Proceedings of 2016 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Harbin, China

A Novel Spatial-temporal Encoding Strategy for Presenting Time on the Wrist using Vibrotactile Cues

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***Abstract* - Presenting time accurately with a high resolution using haptic modality on the wrist is a challenging task. In this paper, we present a novel spatial-temporal vibrotactile encoding strategy using 4 motors for presenting time. The hours and minutes were presented using vibrotactile stimuli with a resolution of 5 minutes. The hours were presented by long duration vibrations while the minutes were presented by short duration vibrations. To validate the design we conducted two experiments and measure the reaction time and the correct rate of 12 participants for perceiving the time in the presence of audio-visual distraction. In the first experiment, the hours and the minutes were presented in the focused state. The average reaction time and the correct rate of the users were 9.60sec and 95.22% respectively. In the second experiment, the hours and the minutes were presented in the distracted state. The average reaction time and the correct rate of the users were 11.09sec and 90.55% respectively. This performance was achieved after ten minutes training. These results indicate the potential of using wrist-based haptic sensation to present time.**

Index Terms - Haptic watch, Time-presentation, Wearable vibrotactile devices, Wrist-worn tactile devices.

I. Introduction

Wearable haptic devices are becoming popular nowadays, one of the main reason for this revolution is that haptic channel is the most private modality possessed by humans. In this haptic realm, one important topic is the development of ambient haptic devices which include haptic wearables [1]. Wristwatch is one of the most common and important wearable used by most of the professionals. Recently versatile smart watches are introduced in the market conveying plenty of information to users using the touch modality. Attending number of meetings and conferences daily is ubiquitous for a professional, but quite often it happens that sometimes meetings prolong and individuals having other commitments realize that the time is running out, resultantly they have to watch time several times by the wrist watch or by the clock hanging on the wall in the conference room, this originates quite embarrassing and awkward situation. In this scenario, a possible solution is to present the time to the individual using the haptic channel. Here arises the concept of the haptic watch which may provide eye-free communication of the current time and avoid embarrassment.

A number of solutions have been proposed to present the time using haptic modality. Haptica™ [2] is a Braille watch which presents time to the blind person effectively and precisely without an audible disruption. This watch presents the time to the user using the standard Braille numbering System. The user perceives the time by touching the dots appeared on the watch surface. While this system might be useful for the blind persons, it is difficult to be used by the sighted people who are not familiar with the standard Braille numbering system. Ohtsuka et al. [3] presented a vibration watch using a cell phone for the visually impaired persons. It takes long training time for participants to memorize the complex vibration patterns. Furthermore, as people normally do not hold the mobile phone, therefore there is a huge chance for missing the vibration if the phone is being carried in pockets or bags. Tam et al. [4] developed Wireless Wrist worn Haptic Notification System (HaNS) to moderate time during oral presentations in conferences and seminars. Experimental results show the effectiveness of the system for reminding the speaker to manage time during oral presentations. To the best of our knowledge, it is still an open problem of presenting detailed information of the current time (i.e. hour, minute, second) on the wrist to the users in a high temporal resolution.

Besides presenting time, haptics-based wristwatches have also been developed to present other information and haptics-based wrist-worn wearables are used to study the fundamental concepts of the human psychophysics related to touch. Lee and Starner introduced that wrist is one of the most socially acceptable body location for the vibrotactile stimuli [15]. Pasquero *et al.* [7] implemented a haptic-enabled wristwatch with a single custom-made actuator to support eye-free communication with a mobile device. Their focus was on enabling gesture-based active interactions in which user gets information about email inbox by touching the watch. Their study indicated an overall accuracy of 73.6% for the identification of delivered number of pulses. Moreover, participants responded positively to the informative tactile feedback. Bosman *et al.* [6] established a wearable wristband system comprising of two vibrotactile devices. Each wrist was mounted with a single actuator. Their experimentation revealed that the system was helpful in delivering directional information to the pedestrians. This system helped in reducing the number of errors to reach the destination. Rekimoto *et al.* [5] developed Gesture Wrist, a gesture input device in the form of a wristband, a wrist-worn device that recognizes the hand gestures and forearm movements. Tsetserukou and Tachi [8] developed BraTact, a tactile wristband comprising of six symmetrically arranged vibration motors. Their objective was to convey the shape and stiffness of any colliding object in teleoperation. Weber *et al*. [9] assessed VibroTac, a system similar to BraTact, for providing spatial guidance (translation and rotation of the hand). Lee et.al [14] explored a design space for the watch back tactile display using 3x3 tactators array and presented practical guidelines for the design of an efficient watch back tactile displays.

In all above wearable haptic watches, the key technical challenge is the design of the vibrotactile encoding strategy. In order to present accurate and efficient communication of current time to the user, the design criterion of the key parameters need to be studied, including the number of the vibrotactile cues, the layout and location of the cues on the wrist/arm, and the spatial/temporal pattern of the cues. Furthermore, the vibration pattern should provide least mental workload for users to memorize diverse patterns, and require as short training time as possible.

In this paper, we designed and evaluated a haptic wrist watch to present time to the user using vibrotactile cues. The watch consisted of 4 low-cost vibration motors that were mounted on a wristband. We proposed a novel 4-area vibrotactile encoding strategy to present current hour and minute in a sequential order. The hours were presented by long duration vibrations while minutes were presented by comparatively short duration vibrations. Experimental results validated the accuracy and efficiency of time perception using the watch. The vibration encoding strategy developed can be easily memorized by an individual after 10 minutes training.

II. Prototype of the Haptic Watch

A. Requirement analysis of time presentation

The original requirement for presenting the time is to provide a fine resolution of second-level (i.e. to tell the exact second of the current time) in a large time span (24 hours). It is a huge challenge to achieve such a goal as the combinations of the current second is 86488 choices (i.e. 24 Hours x 60 Minutes x 60 Seconds). It seems difficult and maybe an impossible task to communicate such huge information through haptic perception channel.

In this paper, we adopted a simple strategy to develop a solution for an eye free communication watch that can provide a relatively high temporal resolution in a limited time span. The resolution in our design is five minutes instead of one second, and the covered time span is 12 hours instead of 24 hours. The underlying assumption is that this watch will be mainly used in day time instead of night time, and the resolution of five minutes will provide sufficient information for people to have a rough idea about the current time during a meeting.

B. Design of vibrotactile encoding strategy

We explored possible design solutions for accurate and effective communication of the haptic watch based on analyzing following parameters: the number of vibrotactile cues, the layout and location of the cues on the wrist/arm, and the spatial/temporal pattern of the cues.

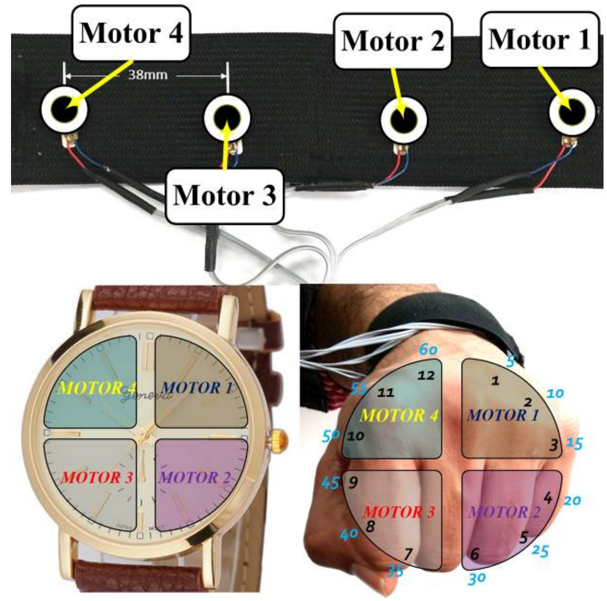

Fig. 1. Motors location on the band and the 4-area vibrotactile encoding pattern

There are two temporal patterns to present the current time. One is the simultaneous presentation of hour and minute through one vibration profile, and the other is the sequential presentation of hour and minute through combinations of several vibration segments. The first option is efficient but requires a large information transfer rate for haptic signals, while the second is less efficient but might ensure smaller perception workload on user's haptic channel.

In this paper, we adopted the sequential presentation of hours and minutes through a combination of several vibration segments. We proposed a 4-area vibrotactile encoding strategy based on sequential presentation approach and we divided the circular region of the wrist into 4 quarters (regions) i.e. dorsal, volar, pinky and thumb region. As shown in Fig. 1 there were 4 motors in the watch, and each motor was assigned to one-quarter (region) respectively. For representing 12 hours, the role of these quarters was defined as follows: motor-1(Dorsal) was displaying the range from 1st to 3rd hour, motor-2(Pinky) for displaying the range from 4th to 6th hour, motor-3(Volar) for displaying the range from 7th to 9th hour, and motor-4(Thumb) for displaying the range from 10th to 12th hour. Similarly, for minutes we divided again into 4-quarters and each motor was assigned to each quarter respectively. Motor-1((Dorsal)) for displaying the range from 1st to 15th minutes, motor-2(Pinky) for displaying the range from 16th to 30th minutes, motor-3(Volar) for displaying the range from 31st to 45th minutes, and motor-4(Thumb) for displaying the range from 46th to 60th minutes.

The complete sequential vibration pattern of the motors is shown in Table 1. The adopted combinations of the segments were easy to be memorized. This pattern consists of a vibration segments for the current hour followed by a distinctive vibration segments for the current minute span (in five minutes resolution). The goal of this design is to create a

TABLE I
SCHEME OF THE MOTORS (HR= HOUR, MIN= MINUTES)

Motor No.	Long duration vibration for presenting Hours			Short duration vibration for presenting Minutes		
	1 cue	2 cues	3 cues	1 cue	2 cues	3 cues
1	1st HR	2nd HR	3rd HR	0-5 MIN	5-10 MIN	10-15 MIN
2	4th HR	5th HR	6th HR	15-20 MIN	20-25 MIN	25-30 MIN
3	7th HR	8th HR	9th HR	30-35 MIN	35-40 MIN	40-45 MIN
4	10th HR	11th HR	12th HR	45-50 MIN	50-55 MIN	55-60 MIN

uniqueness of each segment and to avoid confusion during perception of time cues.

C. Parameter determination

To avoid reliable localization perception performance, four vibration motors were mounted on the wrist band at four different locations (Dorsal, Pinky, Volar and Thumb side of the wrist) having a distance of 38mm as suggested in [12] between each motor. The frequency of the vibration was set to 200Hz because according to Frisina and Gescheider [10] at frequencies above 200 Hz, thresholds were virtually identical for children and adults, but below this frequency, children were more sensitive than adults.

For determining the vibration duration, we conducted a pilot identification experiments and recorded the input from the users. The acceptable durations for sustained vibration were selected as 1 second and 500msec because most of the participants discriminated correctly between these two durations during the pilot study and scored 100%. Another important parameter was the ISI (Inter-stimulus interval) between the vibrations within the hours and minutes. After pilot experiments, we selected the ISI within hours and minutes to be 500 msec.

Based on above analysis, the duration and ISI for the hours and minutes were determined. For hours, each motor vibrates for 1 seconds, and to represent minutes each motor vibrates for 500msec. Motor-1 vibrates one time for 1sec to present one hour, similarly vibrates two times for presenting 2 hours and three times for 3 hours. Similarly for presenting minutes motor-1 vibrates 1 time for presenting minutes from 1 to 5 minutes, two times for presenting minutes from 5 to 10 minutes and three times for presenting minutes from 10 to 15 minutes. Exactly the same pattern is followed by the other three motors. For example, the target time is 3:15, motor-1 vibrates 3 times for 1 sec and then when participant presses minutes button motor-1 vibrates again 3 times for 500msec.

D. Prototype of the haptic watch

We developed a Velcro-attached wristband with four coin vibration motors with 10mm diameter, and 200Hz frequency was mounted on the wristband as shown in Fig. 1. The delay time to drive these motors was 40ms. All the hardware was integrated using Arduino ATmega2560 having a delay of 50µs. Two pushbuttons were used to present the time separately in the form of hours and minutes while the hour's pushbutton was also used to trigger the vibrotactile cues and a timer for computing the reaction time while the recording button was used to stop the timer after the participant has finished perceiving the time. A random synthetic target time was produced for each trial when the pushbutton was pressed. All the data (user responses) were recorded in excel files using the CSV format.

III. HUMAN USER EXPERIMENTS

A. Participants

12 individuals (2 females, ages from 22-30) participated in the experiment. The participants have an average wrist circumference of 15.43cm. All the participants were the graduate students of Beihang University. All the participants gave a written consent to participate in the experiment. All were tested with their left arm wrist.

B. Experimental Procedure

Rigorous experiments were performed to evaluate the performance of the watch. The experiments were divided into three blocks. The first-block was called the training-block while the other two blocks were called the focused state-block and the distracted state-block. The participants were asked to sit on a chair in a comfortable posture. The wristband was worn by the participants on the hand. Firstly the training block comprises of 30 trials presented to the participant. After the training-block, 5 minutes rest was required to avoid fatigue. Then the focused-block was presented to the participant.

C. Training Block

The training-block was divided into two parts, i.e. the spatial-training and temporal-training part. In the spatial training part, each motor on the wristband was actuated one by one to familiarize the participant with the spatial location of the motors. This part comprised of 5 minutes. It was followed by the temporal training part comprised of 5 minutes in which participant were presented by the random temporal combinations of the time. The scheme of the vibration motors was explained to the participants by showing them a picture as shown in Fig. 1. All the combinations produced by the software were synthetic. Participant had to perform 25 trials in this session. After completing the training session participants were asked to take a rest of 5 minutes.

D. Focused State Block

The formal experiments started from the first test-block which we also called it as focused state-block. The participants were asked to wear the wristband on their left arm. The participants were asked to rest their left arm on the table and the hours, minutes and the recording buttons were controlled by the right hand. During the whole focused state-block, the eyes were covered by the eye shield and the ears were covered by the ear muffs to avoid audio-visual distraction. The participants were instructed to focus their attention on the vibrotactile cues while performing the experiment as shown in Fig. 2. The total number of trials during the focused state-block was 30. In each trial, the participant had to press button 1 to perceive the hour and then pressed the button 2 to perceive the minute after perceiving the time the participant had to respond verbally to the experimenter for the answer as quickly as possible. After perceiving the hour, minute and providing the answer to the experimenter the participant had to push the record button

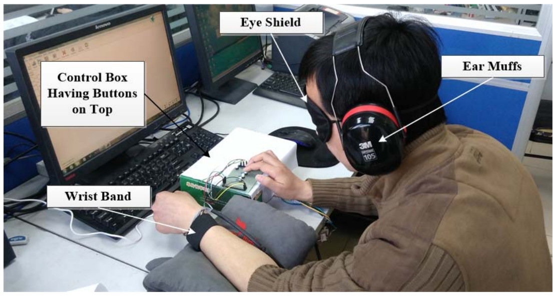

Fig. 2. Participant performs the experiment in the focused state testing block

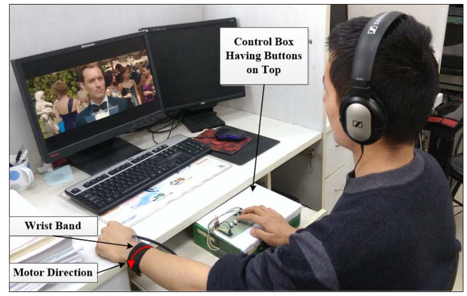

Fig. 3. Participant performs the experiment in the distracted state block

immediately to record the reaction time. The total time of the focused state-block was almost 10 minutes. After the focused state-block, the participant took a rest of 5 minutes again to avoid fatigue.

E. Distracted State Block

The distracted state-block also comprised of 30 trials. The procedure for conducting the experiment and the instructions to the participants were same as in the focused state-block. The only difference in this block was that during the whole distracted state-block, a Hollywood comedy movie "SPY" was played on the monitor to distract the participants from visual and auditory channels. The participants were instructed to look at the screen and watch the movie while at the same time performing the experiment as shown in Fig. 3. The total time of this block was also about 10 minutes. At the end of distracted state-block, every participant was asked to fill a questionnaire to express their reviews regarding the perception of time.

F. Performance matrices

Two performance matrices were evaluated in the experiment. Correct rate and reaction time. The two parameters are defined below:

a. Correct Rate

The most important performance matrix to be evaluated is the correct rate. The number of successful trials and the failed trials was being evaluated by the formula given below:

$$C = \sum_{i=1}^{N} S_i \Big/ N \times 100\% \qquad (1)$$

where C stands for the correct rate. S_i denotes the number of successful trials and N denotes the total number of trials of the two test blocks. In our experiment (N=No. of Test blocks × No. of Phases × No. of trials=60). This formula defines the accuracy of the watch.

b. Reaction Time

The reaction time includes the total time utilized by the participant to compute the time after receiving the vibrotactile cue from the watch. During the experiment, the timer started when the participant pushed the button 1 (Hour presentation button) and it stopped when the record button was pressed. Therefore, the timer computed the total time i.e. time duration of the stimuli, the time utilized by the participant to compute the time and the hardware delay time (mentioned in section-II). As we recorded the exact stimulus time being presented to the participant, therefore, we calculate the reaction time using the formula given below:

$$T_R = T_{Map} + T_S \qquad (2)$$

and

$$T_S = T_H N_H + (N_H - 1) \times ISI + T_M N_M + (N_M - 1) \times \mathrm{ISI} + \mathrm{T}_D \qquad (3)$$

where T_R stands for the reaction time. T_{Map} stands for the mapping time (Time utilized by the participant to map the presented stimuli to the current time presented), T_S stands for the system time, T_H stands for the time consumed by the vibration to present hour, $\mathrm{N_H}$ stands for the number of vibrations to present hour, T_M stands for the time consumed by the vibration to present minute, $\mathrm{N_M}$ stands for the number of vibrations to present minute, ISI = 500msec, T_D stands for the delay time (Hardware delay). This value was computed for every trial.

IV. RESULTS

The data was collected from 12 participants from the 2 blocks separately and as mentioned earlier were recorded using Excel files in the form of CSV format programmed by visual C++. The prototype of the watch was evaluated on the basis of two fundamental parameters, i.e. correct rate and the reaction time, which is to quantify the accuracy and efficiency of the proposed prototype of the watch. Table 2 describes the performance (Correct rate), mean and standard deviation of the mapping time of the watch during the two test blocks.

A. Accuracy and reaction time

In Fig. 4, a comparison between the reaction time of the participants in the focused and the distracted state is presented. The average reaction time of the strategy presented was 11secs and 9sec in the distracted and focused state respectively.

Based on the data presented above, Repeated Measure-ANOVA is performed on the reaction time of the participants. The results revealed that with $F(1,11) = 11.67$, $P<0.05$ there is a significant difference between the reaction time of the participants in the two different conditions. Similarly,based on the data presented in Table 2, RM-ANOVA is also performed at the correct rate and mapping time of the participants during

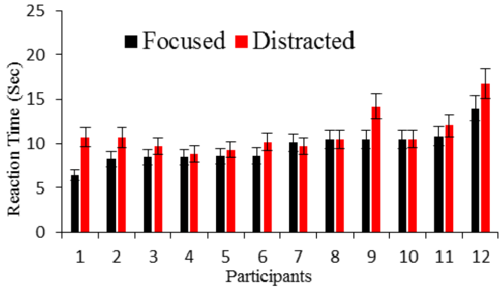

Fig. 4. Comparison between the reaction time of the participants

TABLE II
RESULTS OF THE PARTICIPANTS (C.R. = CORRECT RATE, T_{MAP} = MEAN OF MAPPING TIME S.D. = STANDARD DEVIATION OF REACTION TIME, AVG. = AVERAGE)

S.No.	Focused State			Distracted State		
	C.R.	**T_{Map} (sec)**	**S.D.**	**C.R.**	**T_{Map} (sec)**	**S.D.**
1	100.00%	3.59	0.58	96.66%	5.00	0.99
2	96.66%	4.93	1.06	96.66%	5.12	1.01
3	96.66%	5.01	1.03	93.33%	5.10	0.92
4	96.00%	5.07	0.92	93.33%	5.11	1.02
5	96.66%	4.94	0.99	90.00%	5.00	0.90
6	96.66%	5.14	1.03	93.33%	4.94	1.02
7	96.66%	5.16	1.04	86.66%	4.93	1.01
8	96.66%	5.11	0.97	86.66%	5.11	0.97
9	83.33%	5.00	0.91	80.00%	5.30	1.01
10	93.33%	5.11	0.94	86.66%	5.12	1.02
11	96.66%	4.99	0.94	96.66%	5.11	0.91
12	93.33%	5.14	0.99	86.66%	4.90	0.97
Avg.	**95.22%**	**4.93**	**0.95**	**90.55%**	**5.06**	**0.98**

the two test blocks. The results revealed that with $F(1,11) = 24.22$, $P<0.05$ there is a significant difference in the correct rate of the participants. However, results also revealed that with $F(1,11) = 1.05$, $P>0.05$ there is no significant difference between the mapping time of the participants during the two test conditions. This revealed that audio-visual distraction did not influenced the mapping time.

B. *Questionnaire results*

The participant's reported their opinion about the perception of time using questionnaire. The questionnaire results revealed that the intensity of the vibrations was easily perceptible (100%), the training time was satisfactory got (72.72%) score, the mapping strategy memorization got (81.81%) score, and Inter-stimulus interval (ISI) was quite satisfactory got (100%) score after evaluation. In the perception of motors, Motor-1 got (8.33%), Motor-2 got (41.66%), Motor-3 got (25.00%) and Motor-4 got (16.66%) score for difficulty in perceiving the stimuli. This revealed that the pinky side (motor-2) of the wrist is the most difficult to be perceived by the participants.

V. DISCUSSION

Most of the studies revealed that it is better to present information in the form of spatial-temporal patterns instead of frequency and intensity because it is difficult to discriminate frequency and intensity [15]. Our experimental results revealed that the correct rate achieved by the watch after experimentation in a focused and distracted state were almost 95% and 91% respectively. This revealed the effectiveness of the spatial-temporal vibrotactile patterns and their utilization for presenting time. The most important factor that plays a significant role in perceiving and manipulating information accurately in the case of wearable haptic devices is the cognitive load. In our prototype, we tried to develop a strategy that exhibits minimum cognitive load and presents maximum information in minimum possible time. After the experimentation, the participant's questionnaire results revealed that the mapping strategy was easy to remember almost got 81.81% score. The false rate during the focused state-block was almost 5% whereas in the distracted state-block where the experiment is conducted by creating an audio-visual distraction the false rate measured was almost 10%. In both test blocks, all the errors were recorded and analyzed. The maximum error occurred particularly in the location of motor-2 and motor-3 also there was a high confusion rate between the site of motor-1 and motor-4 also reported by the participants. The possible reason for the confusion between motor-4 and motor-1 might be the misalignment of the motors on the wrist. As the wrist circumference is not consistent and varies from participant to participant, therefore, due to the inconsistency of the distance the error occurred. In the future, this problem can be solved by just using 1 motor only to present time instead of 4 motors.

One of the most important cognitive processes involves in the perception of the vibrotactile cues is working memory. Perceiving hours and minutes consecutively is a high attention-demanding task therefore, we divided the hours and minutes into two separate segments to divide working memory. As the subjects were performing the primary task of watching the movie and secondary task of perceiving time so their working memory or attentional resources were distributed. As suggested by Tyler [15] that vibrotactile working memory shares common qualities with the other working memory systems. Soros et al. [16] also reported that working memory and attention are organized in partly overlapping neural circuits. Our case deals with the two cognitive processes selective attention and working memory. While distributing the workload in two parts perceiving hours and minutes increases the efficiency and reduces the reaction time. Thus, we suggest that it is significant to present information using vibrotactile modality in small chunks instead of presenting all information consecutively.

Furthermore, the spatial orientation should be a key factor in designing tactile displays. We deployed all the vibration motors around the wrist at 4 different locations instead of deploying them on either the dorsal and volar side of the wrist as suggested by Schatzle [13]. Even though the motors were deployed around the wrist but still the error occurred at the pinky (motor-2) and the thumb region (motor-4) of the wrist.

The most challenging metric for an effective usage of the watch is reaction time. If it takes too long for a user to compute the time, the watch may become useless. The average reaction time in our experiments was about 9 seconds and 11 seconds. We still think that this is a large time but even the time was large the perception was still not an easy task.

However, we also assumed that in the scenarios where the participant had to utilize the haptic channel for perceiving time, he/she is familiar with the hour or just need to know about minutes in that case reaction time will be reduced to even less than 4 seconds. The reaction time presented is the total time, including the vibrotactile stimuli durations, the ISIs and the mapping time. The mapping time was 3 to 5 seconds in average but the vibrotactile stimuli time was a bit large. As suggested by Staines *et al.* [17] that the temporal duration of the stimuli determines the quality of sensation. The purpose of making the vibration duration a bit large was to improve the efficiency and increase the correct rate. All the participants reported positively about the stimuli intensity and duration.

In this prototype, we still think that the reaction time is large 10secs but in the future, this reaction time can be improved by improving the spatial-temporal encoding strategy. The hardware utilized for this prototype was low-cost while in the future the hardware can also be improved.

VI. Conclusion

In this paper, we developed and evaluated a prototype of a haptic wrist watch to perceive the current time using a novel spatial-temporal vibrotactile encoding strategy. The main motivation is to develop an eye-free communication watch to perceive the time in such situations when it seems awkward to look at the watch again and again like in meetings etc.

In our study, a 4-area vibrotactile encoding strategy with 5 minutes resolution was proposed. Hours were presented by long duration vibrations and minutes were presented by short duration vibrations. Two experiments were conducted for the evaluation of the prototype in the visually and auditory distracted environment. From the experimentation, two parameters reaction time and correct rate of the device were investigated. Results reveal that the average reaction time in focused and the distracted state were 9.60secs and 11.09secs respectively. One promising feature is that the watch enables a participant to achieve an accuracy of about 95% after 10 minutes training, which implies that the mapping strategy was fairly easy for a user to learn without the need of long training time. This watch could be used as a standalone device as well as this feature might be integrated with the wrist watches.

Although we conducted pilot experiments to select the duration and ISIs to develop a time presentation strategy, the selected parameters may not be optimal as the range of the parameters is quite large. In the future, more experimentation will reveal optimal parameters. Furthermore, we used a movie for the distraction to test the mapping strategy. However, in the future, this watch can be tested with more real world scenarios. In the future, it is a challenging topic to develop more powerful haptic watch being capable of providing a higher time resolution (e.g. to tell the exact current minute or even the current second) with shorter reaction time and training time.

Acknowledgment

This work is supported by the National Natural Science Foundation of China under the grant No. 61170187, 61190125 and 61572055.

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