BuzzWear: Alert Perception in Wearable Tactile Displays on the Wrist

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ABSTRACT

We present two experiments to evaluate wrist-worn wearable tactile displays (WTDs) that provide easy to perceive alerts for on-the-go users. The first experiment (2304 trials, 12 participants) focuses on the perception sensitivity of tactile patterns and reveals that people discriminate our 24 tactile patterns with up to 99% accuracy after 40 minutes of training. Among the four parameters (intensity, starting point, temporal pattern, and direction) that vary in the 24 patterns, intensity is the most difficult parameter to distinguish and temporal pattern is the easiest. The second experiment (9900 trials, 15 participants) focuses on dual task performance, exploring users' abilities to perceive three incoming alerts from two mobile devices (WTD and mobile phone) with and without visual distraction. The second experiment reveals that, when visually distracted, users' reactions to incoming alerts become slower for the mobile phone but not for the WTD.

Author Keywords

Tactile display, wearable computing, attention

ACM Classification Keywords

H.5.2 User Interfaces: Haptic I/O.

General Terms

Experimentation, Human Factors, Performance

INTRODUCTION AND MOTIVATION

Mobile computing generally implies multitasking [18]. Researchers have explored several issues that are considered in designing multitasking friendly mobile user interfaces (UIs) such as proximity and access time [20, 1], resource management for attention [18], and alternative modalities to deliver information [4, 6]. Whether the attempt to perform multiple tasks is processed simultaneously or successively while the user is on-the-go, appropriate management of attentional and motor resources is a key issue in designing multitasking friendly mobile UIs.

Perceiving alerts on handheld devices while on-the-go is relatively expensive because the interaction often requires visual attention and motor distraction. The wide use of vibrating alerts in commercially available mobile phones implies that utilizing the sense of touch as an alternative attentional channel is especially beneficial for mobile interaction, during which audio-visual attention is often unavailable. The recent commercialization of wearable interfaces such as wristwatch phones reflects the emerging trend towards ready-at-hand mobile interactions. One of the benefits of wristwatch interfaces is fast device acquisition [1]. We wish to explore how integration of these two promising trends, mobile tactile displays and wristwatch interfaces, can facilitate distraction-free alert perception.

In this paper, we present the design and evaluation of wearable tactile displays (WTDs) that are developed to eliminate the need for visual attention for alert perception and motor engagement for device acquisition. The first experiment explores how easily users can identify 24 tactile stimuli (patterns) on the wrist by discriminating four parameters (intensity, starting point, temporal pattern, direction). Since we focus on the perception of the tactile stimuli on the wrist, more sophisticated factors [16] in designing tactile information such as mapping the tactile patterns to meanings (tactile icons) or learning are not included in current study. The second experiment investigates the benefits of the WTD in visually distracted conditions. We compare user perception with the WTD with vibro-tactile alerts on a consumer mobile phone.

RELATED WORK

Tactile Perception and Tactile UIs

Tactile sensation is initiated by the contact between the skin and an object when the distribution of the skin deformation excites four mechanoreceptors across the body: Meissner corpuscles, Merkel cells, Ruffini endings, and Pacinian corpuscles. Sensitivity to perceive tactile stimuli depends on various factors such as the characteristics of the stimuli (e.g., intensity, frequency, temporal pattern, spatial pattern) [19], placement, gender, and age [25]. Studies reveal that spatial and temporal patterns are easier to discriminate than frequency and intensity [10, 5]. In general, human perception to localize the locus of the vibro-tactile stimulation is maximized when the sensation is generated near anatomical points of reference, such as the wrist and elbow [8].

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Tactile displays, which are composed of single or multiple actuators, utilize the sense of touch to render information. Researchers have explored the contribution of tactile displays in many areas such as sensory substitution for vision or hearing [2, 13], spatial orientation and navigation [24], and exploration of virtual environments to support augmented user experiences or tele-manipulation [17]. In one-dimensional tactile displays the characteristics of the stimuli are generally determined by intensity, frequency, and temporal patterns focusing on a localized single tactile actuator. Brown and Brewster [5] explored the recognition rate of 27 tactile patterns with three types of rhythms and three types of roughness that were generated on a single point actuator in three positions at the forearm.

Two-dimensional tactile displays enable more sophisticated patterns by utilizing the spatial configuration of multiple actuators. In two-dimensional tactile displays, spatial patterns often involve a directional sensation, in which the stimulation is generated in a sequential manner from locus to locus rather than in isolation. In the directional patterns, a sensory illusion, which is known as sensory saltation or the cutaneous rabbit phenomenon [11], is generated between loci as a gradual movement. Sensory saltation is affected by several factors such as the two-point discrimination threshold in the distance between actuators(TPDT), inter stimuli interval (ISI), saltatory area, and repetition [11]. Borst and Baiyya [3] investigated the recognition accuracy of three parameters (position, direction, and intensity) in a two-dimensional tactile display and revealed that people can interpret multiple parameters in combination.

Attention and Dual Task Performance

Humans perform multiple tasks simultaneously or successively based on their strategy for managing attentional resources (selective, divided, or focused attention). When multiple stimuli are presented, the decision to select, prioritize, or ignore the stimuli is mostly affected by the consistency of the information or user proficiency to process attentional phenomena (automatic or control processing) [22]. In general, the limited capacity or bottleneck of human attention induces the selection of one task at the cost of other stimuli [22] or time-sharing of multiple tasks at the cost of inefficiency [26].

When designing multitasking friendly mobile UIs, exploring the ability to manage attentional resources is essential to ensure safe and efficient interaction. Rubinstein's [21] and Schumacher's [23] studies revealed that people's ability to perform dual tasks depends on resource management for stimulus-response (S-R) channels. In Rubinstein's study [21] where only one S-R channel was provided to process interaction (e.g., visual stimulus and motor response), dual task performance was worse than single task performance because of the frequent shifting of visual attention between tasks. On the other hand, in Schumacher's study [23] which provided an independent S-R channel for each task (i.e., visual stimulus and motor responses for one task, and auditory stimulus and vocal responses for the other task), the tasks did not interfere with each other and people concurrently performed two tasks as fast as separate single tasks after a certain amount of practice. The result of Schumacher's study indicates that humans can perform dual tasks to some extent when the S-R channel for one task does not overlap with the S-R channel for the other task. Thus, touch may provide an appropriate alternative modality to present information in mobile UIs when users have to reserve their visual attention for other tasks.

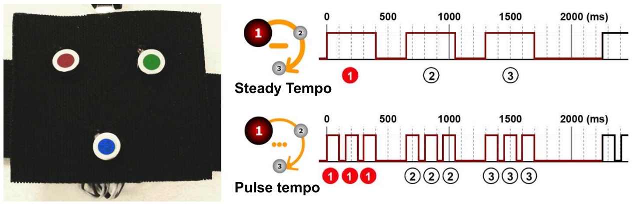

Figure 1. A wrist-mounted tactile display with three vibrating motors (left). A tactile pattern that starts at 1 and moves in the clockwise (CW) direction with strong intensity and steady vibration (right-top). A pattern that starts at 1 and moves in the CW direction with weak intensity and pulsed vibration (right-bottom).

DESIGN OF TACTILE DISPLAYS AND PATTERNS

As recommended by Chen et al. [7], our WTDs were developed with three actuators in a triangular layout (Figure 1) to provide tactile stimuli on the volar side (same side as the palm) of the wrist to ensure clear localization. Unlike Chen's study that only explored the identification of the localized tactors on the wrist, our study focuses on the discrimination of the multiple parameters that are configured to generate directional tactile patterns on two-dimensional WTDs.

The design of the temporal patterns (Figure 1) is based on our previous research [14] in which subjects reached 90% accuracy in perceiving twelve directional patterns in a 4x4 grid (60mm x 60mm). Unlike our previous study, we increased the center-to-center distance between actuators from 16mm to 30mm to ensure easier perception. In our WTD system, three button-shaped shaftless vibrating motors (Precision Microdrives #310-101, d=10mm, h=3.4mm) are attached to an elastic wrist strap. Wiring^{TM} microcontroller (http://www.wiring.org.co/) is connected to a laptop computer to control the motors.

Twenty-four directional tactile patterns were designed by manipulating four parameters: starting point (motor 1, 2, and 3), direction (clockwise and counterclockwise), temporal pattern (steady or pulsed), and intensity (weak or strong). The pattern of the tactile stimulus is repeatedly generated on the wrist until the participants respond through the mouse or keypad. The start-to-start duration of each pattern is 2.25 seconds, including the interval for repetition. (Figure 1)

The design of the testing interface (Figure 2) focuses on the efficient visualization of the icon for each pattern so that the participants can easily narrow down the perceived parameters to match what they feel on the skin with what they see on the screen. In the testing interface, starting point (red, green, and blue for point 1, 2, and 3) and intensity (dark color for strong intensity and pale color for weak intensity)

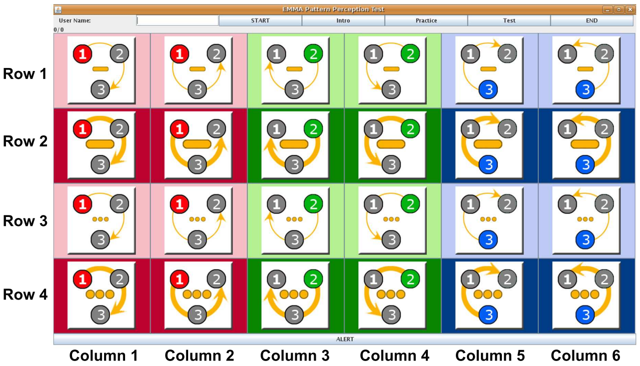

Figure 2. Testing interface, which reflects the design of the 24 patterns: Intensity (Weak: Row 1,3, Strong: Row 2,4), Temporal pattern (Steady: Row 1,2, Pulsed: Row 3,4), Direction (Clockwise: Column 1,3,5, Counterclockwise: Column 2,4,6), Starting point (One: Column 1,2, Two: Column 3,4, Three: Column 5,6)

are color-coded whereas direction (arrow) and temporal pattern (dash for steady vibration and dots for pulsed vibration) are visualized with corresponding symbols. The intensity for the strong and weak patterns is 0.71g (175Hz) and 0.43g (133Hz) respectively.

Through a pilot test with three participants, the intensity for weak patterns (0.43g, 133Hz) was selected as a minimum threshold for detecting incoming patterns. To find the minimum threshold where subjects can clearly distinguish incoming tactile patterns, the input voltage of the system was gradually increased from zero to maximum.

OVERVIEW OF EXPERIMENTS

This paper explores people's alert perception performance in WTDs through two experiments. The first experiment explores user ability to perceive 24 tactile patterns associated with four parameters. The second experiment explores the benefit of WTDs in perceiving three patterns in visually distracted conditions. Additionally, we compare our subjects' ability with the WTD to their ability to perceive three alerts on a current mobile phone.

Preliminary Survey

The data for the first and the second experiment was collected from 28 participants (nine female, 19 male, mean age 26.6 years) who were recruited from the Georgia Institute of Technology. Twelve people participated in the first experiment and 16 people participated in the second experiment. None of the subjects of the second experiment participated in the first experiment or vice versa. Four of the participants were left-handed. However, since all left-handed participants used their right hand when controlling the computer (e.g., with a mouse), all participants were effectively right-handed in both experiments.

The average width of the left wrist (non-dominant hand) for male and female participants was 57.46mm and 50.76mm, respectively. The average circumference around the wrist for male and female participants was 168.08mm and 146.75mm, respectively. 57.14% of the participants did not wear a wrist watch daily. These participants reported that wrist watches were uncomfortable to wear (43.75%), were unnecessary because they used their mobile phone for the time (37.50%), or were only an accessory for special occasions (18.75%).

Study Setting and Analysis

Both experiments were conducted in a quiet lab setting. During the test, participants were asked to wear ear plugs and headphones to block audio cues from the system that might affect the performance.

The three main dependent variables for analysis are accuracy, reaction time and information transfer (IT_{est}). IT_{est} (bits) is calculated as shown in formula (1) for each experiment to assess the combined result of accuracy and reaction time (bits/sec) and the number of correctly recognized patterns (integer part of $2^{IT_{est}}$).

$$IT_{est}(bits) = \sum_{j=1}^{k}\sum_{i=1}^{k}\frac{(n_{ij})}{n}\log_{2}\frac{n_{ij}\cdot n}{n_i\cdot n_j} \tag{1}$$

In formula (1), which is widely used to summarize the results in similar research [7, 24], *k* is number of stimulus alternatives, *n* is total number of trials, *i* and *j* are the indices for stimuli and responses respectively, n_{ij} is the number of trials when the stimulus *i* is reported as *j*, n_i is the total number of trials that the stimulus *i* is presented, and n_j is the total number of trials that the user responds as *j*.

Software and Equipment

For both experiments, software written in Java displays a testing interface and collects log data with time stamps. For the phone alert perception task in the second experiment, the software is implemented in Python on a Motorola E680i camera phone.

EXPERIMENT1: PERCEPTION EXPERIMENT

Twelve subjects participated in this experiment (three female, nine male, mean age 26.54). The test duration was approximately an hour.

Research Question and Hypothesis

The purpose of this experiment is to explore people's ability to perceive patterns of incoming tactile stimuli on the wrist, which involves the simultaneous perception of multiple parameters. Based on the promising result of our previous study [14], we hypothesize that people can reach at least 90% accuracy.

Task and Apparatus

Participants were asked to wear a WTD on the non-dominant wrist while using a mouse with the dominant hand to control the testing interface (Figure 2) on the laptop computer. Once the participants pressed the alert button at the bottom of the testing interface, a 2.25 second long pattern (Figure 1) was generated and repeated until the participants press an icon on the screen (Figure 2). The pattern for the next trial was generated when the participants pressed the alert button again.

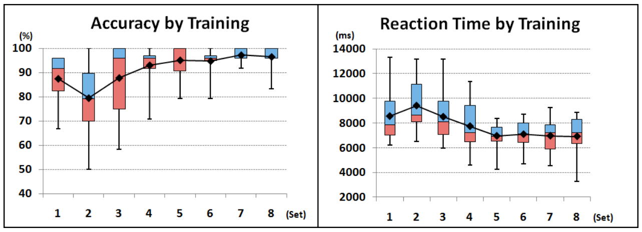

Figure 3. Accuracy and reaction time in the practice (set 1-3) and main sessions (set 4-8) of experiment 1

Procedure

The experimental was divided into three sessions: introduction (one set), practice (three sets), and main (five sets). For each set in all three sessions, each pattern is generated only once. A minimum five minute long break is enforced between sessions. Between trials of each session, participants are encouraged to adjust the location and tightness of the strap to maximize perception sensitivity and comfort and to take enough break time to avoid a possible adaptation effect that may decrease perception sensitivity.

In the introduction session, the color coding and symbols in the testing interface was explained to assist participants. Then each pattern was generated in numeric order as the participants pressed the alert button (one set x 24 patterns). The purpose of the introduction session was to allow participants to experience each parameter of the tactile patterns and to see its associated icon on the testing interface. In the practice session, 72 patterns were generated in random order (three sets x 24 patterns). The purpose of this session was to help participants practice matching what they feel on the wrist with what they see on the screen. The practice session also allowed subjects to optimize the tightness and comfort of the hardware as much as possible. In the main session, 120 patterns were generated in random order (five sets x 24 patterns). During the practice and the main sessions, the accuracy and reaction time for discriminating incoming alerts were measured. After completing the main session, participants were asked to complete a survey to rate their difficulty in distinguishing each parameter.

Results

Accuracy and reaction time

The average time to finish the practice (set 1-3 in Figure 3) and the main session (set 4-8 in Figure 3) was 15.54 minutes and 20.90 minutes, respectively. The break time between trials in the practice and the main session was 4.19 seconds and 2.96 seconds respectively. The break time between the practice and the main session was 7.67 minutes on average.

The learning effect across all eight sets across practice and main session is statistically significant ($p < .05$) both in accuracy and reaction time using a one-way ANOVA (Figure 3).

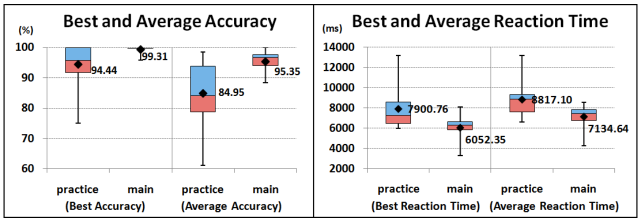

Figure 4. Best and average accuracy by session (practice & main): accuracy (left), reaction time (right)

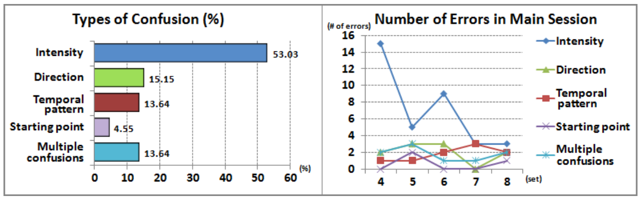

Figure 5. Types of confusion in main session (set 4 - set 8): Types of confusion (left), Number of errors in the main session (right)

The highest set accuracy for the practice and the main session was 94.44% (SD = 7.4) and 99.32% (SD = 1.62), respectively (Figure 4, left). Ten out of twelve participants achieved 100% accuracy in at least one set. The average accuracy for the practice and the main session was 84.95% (SD=10.62) and 95.35% (SD=4.01), respectively.

The fastest set reaction time for the practice and the main session was 7.90 seconds (SD = 2.02) and 6.05 seconds (SD = 1.20), respectively (Figure 4, right). The average reaction time for the practice and the main session was 8.82 seconds (SD=1.91) and 7.13 seconds (SD=1.10), respectively. The IT_{est} calculated by the formula (1), the bits per second, and $2^{IT_{est}}$ (number of correctly recognized patterns) are 4.28 bits, 0.60 bits/sec, and 19, respectively.

Confusion between parameters

The confusion matrix for the main session indicates that intensity is the hardest parameter to recognize (53.03%, Figure 5, left). However, confusion on intensity level is reduced with practice (Figure 5, right) from 75% (set four) to 30% (set eight). The average error caused by intensity, direction, temporal pattern, and starting point are 53.03%, 15.15%, 13.64%, and 4.55% respectively.

A post-hoc analysis indicates that the effects of the temporal pattern in accuracy (Figure 6, left, p=.003) and the effect of the intensity in the reaction time (Figure 6, right, p=.004) are statistically significant after Bonferroni correction. The average accuracy in the patterns with the pulsed vibration and the steady vibration (Figure 6, left) are 96.81% (SD = 2.07) and 93.89% (SD = 2.18), respectively. This result indicates that patterns with the pulsed vibration are distinguished more correctly than patterns with the steady vibration. The average reaction time for the patterns with strong and weak intensity (Figure 6, right) are 6.76 seconds (SD = 0.59) and 7.57 seconds (SD = 0.64), respectively. This result indicates that patterns with the strong intensity enable faster reaction time than the patterns with weak intensity. The effect of the other parameters in the performance are not statistically significant after Bonferroni correction.

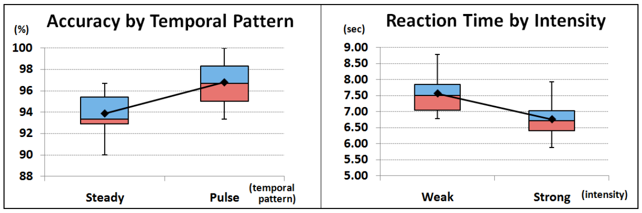

Figure 6. Effect of the parameter in the main session (set 4 - set 8): accuracy by temporal pattern (left), reaction time by intensity (right)

Subjective rating for each parameter and strategy

The participants' subjective rating of the difficulty in perceiving each parameter is slightly different from the confusion that was measured from their performance. For subjective ratings that range from -2 (very difficult) to 2 (very easy), participants reported that intensity was the most difficult parameter to perceive (-0.23), followed by the starting point (0.31), and the direction (0.31). However, the temporal pattern was the easiest parameter (1.62).

Difficulty in perceiving intensity was observed in two aspects. Some participants reported that the difficulty was caused by the fact that the difference between the strong and weak patterns was not significant. On the other hand, other participants reported that although the difference between the weak and strong patterns was significant, the weak patterns were too weak for them to clearly distinguish other parameters such as the starting point. Additionally, some participants reported that a weak pattern generated after a strong pattern was harder to discriminate. This result indicates that sensitivity in perceiving intensity in tactile patterns varies from person to person and from situation to situation.

Difficulty in perceiving the starting point was mainly caused by misaligned hardware and adaptation effects. The tightness of the strap and motor alignment on the skin affected the participants' sensitivity in perceiving the starting point. Participants reported that this difficulty was mostly eliminated by readjusting the hardware during the practice session. An adaptation effect was partially observed during the test. Some participants reported that they felt like the skin under a particular motor was immune to sensation.

Difficulty in perceiving direction was mostly caused by an unfamiliarity in constructing a mental model for circular movement. Some participants reported that building a mental model for clockwise (CW) and counterclockwise (CCW) was difficult. Other participants reported that matching tactile direction on the skin with visual direction on the display was difficult.

Unlike other parameters, difficulty in perceiving temporal patterns was rarely observed. Most people reported that they could easily discriminate the temporal pattern. The easy perception of the temporal pattern affected people's strategy for narrowing down the selection from 24 patterns. Most of the people began narrowing down the selection by discriminating the temporal pattern first. The rest of the procedure varied from person to person.

Summary

After the 40 minutes of training, as we hypothesized, people achieve up to 99.32% accuracy and a reaction time of 6.05 seconds when identifying 24 tactile patterns. The IT_{est} (bits), the bits per second, and number of correctly recognized patterns are 4.28 bit, 0.60 bit/sec, and 19 patterns respectively.

Among the four parameters that are investigated in this experiment (intensity, starting point, temporal pattern, and direction), intensity is the most difficult parameter to perceive. Intensity especially affects reaction time whereas temporal pattern affects accuracy. The subjective ratings and self reports indicate that people have difficulty discriminating intensity, direction, and starting point for various reasons. However, difficulty to perceive temporal pattern is rarely observed.

EXPERIMENT2: DUAL TASK EXPERIMENT

Sixteen subjects participated in the second experiment (six female, ten male, mean age 26.69). The test duration was approximately 1 hour and 30 minutes. The data from one participant who did not follow the described procedure was excluded from the analysis.

Research Question and Hypothesis

This experiment explores the benefits of the WTD in visually distracted conditions (Compared to a mobile phone, does the WTD enable faster and more accurate alert perception in visually distracted conditions?). Two hypotheses are listed as follows: 1) Since device acquisition and visual attention are not required, the WTD enables faster and more accurate alert perception than the phone in visually distracted conditions; 2) As the visual distraction gets harder, perceiving alerts from both WTDs and phones also becomes more difficult. However, WTDs are less affected by the distraction than the phone.

Task, Terminology and Apparatus

On-the-go use of mobile devices involves both interaction with the world (e.g., face-to-face conversation, walking) and interaction with the mobile device (e.g., answering a phone call). Here and throughout the paper, we define the interaction with the world as the primary task and interaction with the mobile device as the secondary task. A visual screening task with three difficulty levels (easy, moderate, difficult) is selected as a primary task (Figure 7, left). An alert perception task with two mobile devices (WTD and mobile phone) is selected as a secondary task. Performance of the primary and the secondary task is measured both in the single and dual task conditions. Dual tasks are composed of one primary task and one secondary task (Table 2).

Primary task

A forced-choice visual screening task with three difficulty levels is provided as a primary task. Participants are asked to find the target stimulus (i.e., the number 57) among other two digit numbers in the screen in five seconds and verbally respond with 'yes' or 'no'. 50% of the trials contain the target stimulus and are presented in random order. The location and combination of presented two digit numbers of

	Task	Stimulus	Response
Primary	Visual screening task	Visual	Vocal
Secondary	Wearable tactile display	Tactile	Motor
	Mobile phone	Tactile + visual	Motor

Table 1. Modality of stimulus and response in each task

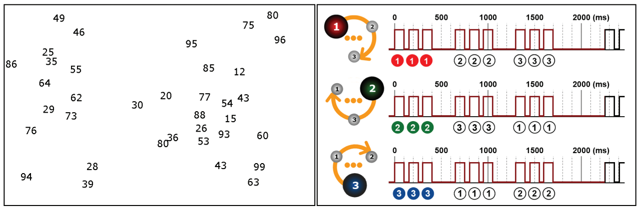

Figure 7. Primary task level 3 with 36 two digits numbers (left), three tactile patterns with three starting points in the WTD (right)

each trial is randomly selected. Participants stand while facing a screen that is configured on the eye level (Figure 8, D). The modality for S-R channel (i.e., screening visually and responding verbally) is selected to avoid modality conflict with the secondary tasks (Table 1). The difficulty level is controlled by the number of stimuli (i.e. two digit numbers) presented in each trial. 9, 25, and 36 stimuli are displayed in level 1, 2, and 3 respectively (Figure 7, left).

The number of stimuli to provide the three difficulty levels for the primary task was selected from a pilot test. In the pilot test with seven participants, visual screening performance with five levels (i.e., 4, 9, 16, 25, and 36 stimuli) was measured. Participants were asked to find '57' in the screen and provide a vocal response. For each participant, 30 trials with five second intervals were provided for each level (30 trials x 5 levels x 7 participants = 1050 trials). Based on the result of the pilot test, three levels with 9, 25, and 36 stimuli were selected because the resulting accuracies (and presumably the difficulties) were evenly distributed as 99%, 95%, and 91%. A 5 second interval was long enough to perform the task in the level with nine stimuli. However, people rarely provided the answer within 5 seconds when presented with 36 stimuli.

Secondary task

For the secondary tasks, the subjects' ability to perceive three types of alerts from the WTD worn on the wrist or the mobile phone (Motorola E680i camera phone with touch screen display) stored in the pocket is explored.

In a preliminary survey, 69% of the participants (nine males and one female) reported that their preferred place to store their phone is the pocket (echoing the survey conducted by Cui et al. [9]). Thus, we used an apron with pockets to standardize device acquisition and alert perception with the mobile phone (Table 3). A wireless keypad is attached on the surface of the dominant hand side of the pocket to enable vision-free motor responses. A mobile phone is stored on the non-dominant hand side of the pocket (Figure 8, A). All keys in the wireless keypad except three buttons are deactivated and covered with a plastic lid to avoid motor errors (Figure 8, C). Participants are asked to stand during the test to ensure easy access to the mobile phone in the pocket.

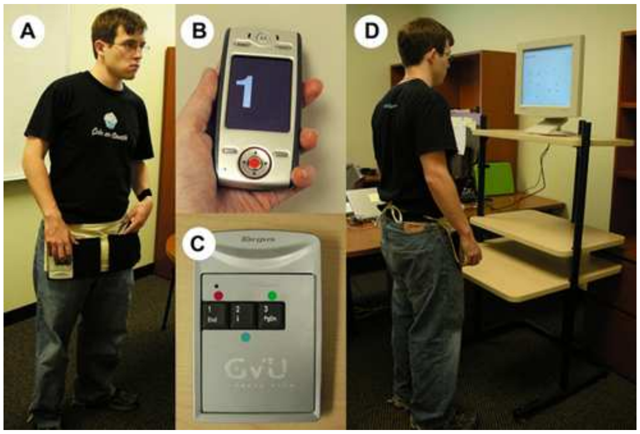

Figure 8. Test setting: A) A participant wears an apron with pockets. A wireless keypad is attached on the dominant hand side and a mobile phone is placed in the pocket of non-dominant hand side. B) A visual alert from the mobile phone. C) A wireless keypad with three buttons. D) Rear view of the participant.

	Single task					Dual task					
ID	S1	S2	S3	S4	S5	D1	D2	D3	D4	D5	D6
Primary	L1	L2	L3	-	-	L1	L2	L3	L1	L2	L3
Secondary	-	-	-	W	P	W	W	W	P	P	P

Table 2. Conditions and tasks in the main session of experiment 2 (L1=level 1, L2=level 2, L3=level 3, W=WTD, P=phone)

For the trial with the mobile phone, a four second vibrating alert (two times x 2 seconds) is generated along with a visual alert that displays 1, 2, or 3 on the phone (Figure 8, B). Once the participant perceives the vibration from the phone, she takes the phone out of the pocket, reads the number on the screen, presses the corresponding button on the wireless keypad, and restores the phone to the pocket. The S-R modality (Table 1) for the phone alert task is designed to simulate representative interactions in the real world.

In the test with the WTD, participants were asked to wear the tactile display on their non-dominant wrist. Three tactile patterns are selected based on the result of the first experiment (Figure 7, right). In these three patterns, the starting point varies (1, 2, and 3), but direction (clockwise), intensity (strong), and temporal pattern (pulsed) are constant. Once the participant perceives the pattern of the incoming alert on the wrist, they key the appropriate response on the wireless keypad.

Procedure

Since individual sensitivity varies in perceiving tactile stimuli, a within-subject design method is used in this experiment. The order of the task conditions (visual screening task, alert perception task from the WTD, alert perception task from the mobile phone) and distraction conditions (single and dual task) are balanced (3x2x2 = 12 orders). The order for three difficulty conditions (level 1, 2, and 3) in the primary task is randomized. The order for the 13th, 14th, 15th, and 16th participant is identical with 1st, 4th, 7th, and 10th participant.

The experimental procedure is divided into three sessions: practice, main, and post. In the practice session, five trials for each level in the primary task (3 levels x 5 trials = 15 trials) and six trials for each device in the secondary task (2 devices x 3 patterns x 2trials = 12 trials) are provided as single tasks. Since the spatial configuration between the three motors in the WTD (triangular) and three buttons in the keypad (linear) is inconsistent, participants are asked to build their own mental mapping between the two during the practice session.

In the main session, the data for accuracy and reaction time is collected through logged data from the secondary task and audio-video recording for the primary task. Primary tasks with three levels and secondary tasks with two devices are tested both in the single and dual task conditions (Table 2). In the single task conditions (Table 2, S1-S5), the performance of the three primary tasks and two secondary tasks are measured independently. In the dual task conditions (Table 2, D1-D6), each level of the primary task is paired with each device of the secondary task. The number of trials in each condition for the primary and secondary tasks is 60 and 15, respectively. The interval between trials in the primary task is five seconds (5 seconds x 60 trials = 5 minutes/condition). The interval between trials in the secondary task is randomly assigned between six and 18 seconds (12 seconds in average). The duration for the secondary task depends on the subject's reaction time.Participants have a short break every 15 minutes to avoid fatigue.

In the post session, a semi-structured interview and a workload assessment survey with the NASA-TLX focusing on the mental, physical, and temporal demand is performed.

Results

Independent variables for the primary task are difficulty (level 1, 2, and 3) and distraction (no distraction, distraction from a WTD, and distraction from a phone). Independent variables for the secondary task are alert type (WTD and phone) and distraction (single and dual task).

Secondary task

The accuracy in perceiving incoming alerts with the WTD and the mobile phone (Figure 9, left) is above 96% in general. In the perception task with the WTD, the effect of the visual distraction is statistically significant with respect to reaction time (Figure 9, right, Figure 10, left, p=0.002) but not with respect to accuracy, as determined by a paired t-test. Interestingly, compared to the single task condition for WTD (Table 2, S4) and dual task with level 1 (Table 2, D1), the reaction time to perceive incoming tactile alerts is faster in a visually distracted condition (D1). As the amount of distraction increases to the moderate (level 2: Table 2, D2) and difficult levels (level 3: Table 2, D3), the reaction time to perceive incoming tactile alerts decreases. However, reaction time to perceive incoming tactile alerts in the most difficult dual task condition (D3) is still faster than the single task condition (S4). We will discuss this counter-intuitive benefit of distraction later.

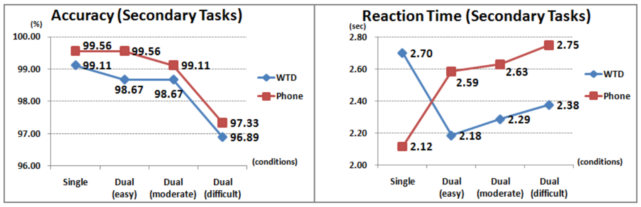

Figure 9. Secondary task: Accuracy (left), reaction time (right)

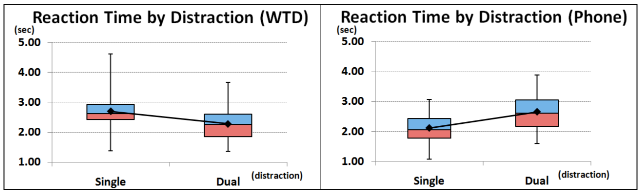

Figure 10. Reaction time by distraction: WTD (left), phone alert (right)

In the perception task with the phone, the effect of the distraction is statistically significant with respect to the reaction time (Figure 9, right, Figure 10, right, p=.003) and the accuracy (p=.028) using a paired t-test. One of the features that might affect the reaction time for the phone alert is device acquisition time. Time to acquire the phone from the pocket is measured by collecting the brightness of the light received by the camera on the Motorola E680i phone. While the participant perceives and responds to the incoming alert on the phone, the changing light level is collected to track time stamp data for each event (Table 3). This technique is the same as the one used in the similar study that explored the device acquisition time of mobile phones [1].

Interaction	Time stamp events
Event1. Alert is generated	Alert is generated
Event2. Participant pulls the phone from the pocket	Light level changes to bright.
Event3. Participant clicks the button on the keypad	Button press
Event4. Participant replace the phone to the pocket	Light level returns to dark.

Table 3. Time stamp events in phone alert task

The time between each event in Table 3 is defined as pocket time (between event 1 and 2), in-hand answer time (between event 2 and 3), and replacement time (between event 3 and 4). The effect of the visual distraction on the pocket time, in-hand answer time and replacement time is not statistically significant. The average time from event 1 to 4 is 3.89 seconds. The average pocket time, in-hand answer time, and replacement time is 1.68 seconds (43.11%), 0.94 seconds (24.10%), and 1.28 seconds (32.79%), respectively.

The IT_{est} for the WTD in single (S4) and dual task condition with difficult distraction (D3) are 0.56 bits/sec and 0.58 bits/sec respectively. This number indicates that although the user is interrupted by the high level of distraction, the information transfer rate did not deteriorate (Figure 11, top).

Primary task

The effect of the distraction (single task, alert perception with a WTD, alert perception with a phone) on the primary

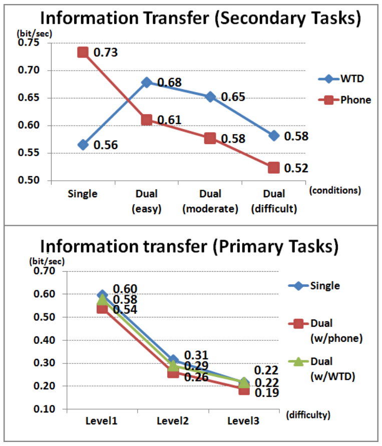

Figure 11. IT$_{est}$: secondary task (top), primary task (bottom)

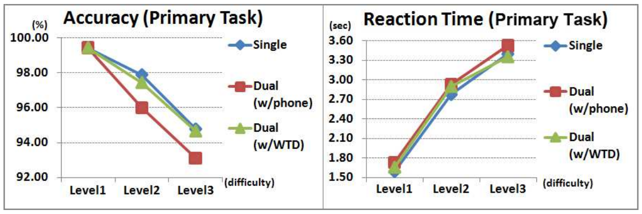

Figure 12. Primary task: Accuracy (left), Reaction time (right)

task is not statistically significant with regard to the accuracy and reaction time. We assume that the distraction does not affect the primary task because of the strategy that prioritizes the primary task to manage multitasking. Details are discussed below. The effect of the difficulty (level 1, 2, and 3) is significant in the accuracy (Figure 12, right, Figure 13, right, $p<.01$) and the reaction time (Figure 12, right, Figure 13, right, $p<.01$) using a one-way ANOVA. The IT$_{est}$ for level 1, 2, and 3 when distracted by the phone alerts perception task are 0.54 bits/sec, 0.26 bits/sec, and 0.19 bits/sec, respectively. These numbers slightly increase to 0.58 bits/sec, 0.29 bits/sec, and 0.22 bits/sec when distracted by tactile alerts perception task with the WTD (Figure 11, bottom).

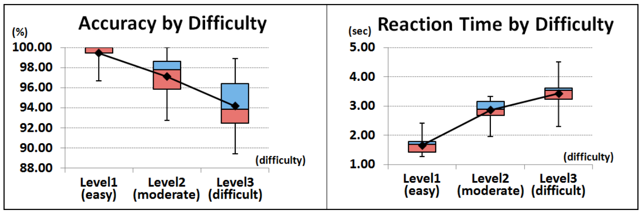

Figure 13. Primary task by difficulty: Accuracy (left), reaction time (right)

Workload assessment and strategy to manage dual tasks

The mental, physical, and temporal demand for the six conditions (i.e., single-primary, single-secondary with a phone, single-primary with a WTD, dual-primary, dual-secondary with a phone, dual-secondary with a WTD) are explored during the post session through open-ended questions guided by the NASA-TLX survey and a semi-structured interview. Participants reported that temporal workload was the most dominant factor that affected the primary task due to the five second time limit in each trial. Thus, when the dual task trial arrived, people tended to prioritize the primary task rather than the secondary task, which could be temporarily set aside and performed later. Compared to the single task condition, mental workload increased in the dual task conditions. Physical workload such as fatigue in the eyes and legs was observed when performing the primary task in both single and dual task conditions.

Physical workload was the most dominant factor in phone alert perception both in the single and the dual task conditions, possibly due to the device acquisition. Mental workload was rarely observed either in single or dual task conditions with phone alert perception.

On the other hand, mental workload was the most dominant factor in tactile alert perception with the WTD both in the single and the dual task conditions. Five different types of mental models were observed from 16 participants when mapping the spatial configuration between the triangular motor layout and linear keypad layout that is associated with the numeric labels (1, 2, 3) [15]. Although participants performed the task with their own preferred mental model, they still reported that matching these two different concepts was difficult. The sequential movement of the stimuli with the WTD contributes to reduce the temporal workload. Even though the participants failed to perceive the first locus in the pattern, the consecutive loci of the remaining two motors guided them to determine the missing locus.

Summary

When performing the secondary task, the effect of the visual distraction is observed only in reaction time but not in accuracy. In the single task condition, the reaction time of the WTD is slower than the phone reaction time. However, in the dual task condition, the reaction time of the WTD is faster than the phone reaction time. Interestingly, when perceiving alerts from the WTD, the reaction time in the dual task condition is faster than the single task condition. In the reaction time for the phone alerts, pocket time to acquire the device took longer (66%) than the in-hand answer time (34%). When performing the primary task, the distraction caused by the secondary task did not affect the performance.

Different types of the workload were observed across tasks from the workload assessment: temporal workload for the visual screening task, mental workload for the alert perception task using the WTD, and physical workload for the alert perception task using the phone. Due to the temporal workload of the primary task, people tended to prioritize the primary task in general.

DISCUSSION AND FUTURE WORK

Benefits of the WTDs in Visually Distracted Conditions

Attention and engagement

In the second experiment, the effect of the light visual distraction (level 1 primary task) in the reaction time of the secondary task is observed differently across the two devices

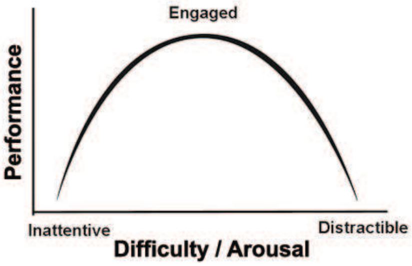

Figure 14. The relationship between performance and perceived difficulty: Yerkes-Dodson Law (adapted from [27])

(Figure 9, right). Although the effect of engagement, stress, and emotion is not measured in our experiments, this different effect implies that the difficulty of the primary task is perceived differently across two devices. According to the Yerkes-Dodson Law, the performance decreases when the difficulty is too low (inattentive) or too much (distractible) [27]. On the other hand, the medium level difficulty maximizes the performance by generating optimal arousal and engagement (Figure 14). Thus, we assume that the perceived difficulty caused by the light visual distraction is too much in one device and moderate in the other. That is, when the light visual distraction (level1-easy) is applied, the perceived difficulty of the phone alert perception changes toward a distractible level that results in a slower reaction time whereas the perceived difficulty of the tactile alert perception with the WTD changes toward an engaged level that results in a faster reaction time.

As already proven by a similar study that measured the relationship between task difficulty and engagement [12], we observed that a small amount of visual distraction was still manageable in perceiving tactile stimuli from the WTD and eventually increased the performance engagement. However, since our second experiment was performed in a controlled lab setting, the external validity of this result in the real world situation is unclear. Thus, to generalize this result, future studies that explore the benefits of the WTD in more natural conditions are required.

Attention and automatic processing

Our participants' strategy to prioritize the primary task in the dual task condition implies that selective attention is employed to manage the attentional bottleneck. In the selective attention paradigm, the costs are mainly observed when processing novel and inconsistent information (control processing). Unlike control processing, automatic processing is ideal to bypass attentional bottlenecks [22]. In our secondary task configuration in the second experiment, the alert perception through the WTD, which is novel and requires the additional workload to construct the mental model, is control processing whereas the alert perception through the mobile phone, which is already well-established through the daily use, is automatic processing. Despite this disadvantage in processing attentional phenomena, the IT_{est} in perceiving incoming alerts is higher with the WTD than with the mobile phone.

We assume that higher performance with the WTD in the single and the dual task conditions is possible as the task becomes more automatic. Since our participants reported that the mental workload in perceiving alerts with the WTD was problematic, automatic processing might be facilitated by improving the system (e.g., providing a consistent spatial mapping between the motor and the keypad) and by practice. However, this improvement would be surprising with the mobile phone because the performance is mainly limited by the inherent motor constraints and inefficient time-sharing of visual attention.

Relevance

We have observed various aspects of multitasking behavior in daily interaction. Some of our participants reported that multitasking while on-the-go is unsafe, inefficient, and impolite. However, other participants reported that multitasking while on-the-go helps save time and is becoming more and more ubiquitous. Subjects who already knew or even experienced the unsafe nature of mobile multitasking reported that they were still inclined to do mobile multitasking on a daily basis. As users consume up-to-date services and applications using today's mobile devices, augmenting the safety of on-the-go users by using vision-free WTDs is a promising way to support increasingly ubiquitous mobile interaction.

Limitations of the Study

Although the main focus of this study is limited to the perception of tactile stimuli on the wrist, additional features that may affect the results of the experiments were added while designing the experiments: mapping tactile patterns to visual representations (first experiment); constructing mental models to map the triangular layout of the tactile loci to the linear layout of the keypad (second experiment) [15]. The effect of these factors in the result of the experiments is unclear.

Our study explores only one type of distraction. However, distraction in the wild is richer, more complicated (e.g., ambient noise, presence of other people in the public space, motor demand for walking or holding bags), and less controllable. Based on the result of this study, adding and evaluating the effect of other distractions would help to explore the benefits and limitations of WTDs in more realistic scenario. We also observed possible adaptation effects on the skin in the first experiment and mechanical fatigue (e.g., eyes, legs) in the second experiment. A more longitudinal study with less trials over multiple days would improve these issues. Since the average age of our participants is mid-20s, performance of other age groups should be investigated to ensure the universal benefits of WTDs.

CONCLUSION

Discriminating four parameters (intensity, temporal pattern, direction, starting point) to perceive 24 tactile patterns was easy (up to 99%) after 40 minutes of training. The reaction time to perceive three different incoming tactile alerts on the wrist was not deteriorated by visual distraction. Based on these results, we conclude that wrist-mounted tactile displays are appropriate for implementing multitasking-friendly mobile user interfaces that enable easy alert perception.

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