dotted rectangle in Figure 2). For short, we will refer to these two ends of a possible spectrum of different tactor placement strategies as "face" and "wrist", respectively. Intuitively, "face" represents a more focal, pointed or spotted zone of vibro-tactile stimulation area, while "wrist" embraces the whole wrist joint with tactors, thus loosening the information density as compared to "face". (Assuming a constant number of tactors t, the approximated information density of "face" -considering a standard wrist watch- would be $\frac{40mm^2\cdot\pi}{4t} \approx 1,250mm^2/t$, whereas the information density of "wrist" would be $\frac{100mm\cdot 22mm}{t} \approx 2,200mm^2/t$.) As for the choice of t, empirical evidence has been found on the minimum space separation of tactor stimuli to be separable by human perception (two point discrimination) already in 1968 [14].

The remainder of the paper is organized as follows. Section 2 discusses the experimental setting based on physiognomic and technical capabilities, and describes the tactor and microcontroller hardware platform. Section 3 looks at the experiment design, the execution of the experiment, and provides a discussion of results. Section 4 assesses the findings and concludes the paper.

2. Tactor Placement in Wrist Worn Wearables

When designing and implementing wearable vibro-tactile technology, we find ourselves constrained by two types of boundaries: First, the distribution and sensitivity of mechanoreceptors in the human skin imposes constraints upon the perception of vibro-tactile stimuli. Second, the placement of tactor elements and their respective computational control poses technological constraints.

2.1. Physiognomic Constraints

Four types of mechanoreceptors residing in the human skin are responsible to sense pressure and vibration, each of them with specific perceptional features. With respect to the requirements (i) high spatial resolution, (ii) high sensitivity, (iii) availability on the wrist (fore arm), and (iv) fast adaptation speed, the Pacinian Corpuscles (PCs) appear to be the receptors to be addressed with a tactile stimulation systems [15]. As for the placement of tactors in order to be unambiguously perceivable, we follow the suggestions of the two point discrimination experiment by Weinstein [14], which finds the minimum distance between two stimuli to be differentiated is about $38mm$ on the left forearm. (Literature reports that there is no evidence for differences in two point discrimination perception among the left and right forearm, or among males and females, thus giving rise for gender-neutral tactile displays.) The potential placement of tactors on the wrist finally remains constrained by the "skin space" one finds underneath the wearable, thus raising the question of physiognomic constraints for the wrist: According to a large data set recording of 252 men by Johnson [16], the mean wrist circumference is $18.38cm$ for US males. Another measure on 20 men and 20 women by Shih and Tsai [p. 2][17] indicates a mean wrist circumference on the right arm of $16.0 \pm 0.7cm$ for male, and $14.8 \pm 0.8cm$ for female test persons. The effective width of the wristband used in our study (an elastic wrist support with velcro strap to adapt to individual length) hence was $70mm$, thus the area available for vibro-tactile stimulation calculates to $\approx 160mm \times 70mm$=$11,200mm^2$ (wrist circumference × wristband width). Considering the two point threshold of $38mm$, our choice on the number and placement of tactile elements for the current studies is four tactors placed (i) on top (clock face) and (ii) around the wrist.

2.2. Tactograms

Information to be "displayed" via the wearable systems demands an encoding into spatio-temporal tactile stimulation patterns, i.e. tactograms. A tactogram (or tactile pattern) represents one "symbol" out of the tactile alphabet. The variation range of parameters to design tactile patterns is – up to the physical limits – only restricted by the flexibility of the utilized soft- and hardware. The following control parameter variations are possible with the current implemented prototype, the agreement for the setting finally applied to the experiments follows either recommendations from earlier experiments, physical characteristics or was determined empirically.

(i) *Intensity:* These parameter controls the perceived strength (gain) of the tactile signal in general and can be seen as a *amplification factor*. Gain level is not the only factor controlling the perceived vibration strengths – frequency offers much more potential. For this reason, vibration intensity was set to a fixed value of 50% for the entire experiment in order to be felt comfortable (experimentally determined in a preparatory study).

(ii) *Frequency:* The feasible frequency range for tactile stimulation depends on the kind of mechanoreceptor to be innervated. In this experiment the Pacinian corpuscles are stimulated. The full range of stimulation for PC varies from about 30 to $1,000Hz$ with highest level of perception in the frequency range 200 to $300Hz$ (the stimulus threshold plot follows a U-shaped function [18, pp. 142–143]). For the current experiment, the oscillation frequency was fixed to $250Hz$ to allow best perception at the receptors (utilized hardware allows for variation between 31 and $300Hz$). According to Cholewiak and Collins [19], frequency variations between 100–$250Hz$ have a rather low impact on recognition rates.

(iii) *Duration:* The length of one vibration signal depends on several factors, such as (i) the complexity (=length) of the signal sequence, (ii) the level of dynamicity to be achieved with the system (update rate), (iii) the kind of signal to be used for stimulation (annoying vs. comfortable), (iv) the kind of notification (information, warning, alert; =Level of Attention (LOA)), etc. The length of one tactile signal was also determined experimentally and fixed to $500ms$, leading to a constant $2,000ms$ activation time for one pattern (tactile character) out of the tactogram alphabet.

(iv) *Modulation:* Superposition of two signals to get a more complex waveform was not considered in order to keep signals and their recognition as simple as possible.

(v) *Sequences:* The vibro-tactile alphabet designed and used for the experiment is described in length in subsection 2.3. First of all, the employed alphabet consists of eight tactograms, each a combination of four individual, consecutive tactor activations.

2.3. Tactor and Control System Setup

The system setup of the wearable, vibrating wristband interface consists of four linear voice-coil actuators connected to the tactile controller board. The C-2 type tactors are designed with a primary resonance in the 200–$300Hz$ range that coincides with peak sensitivity of the Pacinian corpuscle (PC), thus providing optimum vibration efficiency. The circuit board as shown in Figure 3 is installed in a synthetic housing, and connected via 4 two-core cables to the vibration elements as well as either with a Bluetooth or with a standard USB cable to the computer hosting the test application. The main electronic parts on the board are a CMOS single-chip micro controller (type M30879FLGP), embedding the high-performance M32C/80 series CPU core, a LM324A high-gain frequency-compensated transducer amplifier, and a Free2Move low power embedded Bluetooth module (type F2M03GLA) for wireless communication. After first experiments with the wireless communication channel, the experiments have finally been conducted using USB connection by reason of a lower communication latency compared to the Bluetooth communication.

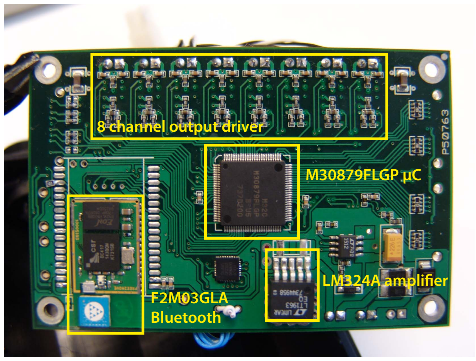

Figure 3: Circuit board of the tactor controller.

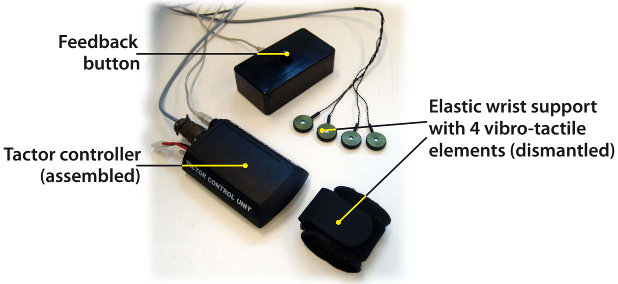

Figure 4: Main components of the tactile display setup.

The feedback device was designed as a single sturdy black box with a button to push as response during the visual distraction test. The wristband is based on a customary sports armband and extended with sewed in pockets at the inside of the band to hold the tactors and prevent any shifts. The wristband was flexible enough to fit both smaller and broader arms at the same time and had a hook and loop fastener to ensure stable placement.

On the software end a highly configurable JAVA software framework was developed, permitting both flexible generation of trials and easy adjustment of primary (visual distraction) and secondary (tactile) tasks. The software ensured accurate execution of trials, detailed creation of logs, and recording of all user responses.

Two different tactor setups were used, (i) for the "wrist" placement one tactor was on the volar and one on the dorsal side of the wrist, while the other two were one on the left and right side of the wrist, (ii) for the "face" placement all four tactor elements were placed on the dorsal side of the wrist in a clock face shaped pattern (according to a "3", "6", "9", and "12" position of the little hand; see Figure 5 for a more detailed overview).

In both the "face" and the "wrist" settings four tactile elements have been integrated into the wristband. Each of the eight tactile patterns to be analyzed within this experiment consists of a series of exactly four tactor activations (the position of each of the four tactors is a starting point for two tactograms, one running clockwise the other counter clockwise – adding up finally into a total of 8 patterns). With this setting, the maximum possible information transfer calculates to $\widehat{T} = 3$ bits.

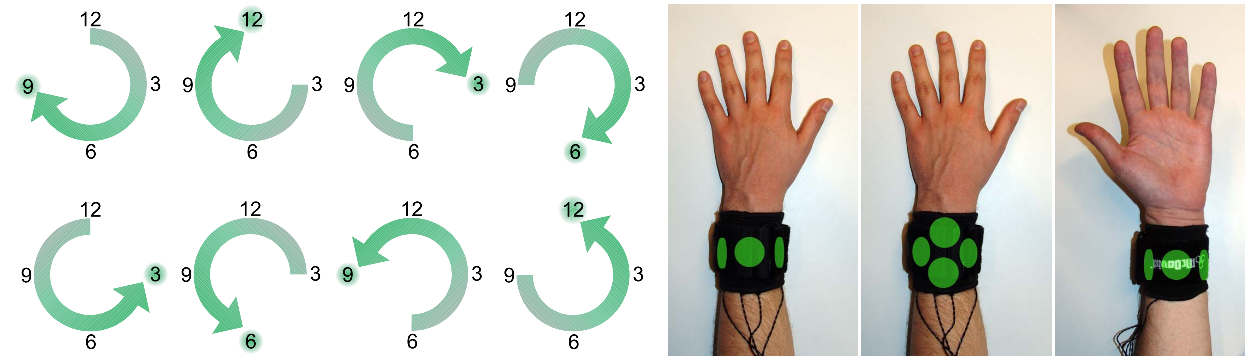

Figure 5: The eight tactor sequences (left-hand side) and the tactor placement actually used for both the "face" and "wrist" configuration (right-hand side). For the "face" placement tactors were arranged like a clock face (left photo), for the "wrist" configuration the 12 o'clock tactor was placed on the dorsal wrist side, the 3 o'clock tactor on the thumb side, and so on (right series of photos).

3. Experiment Setup and User Study

Addressing the research question of identifying the optimal tactor placement on or around the wrist, to deliver the most information to an engaged individual via a vibro-tactile display, an experiment setup has been chosen to reflect the following desired features:

(i) To avoid the impression of an empirical research test setting, the experiment was not conducted in a test lab, but in places where subjects live -in their kitchen- with the perception of side activities as they would occur in an everyday situation.

(ii) Since perception performance is known to be depending on individual capabilities, but decreasing with growing levels of "mental load", the experiments were designed at various different levels of engagement in the primary task ("low", "moderate", "high"). An artificial visual-motor S-R modality task was designed (numbers randomly appearing on a computer screen, and keeping the subject attentive to the occurrence of a particular one, here: "42"). Increasing levels of mental load were "simulated" with the speed of number occurrences.

(iii) The wrist worn technology was hidden as far as possible, but every test subject (by intent) was well informed that the purpose of the device was for tactile communication. Each subject was given the chance to investigate, understand and test the device as long as she or he liked (trial session). Then the test experiment was conducted in sequences of trials.

(iv) Only a small alphabet (eight tactograms) was considered, and all the subjects had the chance for an individual training phase. It was recommended to the test subjects, that correctly identifying a tactogram three times in sequence is sufficient level of recognition rate, so that no further training was advised.

(v) Subjects being tested for their individual perception performance for vibro-tactile notifications during the execution of everyday task should not be attentively expecting a notification signal to come. The occurrence of stimuli therefore was randomized.

3.1. Scenario Definition

Restricting to the two aforementioned tactor arrangements ("face" and "wrist"), the setting was designed to reflect a typical/everyday) dual-task situation. As primary task, we chose a visual distraction task, with 3 increasing levels of distraction. The three visual distraction levels "low", "moderate", and "high" were fixed in a preparatory study with four test persons (later not participating in the main experiment). For the setting of low distraction we expected an accuracy of 99% if the person was fully focused on the visual task, whereas for the moderate and high distraction rates we expected accuracy to drop significantly. Random numbers ranging from 10 to 50 were generated and placed on random, non overlapping positions on the computer screen. Task difficulty could be adjusted by either changing the amount of visible numbers or the duration of announcement. The amount of numbers was fixed to 10 at a time and the display duration follows a normal distribution of $1,750 \pm 250$, $2,250 \pm 250$, and $2,750 \pm 250ms$ for the respective distraction levels high, moderate, and low.

The secondary task was to recognize tactile patterns on the wrist, occurring at unexpected (random) time intervals. The number of correctly recognized tactile patterns, while performing well in the primary task was taken as evidence on the performance of the two different tactor placements. Additionally, the different distraction levels in the primary task allowed us, to roughly measure the impact of distraction on tactile perception.

The experiment took place in a kitchen setting (see Figure 6), with one or more unrelated persons causing passive distraction. (We have introduced this aspect into our experiments according to [2], so as to make our scenario closer to real life.) Prior to the experiment, jewelry, watches or other objects were removed from the left forearm and the elastic wrist band was pulled over and placed in a comfortable position. The position of tactors in the wrist band was controlled and/or adjusted to ensure equal pressure on the skin and a uniform separation distance for all elements. All experiments were conducted on the left wrist (a distinction between left and right handed persons was left out). The experiment was conducted by two instructors, the one controlling the software and processing the spoken feedback from the test participant after each trial, the other attaching the wrist band to the test person, controlling its placement during the experiment, and monitoring the participants for possible noticeable problems.

Prior to the actual experiment, a short briefing session took

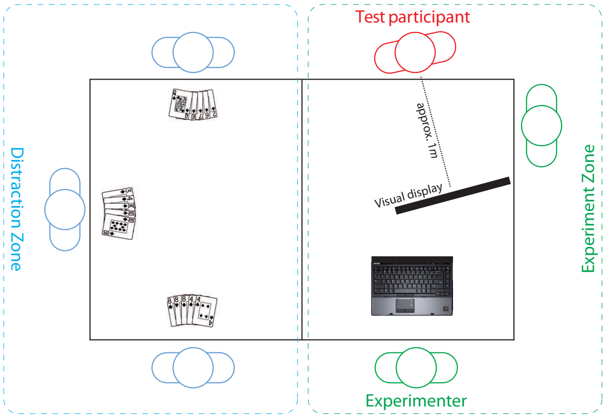

Figure 6: The top view shows the installation in a kitchen with a natural distraction zone as used for the experiments. Persons sitting on the kitchen table in the "distraction zone" are communicating as usual and unaffected from the processing of user studies; however, a direct interaction between the two zones never appeared (by regulation).

place, explaining the primary (visual) and secondary (tactile) tasks. For that, individual tactors were activated separately to give the test person a feeling on how they operate and which kind and strength they could expect. In this stage, tactor placement was also adjusted if the one or other vibrating element was not felt at all or at a lower/higher intensity than the others. In the next step the eight tactile patterns were explained orally, shown visually on the screen, and then replayed using the tactile wristband until the test person was confident about them and responded correctly to at least three tactograms in a row. To familiarize the participant with both speed and amount of numbers to be expected in the primary task, this visual distraction task was also demonstrated.

In preparation for the real experiment, each trial of $10sec.$ was preceded by a $3sec.$ countdown, shown on the display, to attract the attention of the test person. During the primary, visual distraction task the secondary, tactile task was activated exactly once per trial at random times and either between 2 and 5 or between 5 and $8sec.$ to discover the memorability effect as discussed later. As can be seen in Figure 8, visual tasks appear at random intervals depending on the level of distraction desired (as described previously). A second visual task may be triggered before the subject responds to a first one. Correspondingly, a user might respond to a visual task and have a delay before the next visual task is presented. Thus, the secondary tactile task may be presented when there is, or is not, a visual stimulus waiting for a response. While the subjects may finish searching for the "42" in the field of numbers, they must continuously monitor the screen for the next visual task. At the end of each trial the eight tactograms were shown on the screen (photo 2 in Figure 7), requesting the participant to verbally express the perceived pattern (one out of A–H, none or unidentified). Not at any time during the experiment feedback on the decisions of a test person was given. The entire experiment of 48 trials took about 20 minutes in time and was repeated, after a relaxation phase of about $15min.$, with the $2nd$ setting of tactor placement; 50% of the tests were started with the "face" configuration, the remaining half with the "wrist" configuration.

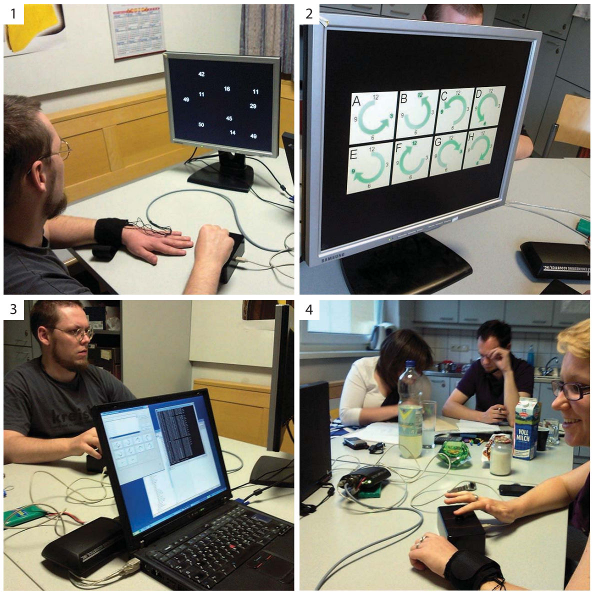

Figure 7: Picture 1 shows the experimental arrangement from a test person's view sitting about 1m in front of the screen. The elastic wrist support is mounted on the left forearm and the right hand is used to push a button (response on the primary, visual task). Picture 2 shows the screen presented after each trial and requesting a spoken feedback of the recognized tactile sequence (one out of A–H). Photo 3 shows both software and hardware environment as used in the studies, photo 4 finally shows interactions taking place in the distraction zone while conducting an experiment.

3.2. Evaluation

The experiments were conducted with 19 volunteers (8 females, 11 males) in the age range 21 to 32. All of them were recruited from a students' hall of residence or the nearby settlement, none of them were related in any kind to our department, had previous knowledge about the experiment or any experiment related interaction with previously tested people. All of the participants felt comfortable with the placement of the wristband and apart from some minor discomfort on participants with stouter wrists no aggravating circumstances were reported.

In order to be able to quantify the amount of information I delivered via the tactile channel we adopt a metric that has been used in previous work (e. g. by Chen *et al.* [11] or Lee and Starner [2]), often referred to as "information transfer". Here, we estimate the information transfer T to a single individual within an experiment of several stimulation trials to be

$$\widehat{T} = \sum_{j=1}^{k}\sum_{i=1}^{k}\frac{n_{ij}}{n} log_2 \frac{n_{ij} * n}{n_i * n_j} \qquad (1)$$

on average per trial. The variables i and j represents stimuli and response, n is the number of total trials, k the number of different stimuli, n_i the total number of trials where stimulus i occurred, n_j the total number of trials where response j was given, and n_{ij} the number of times where stimulus i was responded with j.

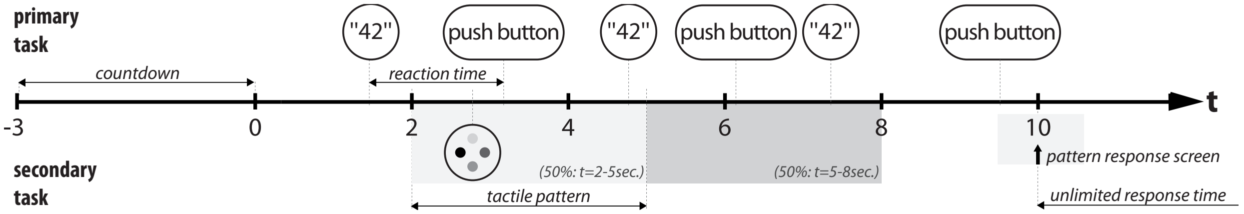

Figure 8: Example timeline of events during one trial. Visual (primary) tasks occur uniformly distributed, their number depending on the level of distraction. One secondary (tactile) task occurs during the trial, randomly placed between 2-5 seconds or between 5-8 seconds. Subjects say which of the eight tactile patterns (A-H) they perceived at the end of the 10 second trial (forced choice).

For evaluation only trials in which test persons correctly perceived all target numbers in the primary visual distraction task (proof of focus on the primary, not the secondary task) were regarded for the calculation of the estimated information transfer $\widehat{T}$ ($1,332$ out of $1,823$ trials, 73%). Furthermore, responses to stimuli in the primary task were only considered to be correct within a time window of 0.2 to $2.85s$ (see Figure 9) as elaborated in the following.

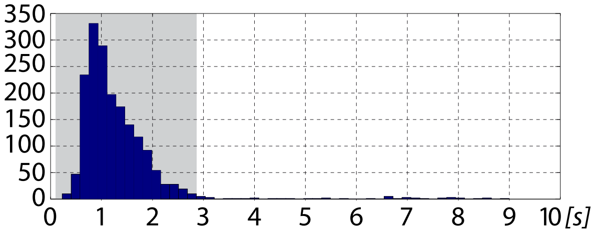

Figure 9: Reaction time histogram for the primary task. The light gray area indicates the resulting target window (range 0.2 – $2.85s$) for a confidence interval of CI=95%.

It is elaborated that human reaction (or task activation) time is, dependent on the stimulated sensory channel, between $140ms$ (auditory) and $180ms$ (visual) [20], [21]. The reason for this variation comes from the different times for information to reach the brain, which is about 8–$10ms$ for an auditory [22], but 20–$40ms$ for a visual stimulus [23]. According to these findings, the minimum reaction time between stimulus activation (in this case the appearance of "42") and user response (button pushed) considered true is set to $200ms$; for the upper limit a confidence interval of CI=95% has been taken into account; consequently, reaction times exceeding $2,894ms$ are considered as missed and the corresponding data sets have been excluded from evaluation.

3.3. Discussion

3.3.1. Information Delivered via a Tactile Display. The "wrist" placement achieved a bit transfer of $\widehat{T} = 2.44bits$, which is, compared to the "face" placement ($1.72bits$), an increase of 41.6% (see Figure 10). The value of $2^{\widehat{T}}$ shows a respective perception of 3.23 patterns for the "face" and 5.42 for the "wrist" tactor placement. The different levels of attention attracted by the primary task seem to have no significant impact on the information transfer rate, at least for the "wrist" setting where a decrease of only 3.26% from low to high can be detected. In contrast, $\widehat{T}$ decreases by 16.67% from low to high load for tactor placement on the top (clock face). This confirms our assumptions that a tactogram perceived at the "face" setting is harder to remember, thus needs a higher brain load to differentiate so that in succession less cognitive capacity remains free for the primary task.

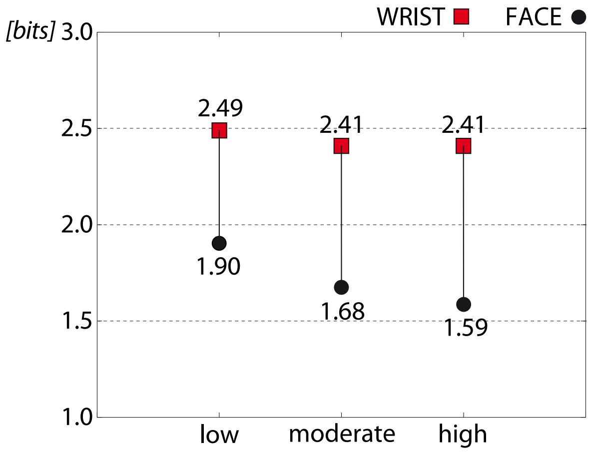

Figure 10: The estimated information transfer per trial ($\widehat{T}$) is, as expected, higher for a lower level of attention attracted by the primary task for both "face" and "wrist" configurations. The "face" (or top) configuration achieved, on average, $1.72bits$, the "wrist" configuration $2.44bits$ (increase of more than 40%, almost independent from the level of distraction).

3.3.2. Statistics. As clearly visible in Figure 11, the "wrist" configuration achieved much better results than the "face" configuration. A repeated measures t-test has been performed to ensure the means are different at each of the three distraction levels. Significance α was set to 0.01: $t(1-\alpha, n-1) = t(0.99, 18) = 2.878$. Zero difference between "wrist" and "face" means has been rejected for low, moderate and high distraction: $t_{low} = 5.959$, $t_{moderate} = 5.583$, $t_{high} = 5.151$.

3.3.3. Memorability. The timely flow and the relationship between primary and secondary tasks for one trial is outlined in Figure 8. This time lapse is repeated 48 times per test, with a random variation of primary task complexity ((i) low, (ii) moderate, and (iii) high; 16 trials each) and time of appearance of the tactile signal ((i) in the range 2–$5sec.$ and (ii) 5–$8sec.$; 50% for each of the two cases).

We expected results to show an increased perception in the visual task after the tactile pattern was sent, since it

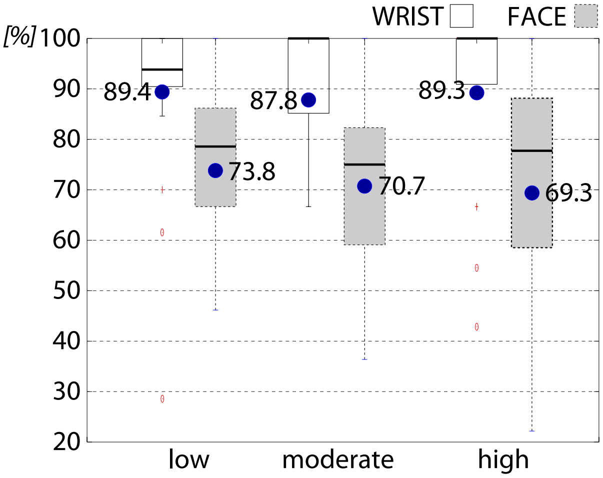

Figure 11: The “wrist” configuration achieved a much better rate of correct responses compared to the “face” configuration, valid for all three investigated levels of attention (the dots represent corresponding mean values).

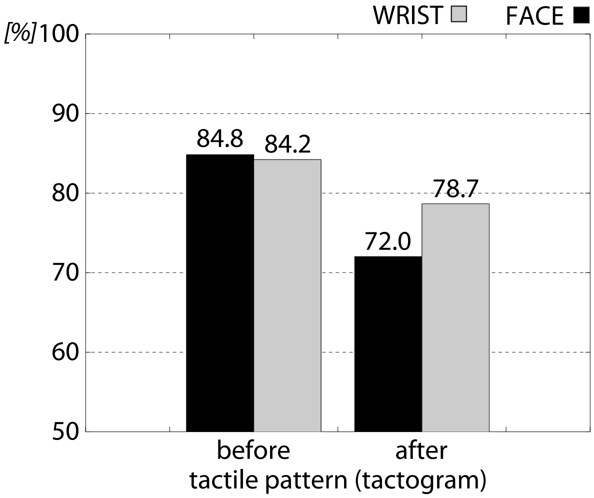

Figure 12: Correct hit rate for the primary task and both configurations before and after the appearance of the secondary task (recognition of a tactile pattern).

was predefined that only one tactogram per single trial would appear (see Figure 8). Following this, the test person’s attention could completely be shifted toward the primary task after recognition of the tactile pattern (sequence). Results showed quite the contrary: after the end of the tactile task, visual perception of the target number “42” decreased by $84.8-72.0{=}12.81\%$ in the “face” and $84.2-78.7{=}5.55\%$ in the “wrist” configuration (see Figure 12). It is supposed that, based on our observations during and questionnaires after the experiment, the test persons were busy in (i) translating the perceived sequence of tactile stimuli into a memorable pattern (e. g. direction of activation and last vibrating tactor) and (ii) remembering the stated pattern. These two subtasks demanded a certain level of cognitive load and thus, lead to a reduced brain capacity remaining free for the primary task.

The observed differences in the decrease of the correct hit rate for the primary task between “face” and “wrist” configurations gives rise to the suspicion, that it is more difficult to recognize and temporarily remember a tactile pattern according to the “face”, rather than to the “wrist” configuration (see Figure 12).

4. Conclusion

Wrist worn wearables have a long tradition in wearable computing research. Only recently, the potential gains of a wrist worn device serving as a nondistracting, nondisruptive tactile display have attracted research efforts towards vibrotactile information delivery via tactor signals as a secondary channel of perception. Among the most crucial issues along these efforts are tactor placement, tactor alphabet design and human perception performance based on the respective modality of communication.

With this work we have raised the question, whether tactile patterns formed with a 4 vibrator display be better perceived when the display is arranged under a watch face on the dorsal side of the wrist versus arrayed around the wrist. Clearly, this research question has a broader context. Ultimately we would be interested in the “amount of information” that could be delivered in a perceivable way to an engaged individual via tactile stimulation patterns.

We have addressed this research issue with (i) the development of a wrist worn vibro-tactile notification system, and systematically and thoroughly analyzing the design space for tactor placements, and (ii) with the design of an experiment reflecting an everyday dual-task situation, where a visual-motor stimulus-response modality task is considered primary, and the tactile-vocal secondary.

On the system development side we have identified a spotted (“face”, underneath the watch face) and an embracing (“wrist”, inside and along the watch band) placement as being the two diametral ends of a spectrum of possible placement strategies. We have built a tactor system according to the physiognomic characteristics of tactile signal perception (two point discrimination), and have experimented in $1,823$ trials on human perception performance from wrist worn wearables. Particularly, our experimental studies investigated the feasibility of wrist worn, watch-type vibro-tactile displays in heavy primary visual task engagements of individuals, using three distraction load levels. We deliver evidence, for the “wrist” placement achieving an 41.6% increase in estimated information transfer $\widehat{T}$ over the “face” placement.

Further, our experiments show that distraction load has low impact on information transfer for “wrist” (3.23%) but a rather high (16.67%) for the “face” placement. This confirms the hypothesis of increased task complexity of perceiving and memorizing the tactile pattern in the face (i. e., spotted) configuration. This leads to a decrease in primary task success rate (12.81% in the “face” vs. 5.41% the “wrist” placement. The lower spatial information density in the “wrist” placement seems to have an effect on both the information transfer and level of attention in the primary task. Our results suggest, that the “wrist” placement is more suited for a wrist worn tactile displays, just because the “face” placement severely restricts the design space wrt. the two point discrimination requirements.

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