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Research Article

Design and Evaluation of Encoded Haptic Pulses for Smartwatches

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As smartwatches gain popularity in the marketplace, various smartwatch context studies have been conducted. The use of smartwatches can be divided into situations with and without constraint both physically and psychologically. Notably, in constrained situations, if the user wants to check the information received in the smartwatch visually, a high cognitive load is involved. To solve this problem, we propose a method to encode and transmit information from the smartwatch with haptic pulses. First, we determine the informational category of the smartwatch and generate various haptic pulses. Next, we propose and verify a haptic pulse set that can represent the informational category of the smartwatch. Using the proposed haptic pulse set, users can receive smartwatch information in constraint situations. The use of encoded haptic pulses needs to be considered to provide information effectively from the smartwatch to the wearer.

1. Introduction

Smartwatches are gaining popularity in the marketplace [1], which has led to studies identifying lifestyles using smartwatch sensing data [2, 3] and studies on the context of using smartwatches. In particular, research on the context of using smartwatches has been actively conducted and can be divided into situations with and without physical and psychological constraint [4–7]. A situation with physical constraint refers to a situation where the wrist with a smartwatch is not readily available due to tasks such as driving a car or working with tools. A situation with psychological constraint refers to a situation where there is a restriction on the use of the smartwatch due to psychological pressure, such as being in a meeting or having communication with others. Visually identifying the information received on the smartwatch in the context of physical or psychological constraints can result in a high cognitive load on the user and can result in misrecognition of the information received [8]. Therefore, we are going to explore a method to transmit information to smartwatch users which does not require visual attention.

When there is visual overload, a haptic interface allows information to be delivered without a sizeable cognitive load [9]. In this context, studies transmitting information through tactile sense alone were conducted. These studies were divided into three directions: the one that distinguished information through tactile sense [10–12], the one that recognized direction through tactile sense [13–15], and the one that recognized space through tactile sense [16, 17]. Among the research completed for distinguishing information through tactile senses, there was an idea developed to provide different haptic feedback depending on the application so that the user could know what the application is by vibration [12]. However, there was a problem that it was impossible to design richly because it only used three levels of vibration intensity (Long, Short, and Pause). Although it was not a study that distinguished information by providing vibration, there was also a study that designed light pulses representing each informational category of smartphone [18]. However, the use of light pulses has a limitation in that it cannot transmit information unless the user is looking directly at the light-emitting diode (LED). In summary, the study that delivers the information of smartwatch to the user only by vibration has a problem that the implemented pulse is limited, and the study that encodes the information into various pulses does not use the vibration, so it is difficult to convey the information in the constraint situation.

Therefore, we need to design a haptic pulse that can represent each informational category on the smartwatch based on the advantages of the two previous ideas.

The purpose of this study is to design haptic pulses suitable for representing the information transmitted by the smartwatch so that it can be understood without looking at the smartwatch. Section 2 deals with the process of finding and generating various haptic pulses before deriving pulses suitable for each informational category of smartwatch. Section 3 explains the experiments to obtain haptic pulses suitable for each informational category of smartwatch, and Section 4 describes the results of the experiments. In Section 5, we show that the information of the smartwatch can be distinguished only by haptic pulses in constraint situations. Section 6 discusses the results, and Section 7 concludes our study.

2. Design of Haptic Pulses

Before deriving a haptic pulse for each informational category on a smartwatch, the haptic pulse was collected and refined. To make it easier to understand the process of collecting and deriving pulses, the entire process is shown in Figure 1.

2.1. Pulse Collection. Apple Watch and Samsung Galaxy Gear, which are the most popular smartwatches on the market, offer only a few haptic pulses. If the number of haptic pulses provided by the smartwatch is insufficient, it is difficult to encode the informational category of each smartwatch with unique vibrations. Therefore, to collect various haptic pulses, we searched for a study that encodes information through waveforms. Most haptic pulse studies were performed with microscopic vibration unit studies [19, 20], so we examined light pulse studies to collect long pulses that could be used for smartwatch vibration. Starting from the light pulse study of Harrison et al. [18], a total of 57 light pulses were collected from five studies [18, 21–24]. The accumulated light pulses must be refined before conversion to haptic pulses because some waveforms and light flashes are not eligible for conversion.

2.2. Primary Filtering of Light Pulses. Three criteria were used to filter the 57 light pulses. First, seven random pulses that cannot be generalized (Figure 2(a)) and two simple on-off pulses were removed (Figure 2(b)). Next, after removing the light pulses with similar waveforms, only one was left (Figure 2(c)), resulting in a total of three light pulses removed. Last, three light pulses contained a light flash, which is difficult to be expressed by vibration motors, so it was removed (Figure 2(d)). An example of light pulses filtered by the above three criteria is shown in Figure 2. The primary filtering removed 15 light pulses, resulting in only 42 light pulses remaining.

2.3. Classification and Duration Determination of Haptic Pulses. Pulses can be classified into periodic pulses and nonperiodic pulses depending on their waveform [22]. A periodic pulse is the one whose waveform is repeated at equal intervals; 20 of the collected light pulses fell into this category, the rectangle, triangle, and sinusoidal waveforms (Figure 3). A nonperiodic pulse is the one whose waveform has no repetition and has a specific shape; 22 of the collected light pulses were considered to be similar to nonperiodic pulses.

Since periodic pulses repeat the same waveform, different pulses can be generated based upon how many times per unit time they are repeated. That is, if the duration of a pulse is determined, a periodic pulse can be generated by determining the number of repetitions within the period. As a result, all 20 periodic pulses were removed and integrated into the three types (rectangle, triangle, and sinusoidal). However, when providing discrete vibration levels, the triangle waveform and the sinusoidal waveform can be treated as the same haptic pulse. Therefore, for simplicity, we removed the sinusoidal waveform, leaving only the rectangle and triangle waveforms in the periodic pulse. It was then necessary to determine the duration of the pulse before generating the haptic pulse; we used 22 nonperiodic pulses for this purpose.

A 75 mA eccentric rotating mass- (ERM-) type motor and an Arduino Uno main board with pulse wide modulation (PWM) pin were used to adjust the vibration intensity for the haptic pulse provided by a 5-volt battery. The prototype used in the experiment is written in C language and is shown in Figure 4. To implement the 22 nonperiodic pulses without overlapping, we needed to have a vibration strength of at least 5 levels. Therefore, all waveforms were implemented with 5 levels of quantized vibration intensity. The vibration was implemented by using Arduino's analogWrite function. Table 1 shows the voltage and current values for each vibration intensity.

In the duration determination experiment, the 7 participants watched the waveform of the haptic pulse by eye, felt the haptic pulse with their wrist by wearing a strap with the vibration motor, and evaluated the degree of correspondence between the visual waveform and the vibration provided. The experiment took an average of 30 minutes. The goal of the experiment was to determine the duration that allowed as many haptic pulses as possible to be recognized when the 22 nonperiodic pulses were implemented as haptic pulses with the same duration. The independent variable was pulse duration and it was divided into four levels: 1.3, 2.1, 2.9, and 3.7 s. When the haptic pulse was provided to the motor, it was designed to determine the approximate duration by setting 1.3 s at the lowest level, where vibration intensity starts to be distinguished; the levels then increased at intervals of 0.8 s. The dependent variable was the degree to which the visual waveform and vibration were the same and was measured on a 5-Likert scale. After experiencing each haptic pulse twice, participants assessed the correspondence of 22 haptic pulses. An example of the questionnaire used in the experiment is shown in Figure 5.

At a significance level of 0.05, the ANOVA result for the duration determination experiment showed a significant difference about the duration ($F_{(3,612)} = 35.273$, $p < 0.001$). As a result of the post hoc analysis at a significance level of 0.05, it was divided into three groups, and duration of 2.9 s

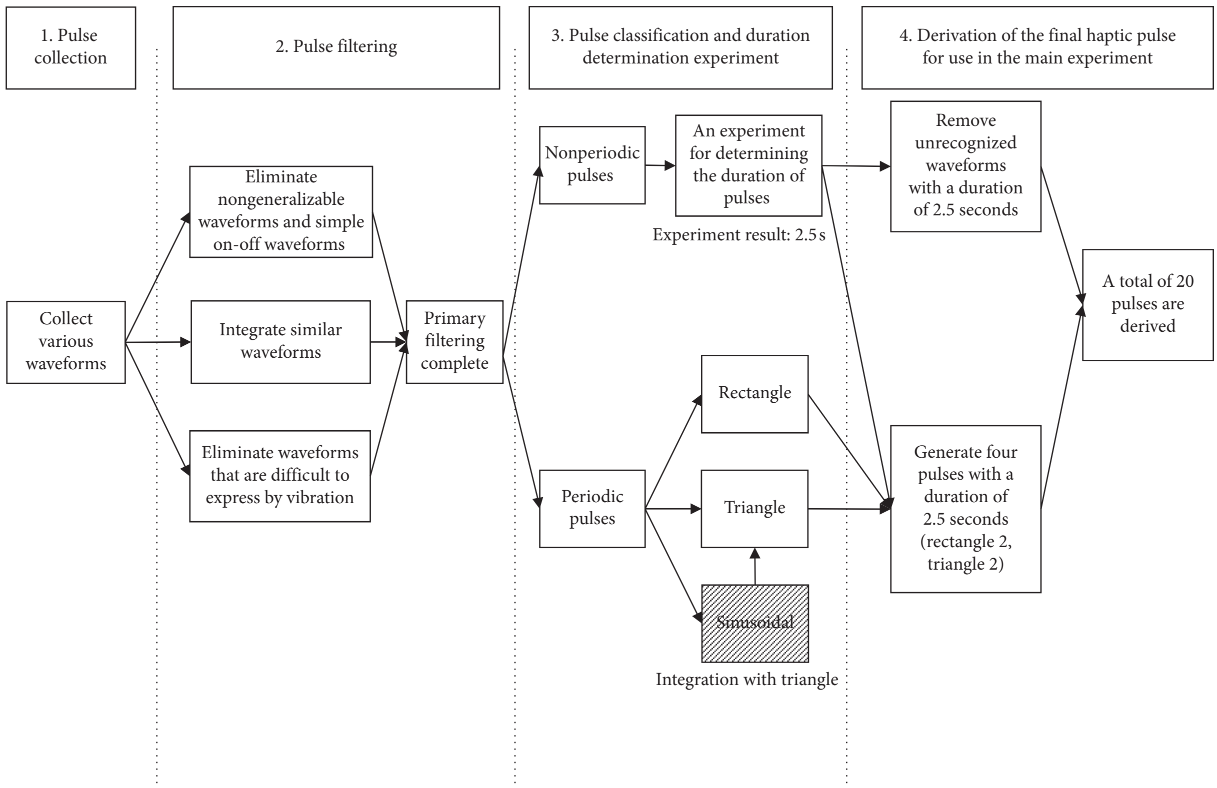


Figure 1: Haptic pulse design process.

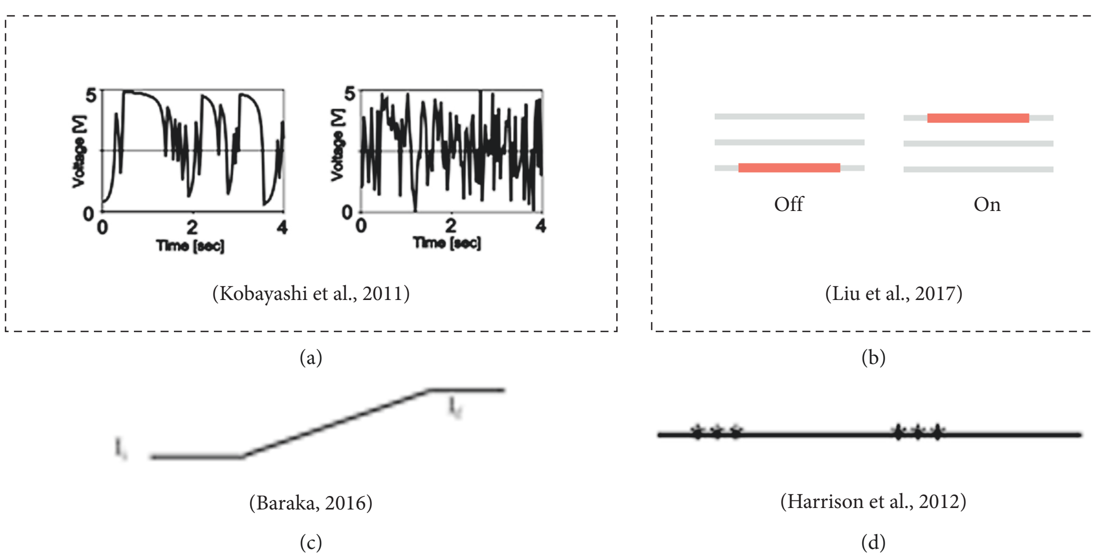


Figure 2: Example of light pulse removal criteria: (a) random pulses that cannot be generalized; (b) simple on-off light pulses; (c) light pulses of similar waveforms are removed, and only one is left; (d) pulses that contain light flash that is difficult to be expressed by vibration motors.

and 3.7 s was grouped into upper groups (Figure 6). Many participants stated that "the shorter the duration is at the level at which vibration is perceived, the better." Based on these comments, the shorter duration of 2.9 s in the upper group was chosen.

Next, the same experiment was further subdivided into 0.2 s units based on the duration of 2.9 s. The duration of the second experiment consisted of five levels: 2.5 s, 2.7 s, 2.9 s, 3.1 s, and 3.3 s. At a significance level of 0.05, the ANOVA result for the second duration determination experiment showed no significant difference in the duration ($F_{(4,765)} = 2.345$, $p = 0.053$). Finally, 2.5 s, which is the shortest duration in the group, was determined as the duration to be used in the main experiment.

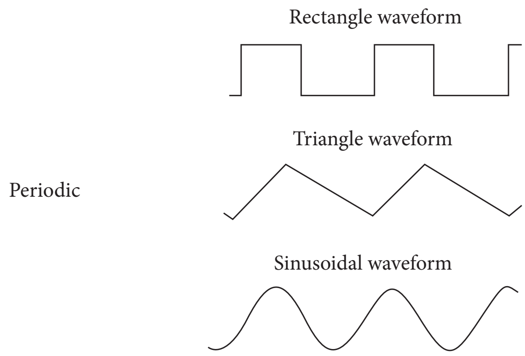


Figure 3: Three types of periodic pulse.

Figure 4: Prototype and control board with ERM-type motor.

Table 1: Voltage and current by level of vibration intensity.

Vibration intensity	V	mA
Level 5	5.0	69.0
Level 4	4.3	59.5
Level 3	3.6	50.5
Level 2	2.9	41.0
Level 1	0.0	0.0

2.4. Haptic Pulse to Be Used in the Main Experiment. According to the previous experiment, the best length of the haptic pulse was determined to be 2.5 s. At the same time, among the 22 nonperiodic pulses, 6 pulses with an average score of less than 3 at 2.5 s were regarded as a pulse that the user could not recognize and were removed. Next, a total of four periodic pulses were generated, two rectangle and two triangle waveforms. The generated periodic pulses are repeated 2 or 4 times within a duration of 2.5 s. The 16 nonperiodic pulses and 4 periodic pulses are shown in Figure 7. Blink slow and blink fast appear at the right end and are the rectangle waveform and pulse slow and pulse quickly are the triangle waveform.

3. Methods

We investigated smartphone informational categories and smartwatch usage behaviors to determine the relevant informational categories for smartwatches. According to Harrison et al. [18], there are five such categories for smartphone: *Notification*, *Active*, *Unable*, *Low-Energy State*, and *Turning On*. *Notification* can be subdivided into four applications: *e-mail*, *instant message (IM)*, *call*, and *healthcare* [21, 25–27]. *Active* is defined as the status of data transmission-reception and operation-monitoring. *Unable* is defined as unconnectable status and user command denied status. *Low-energy state* is defined as low-battery status, standby mode, and sleep mode. *Turning On* is defined as booting the device. Since the five informational categories of smartphones can apply to smartwatches [21, 25], we will use the categories in this study. Table 2 summarizes the results of searching the informational category of smartwatches.

For smartwatch users to be able to distinguish smartwatch information only with a haptic pulse, it is necessary to find out which haptic pulse is suitable for each informational category. Therefore, we designed an experiment to find a correlation between haptic pulses and informational categories. Tests were divided into two parts. First, we investigated the relationship between five informational categories (*Notification*, *Active*, *Unable*, *Low-Energy State*, and *Turning On*) and 20 haptic pulses. Next, we subdivided *Notification* into application categories (*e-mail*, *IM*, *call*, and *healthcare*) and investigated the relationship between four application categories and 20 haptic pulses. Participants were asked to give evaluation at the same level throughout the experiment.

3.1. Devices. The experimental device is the same as the prototype used in the duration determination experiment, and the participants wore the strap with an ERM-type vibration motor on their wrist. The experimental device and environment are shown in Figure 8.

3.2. Task Domain. In the two-part experiment, the participants were asked to feel the vibration and perform a task to assess the extent to which the haptic pulse was appropriate for each category. Participants experienced 20 haptic pulses once in a row and evaluated the five informational categories of smartwatch. After a second round of 20 haptic pulses, participants evaluated the four categories of *Notification*. As a result, each participant felt a total of 40 vibrations.

3.3. Subjects. A total of 30 participants (16 males and 14 females) were recruited using in-house advertising. The mean age of participants was 24.5 years and the standard deviation was 2.36. The experiment took an average of 25 minutes and participants received $5 as compensation.

3.4. Independent Variables. In this experiment, two variables act as independent variables. First, when analyzing the fitness of haptic pulse for each category, haptic pulses act as independent variables and consist of 20 levels. We ask whether the pulses are appropriate for each category using a 5-Likert scale. Next, when analyzing the eligibility of the category for each haptic pulse by changing the axis, the categories themselves act as an independent variable.

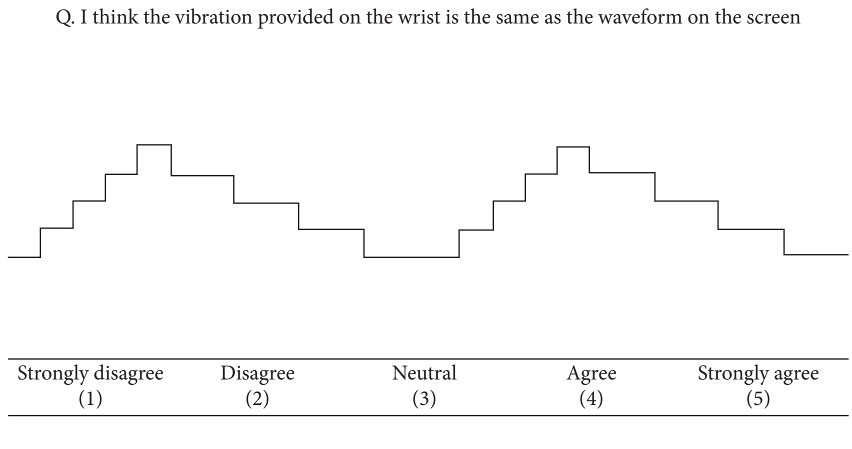


FIGURE 5: Example of questionnaire used in duration determination experiment.

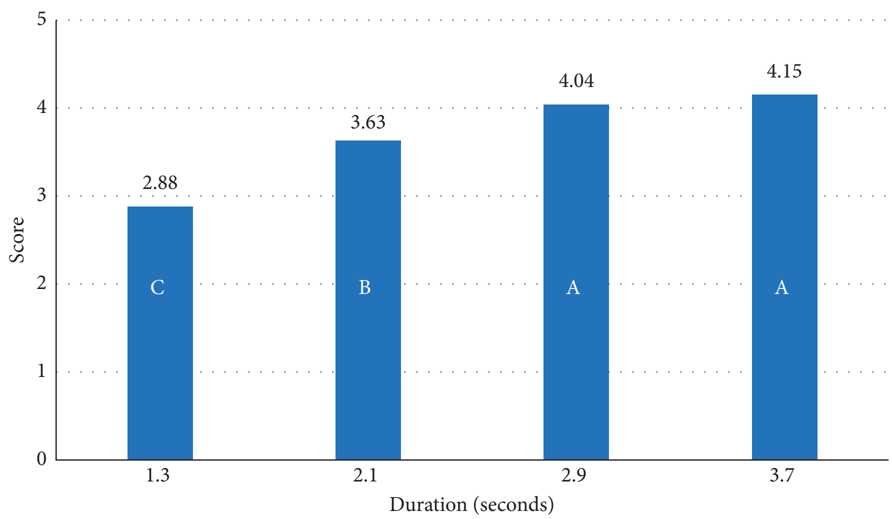


FIGURE 6: The result of the posttest of the duration determination experiment.

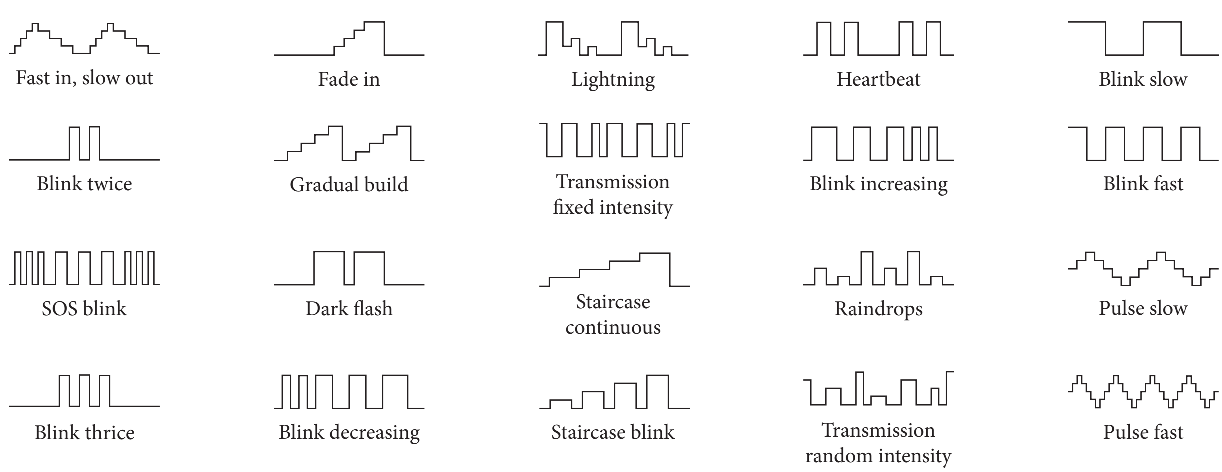


FIGURE 7: Twenty haptic pulses to be used in the main experiment (four of the rightmost columns are periodic pulses). (a) Fast in slow out. (b) Fade in. (c) Lightning. (d) Heartbeat. (e) Blink slow. (f) Blink twice. (g) Gradual build. (h) Transmission fixed intensity. (i) Blink increasing. (j) Blink fast. (k) SOS blink. (l) Dark flash. (m) Staircase continuous. (n) Raindrops. (o) Pulse slow. (p) Blink thrice. (q) Blink decreasing. (r) Staircase blink. (s) Transmission random intensity. (t) Pulse fast.

Table 2: Informational categories of smartwatch.

Category		Informational states
Notification	E-mail	Notifications from the e-mail application
	Instant message (IM)	Notifications from the IM application
	Call	Notifications from the call application
	Healthcare	Notifications from the healthcare application
Active		Transmitting or receiving data
		Active, monitoring, . . ., or progressing
Unable		Unable to connect
		Unable to accept user input or command
Low-energy state		Low battery
		Sleeping, suspended
Turning on		Turning on, booting, or warming up

Figure 8: Experimental environment and devices.

Participants rate how proper the informational categories are for each pulse using a 5-Likert scale. The level of the category is determined based on the analysis of the haptic pulse.

3.5. Dependent Variables. The fitness score of the haptic pulse about the category of smartwatch acts as a dependent variable. The fitness score is collected after each participant experiences each vibration and evaluates it based on a 5-Likert scale. The closer the fitness score is to 5, the more appropriate the given vibration is for the category, and the closer the fitness score is to 1, the less appropriate the given vibration is for the category.

3.6. Experimental Design. The experiment was designed as a one-way design, and all independent variables acted as within-subjects. To remove the order effect, the order of providing the haptic pulse was random.

3.7. Procedure. Each participant performed the fitness evaluation of haptic pulse for five informational categories and four *Notification* application categories. The participant wrote his or her demographic information before the experiment and then listened to the experiment coordinator regarding the category being judged. Next, the participant evaluated the fitness of the haptic pulse for the five informational categories. After the previous evaluation was over, the participant assessed the fitness of the haptic pulse for the four *Notification* application categories. Participant's comments were collected at the end of the experiment (Table 3).

Table 3: Experimental procedure.

Period 0	Step 1: get the participant's demographic information
Period 1	Step 2: describe the informational category of smartwatch
Period 2	Step 3: perform experiments on 5 informational categories 1st haptic pulse provided 5 informational categories' evaluation 2nd haptic pulse provided . . . . 20th haptic pulse provided 5 informational categories' evaluation
Period 3	Step 3: perform experiments on 4 informational categories (*Notification* application)
Period 4	Step 4: collect comments from participants

4. Results

After gathering the initial results and analyzing the haptic pulse scores within each informational category, we changed the axis to compare scores between informational categories for each haptic pulse. Next, we proposed a haptic pulse suitable for representing each informational category of smartwatch.

4.1. Score of Haptic Pulse for Each Informational Category. First, we analyzed the fitness of haptic pulses for each of the 5 informational categories of smartwatch. In each category, haptic pulses were analyzed as independent variables and one-way ANOVA was performed. At a significance level of 0.05, haptic pulse ($F_{(19,580)} = 4.026$, $p < 0.001$) had a significant effect on the *Notification* category score. Tukey's HSD post hoc analysis was performed and there was no significant difference between haptic pulses with high scores at the 0.05 significance level. The majority of participants also noted that the *Notification* category was associated with many applications and gave a high score to most haptic pulses. Therefore, the *Notification* category cannot use these results; application-specific haptic pulses will be covered in Section 4.2. The average score of the haptic pulses in the *Notification* category is shown in Figure 9.

At a significance level of 0.05, haptic pulse ($F_{(19,580)} = 1.482$, $p = 0.085$) did not have a significant effect on the *Active* category score. Analysis of the reasons why no

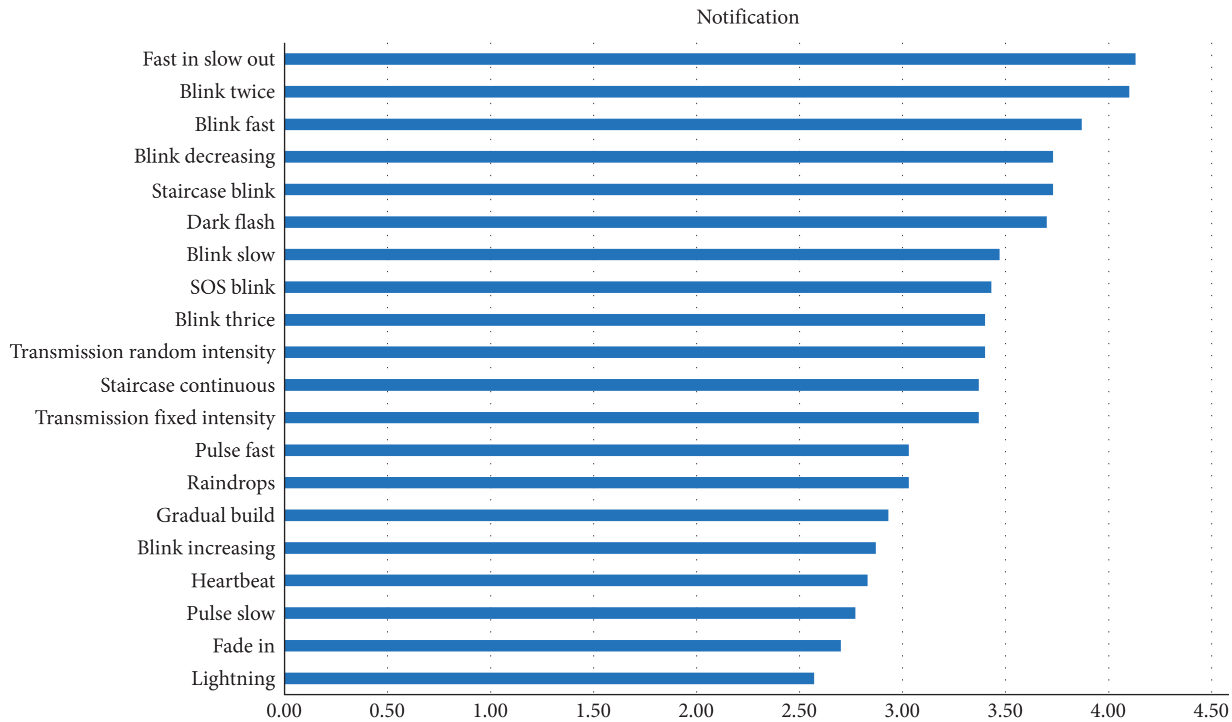


Figure 9: Rating of haptic pulses in indicating the notification category.

significant results were obtained through participant comments revealed that most participants did not want to be provided with vibrations in the *Active* category. Therefore, we propose that the *Active* category should not provide vibration. The average scores of the haptic pulses in the *Active* category are shown in Figure 10.

At a significance level of 0.05, haptic pulse ($F_{(19,580)} = 1.91$, $p = 0.011$) had a significant effect on the *Unable* category score. Next, at a significance level of 0.05, haptic pulse ($F_{(19,580)} = 2.26$, $p = 0.002$) had a significant effect on the *Low-Energy State* category score. Next, at a significance level of 0.05, haptic pulse ($F_{(19,580)} = 5.069$, $p < 0.001$) had a significant effect on the *Turning On* category score. However, Tukey's HSD post hoc analysis for each of the *Unable*, *Low-Energy State*, and *Turning On* categories showed no significant differences between the high score haptic pulses at the 0.05 significance level. Therefore, it was not possible to propose a haptic pulse that represents the informational category simply by ranking the average score. Figures 11–13 show graphs of haptic pulses within the *Unable*, *Low-Energy State*, and *Turning On* categories, respectively.

As discussed previously, the *Notification* category should be analyzed for each application. At a significance level of 0.05, haptic pulse ($F_{(19,580)} = 10.57$, $p < 0.001$) had a significant effect on the *e-mail* application score in the *Notification* category. Next, at a significance level of 0.05, haptic pulse ($F_{(19,580)} = 12.39$, $p < 0.001$) had a significant effect on the *IM* application score. In addition, at a significance level of 0.05, haptic pulse ($F_{(19,580)} = 7.982$, $p < 0.001$) had a significant effect on the *Call* application score. However, Tukey's HSD post hoc analysis for each of the *e-mail*, *IM*, and *Call* categories showed no significant differences between the high score haptic pulses at the 0.05 significance level. Therefore, it was not possible to propose a haptic pulse that represents the informational category simply by ranking the average score. Figures 14–16 show graphs of haptic pulses within the *e-mail*, *IM*, and *Call* categories, respectively.

Finally, at a significance level of 0.05, haptic pulse ($F_{(19,580)} = 0.833$, $p < 0.668$) did not have a significant effect on the *Healthcare* application score in the *Notification* category. As a result of analyzing participants' comments on the reason for the above findings, it was found that most participants did not have a mental model for *Healthcare* application. In the human-computer interaction (HCI) field, a mental model refers to the dynamic model that users have in their minds about the function, structure, and value of a particular system [28]. Therefore, we could not propose a haptic pulse in *Healthcare* application as a result of this experiment. Figure 17 shows a graph of haptic pulse score in *Healthcare* application.

4.2. Score of Informational Categories for Each Haptic Pulse. In Section 4.1, we looked at the score of the haptic pulse within each informational category of smartwatch, and it is difficult to propose a haptic pulse for each based solely on the results of this analysis. Therefore, we changed the axis of analysis and compared the scores by informational category based on each haptic pulse. Before the analysis, we excluded three informational categories: *Notification* for which we cannot propose haptic pulses, *Active* that does not provide vibration, and *Healthcare* that does not have a significant difference since no mental models have been built.

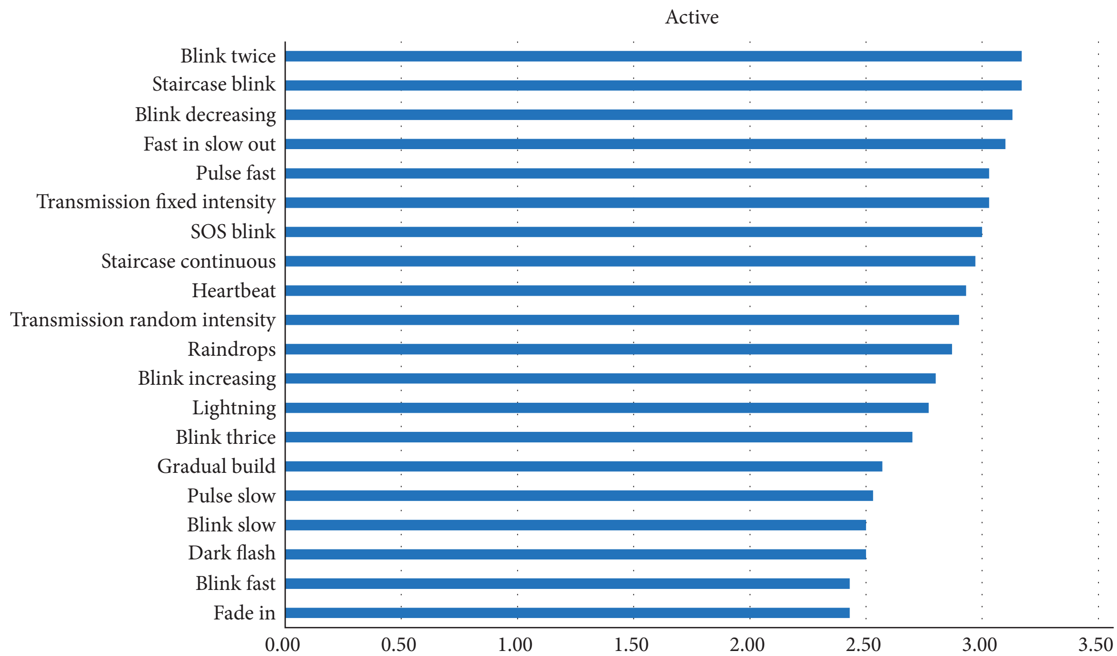


Figure 10: Rating of haptic pulses in indicating the active category.

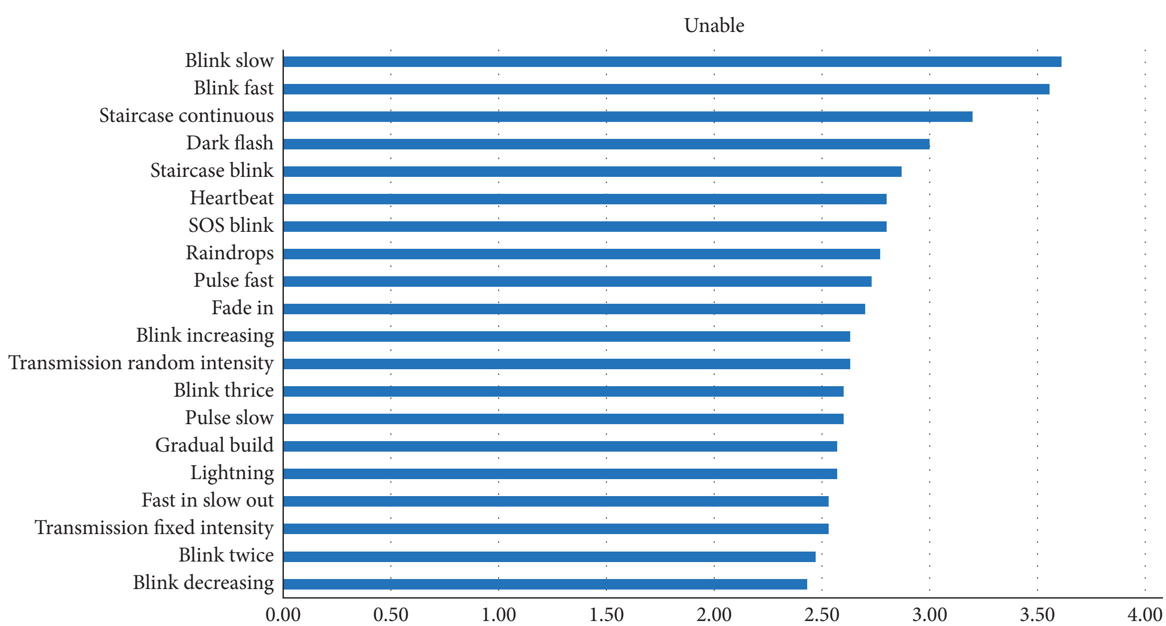


Figure 11: Rating of haptic pulses in indicating the *Unable* category.

Therefore, we performed the analysis with only the remaining six informational categories. ANOVA analysis and Tukey's HSD post hoc analysis were performed for each of the 20 haptic pulses, which are shown in Table 4. Of the 20 haptic pulses, only three haptic pulses, fade in, gradual build, and SOS blink, showed no significant difference at the 0.05 significance level, and the remaining 17 haptic pulses showed significant differences at the 0.05 significance level. The group with the highest score of Tukey's HSD was A, and the group with significant difference at the level of 0.05 was B, while the group with no significant difference from both groups A and B was AB. Also, the group with significant differences from both groups A and B was C, while the group with no significant difference from both groups B and C was BC.

Based on the post hoc analysis, the informational categories that were significantly different from the high-scoring informational categories group in each haptic pulse in Table 4 were as follows. Blink decreasing had the highest score in the *Call* category (4.03) and was significantly

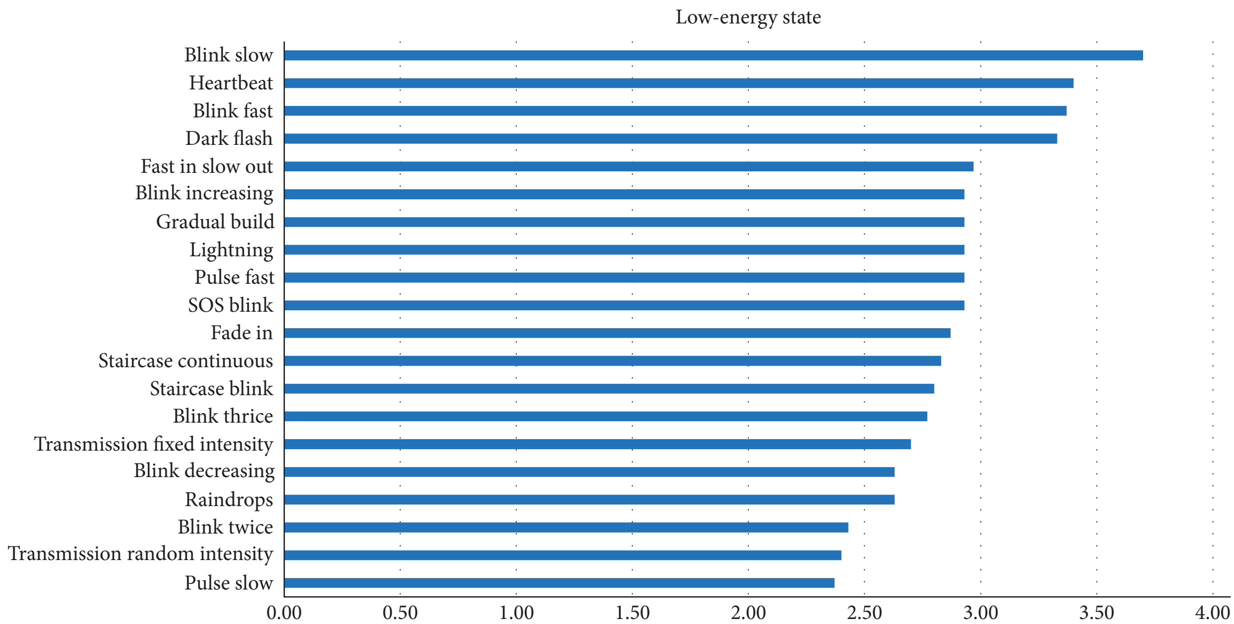


Figure 12: Rating of haptic pulses in indicating the *Low-Energy State* category.

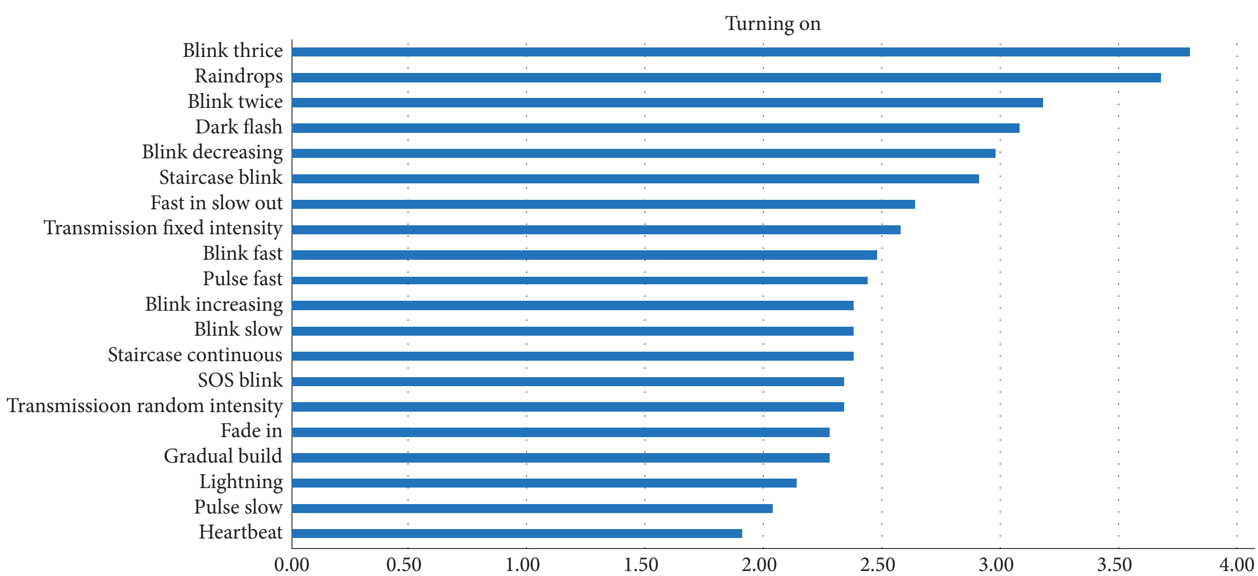


Figure 13: Rating of haptic pulses in indicating the *Turning On* category.

different from the other five categories. Next, the blink fast score was the highest in the *IM* category (4.27) and was significantly different from the three categories: *Turning On*, *Low-Energy State*, and *Call*. Blink increasing had the highest score in the *Low-Energy State* (2.93) and *Call* (3.27) and was significantly different from the two categories: *IM* and *e-mail*. Blink slow was classified as a group with high scores in the *Unable* (3.57), *Low-Energy State* (3.70), *IM* (4.07), and *e-mail* (3.80) categories, respectively. This group was significantly different from the two informational categories of *Turning On* and *Call*. Next, the blink thrice score was the highest in the *Turning On* (3.80) and *IM* (3.80) categories and was significantly different from the three categories: *Unable*, *Low-Energy State*, and *Call*. Blink twice had the highest score in *Call* (3.93) and a significant disparity from the four categories: *Unable*, *Low-Energy State*, *IM*, and *e-mail*. Next, the dark flash score was the highest in the *IM* (3.87) and *e-mail* (3.83) categories and was significantly different from the *Call* category. Fast in slow out had the highest score in the *IM* category (3.57) and was significantly different from the *Unable* category. Next, the heartbeat score was the highest in the *Low-Energy State* (3.40) and was significantly different from three categories: *Turning on*, *IM*, and *e-mail*. Lightning had the highest score in the *Low-Energy State* category (2.93) and was significantly different from the *e-mail* category. Pulse fast had the highest score in

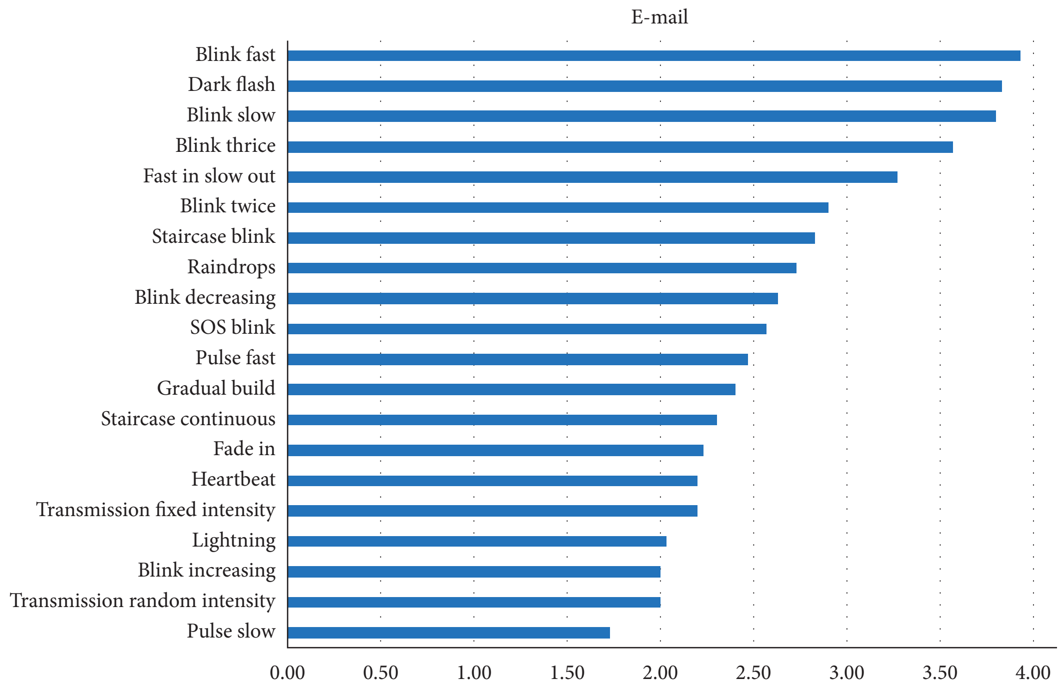


Figure 14: Rating of haptic pulses in indicating the *e-mail* application.

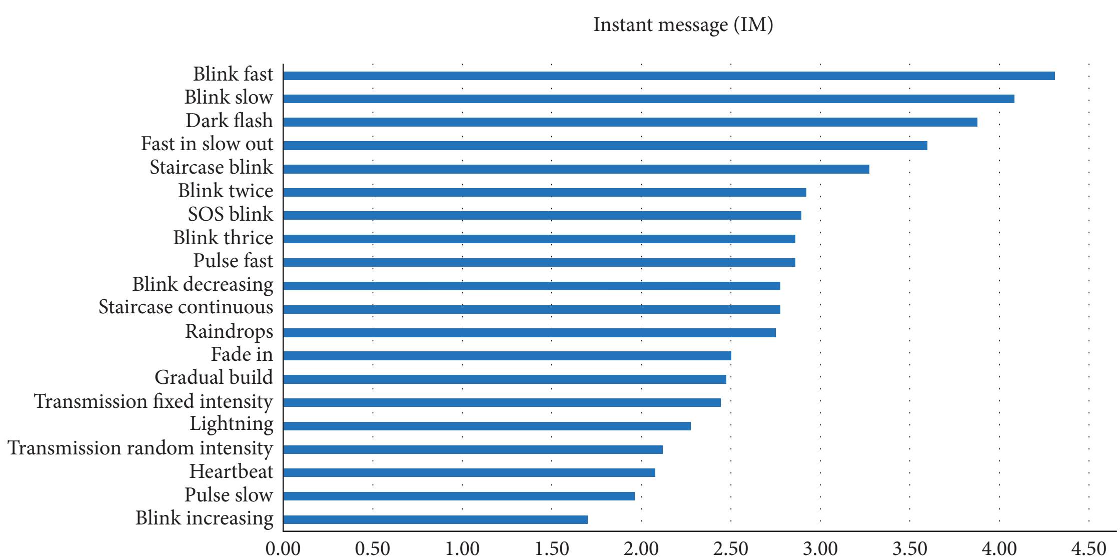


Figure 15: Rating of haptic pulses in indicating the *IM* application.

the *Call* category (3.53) and was significantly different from the two classes: *Turning On* and *e-mail*. Next, the pulse slow score was the highest in *Call* (3.23) and was significantly different from four categories: *Turning on*, *Low-Energy State*, *IM*, and *e-mail*. According to the ANOVA results, raindrops showed a significant difference in the informational category at the 0.05 significance level with a p value = 0.011, but Tukey's HSD test showed no significant difference at the 0.05 significance level. Staircase blink had the highest score in the *Call* category (3.83) and was significantly different from the four categories: *Unable*, *Turning On*, *Low-Energy State*, and *e-mail*. Next, the staircase continuous score was the highest in *Call* (3.53) and was significantly different from the two categories: *Turning On* and *e-mail*. Finally, the transmission fixed intensity and the transmission random intensity were classified into the group with a high score of 3.97 and 3.93, and the *Call* category showed a significant difference from the other five categories.

4.3. Haptic Pulse by Informational Categories in Smartwatches. We proposed dominant haptic pulse in the smartwatch for each informational category. This is shown in Table 4, representing the statistical difference that was

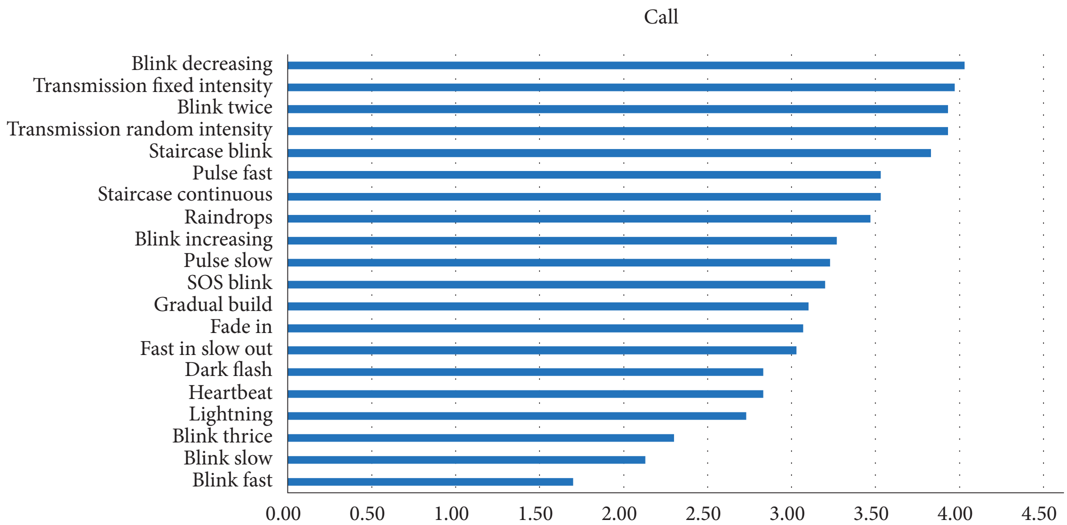


Figure 16: Rating of haptic pulses in indicating the *Call* application.

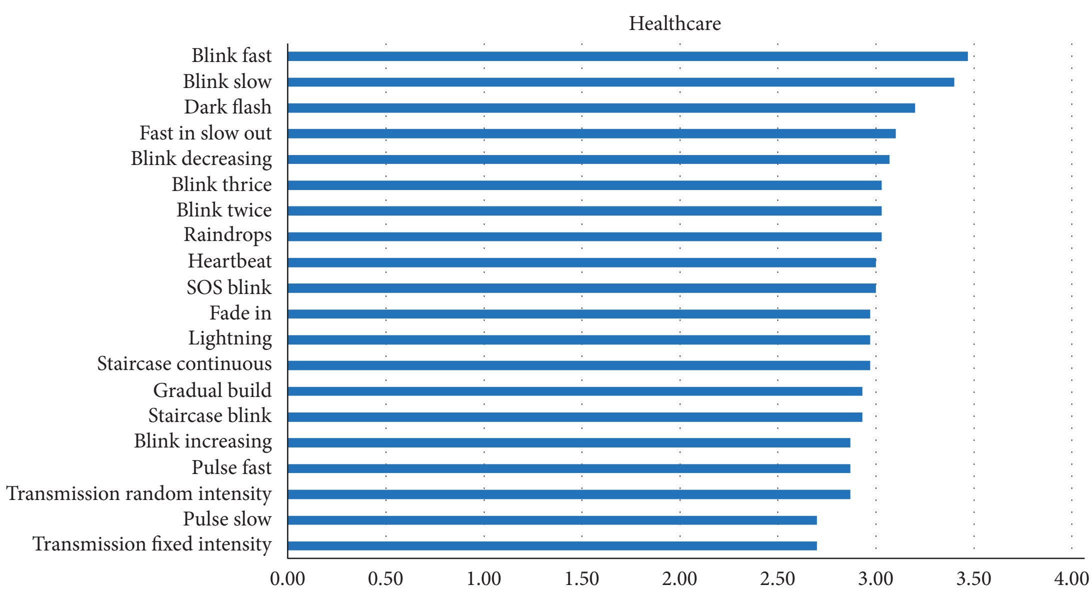


Figure 17: Rating of haptic pulses in indicating the *Healthcare* application.

used as a judgment criterion. Since the dominant haptic pulse in each informational category should be clearly distinguished from other informational categories, the higher the number of statistically significantly lower categories than the score of the reference category was, the more we judged it as the dominant haptic pulse in the criterion category. Also, to avoid assigning the same haptic pulse to different informational categories, if there was only one dominant haptic pulse in each informational category, we assigned a haptic pulse to this informational category so that it did not overlap with the other informational categories.

In the *e-mail* informational category, both haptic pulses of blink fast and blink slow were significantly higher than those of the *Call* and *Turning On* informational categories. In the *IM* informational category, the blink fast was substantially higher than the scores of the three informational categories of *Turning On*, *Low-Energy State*, and *Call*, and blink thrice was significantly higher than the scores of the three informational categories of *Unable*, *Low-Energy State*, and *Call*. Next, in the *Call* informational category, blink decreasing, transmission fixed intensity, and transmission random intensity were significantly higher than those of the other five categories. In the *Unable* informational category, blink fast and blink slow were markedly higher than the scores for *Turning On* and *Call*. Next, in the *Low-Energy State* informational category, the heartbeat was significantly higher than the three categories: *Turning On*, *IM*, and *e-mail*. Finally, in the *Turning On* category, the blink thrice was considerably higher than the other three informational categories: *Unable*, *Low-Energy State*, and *Call*. Table 5 shows the dominant haptic pulse for each informational category.

Table 4: Results of ANOVA and Tukey's HSD test for each haptic pulse.

Haptic pulses	Groups and scores divided through Tukey's HSD test						ANOVA results
	Unable	Turning On	Low-Energy State	Instant Message (IM)	E-mail	Call	p value
Blink decreasing	2.43 (B)	2.97 (B)	2.63 (B)	2.73 (B)	2.63 (B)	4.03 (A)	<0.001*
Blink fast	3.53 (AB)	2.47 (C)	3.37 (B)	4.27 (A)	3.93 (AB)	1.70 (C)	<0.001*
Blink increasing	2.63 (AB)	2.37 (AB)	2.93 (A)	1.80 (B)	2.00 (B)	3.27 (A)	<0.001*
Blink slow	3.57 (A)	2.37 (B)	3.70 (A)	4.07 (A)	3.80 (A)	2.13 (B)	<0.001*
Blink thrice	2.60 (B)	3.80 (A)	2.77 (B)	3.80 (A)	3.57 (AB)	2.30 (B)	<0.001*
Blink twice	2.47 (B)	3.17 (AB)	2.43 (B)	2.87 (B)	2.90 (B)	3.93 (A)	<0.001*
Dark flash	3.00 (AB)	3.07 (AB)	3.33 (AB)	3.87 (A)	3.83 (A)	2.83 (B)	0.002*
Fade in	2.70 (A)	2.27 (A)	2.87 (A)	2.50 (A)	2.23 (A)	3.07 (A)	0.063
Fast in slow out	2.53 (B)	2.63 (AB)	2.97 (AB)	3.57 (A)	3.27 (AB)	3.03 (AB)	0.030*
Gradual build	2.57 (A)	2.27 (A)	2.93 (A)	2.47 (A)	2.40 (A)	3.10 (A)	0.106
Heartbeat	2.80 (AB)	1.90 (B)	3.40 (A)	2.07 (B)	2.20 (B)	2.83 (AB)	<0.001*
Lightning	2.57 (AB)	2.13 (AB)	2.93 (A)	2.20 (AB)	2.03 (B)	2.73 (AB)	0.013*
Pulse fast	2.73 (AB)	2.43 (B)	2.93 (AB)	2.80 (AB)	2.47 (B)	3.53 (A)	0.006*
Pulse slow	2.60 (AB)	2.03 (BC)	2.36 (BC)	1.93 (BC)	1.73 (C)	3.23 (A)	<0.001*
Raindrops	2.77 (A)	3.67 (A)	2.63 (A)	2.70 (A)	2.73 (A)	3.47 (A)	0.011*
SOS blink	2.80 (A)	2.33 (A)	2.93 (A)	2.83 (A)	2.57 (A)	3.20 (A)	0.093
Staircase blink	2.87 (B)	2.90 (B)	2.80 (B)	3.27 (AB)	2.83 (B)	3.83 (A)	0.006*
Staircase continuous	3.20 (AB)	2.37 (B)	2.83 (AB)	2.73 (AB)	2.30 (B)	3.53 (A)	<0.001*
Transmission fixed intensity	2.53 (B)	2.57 (B)	2.70 (B)	2.43 (B)	2.20 (B)	3.97 (A)	<0.001*
Transmission random intensity	2.63 (B)	2.33 (B)	2.40 (B)	2.10 (B)	2.00 (B)	3.93 (A)	<0.001*

*Different letters indicate significant differences between groups (significant at $\alpha = 0.05$).

Table 5: Dominant haptic pulses of each informational category.

Informational category		Haptic pulses
Notification	E-mail	Blink fast, blink slow
	IM	Blink fast, blink thrice
	Call	Blink decreasing, transmission fixed intensity, transmission random intensity
Unable		Blink fast, blink slow
Low-Energy State		Heartbeat
Turning On		Blink thrice

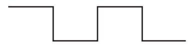
Based on Table 5, we assigned haptic pulses to each information category so that they were not duplicated and preferentially assigned haptic pulses to information categories with only one dominant haptic pulse. In the *Low-Energy State*, a heartbeat was assigned because only one heartbeat was a dominant haptic pulse. Next, since *Turning On* category has only one dominant haptic pulse as blink thrice, blink thrice was assigned to *Turning On*. The *Call* informational category has no overlap with the dominant haptic pulses of other informational categories, so blink decreasing, transmission fixed intensity, and transmission random intensity were assigned to the *Call* informational category. Next, the dominant haptic pulses in the *IM* informational category were blink fast except for the blink thrice previously assigned to *Turning On*, so only blink fast was assigned to the *IM* informational category. *E-mail* and *Unable* informational categories had the same dominant haptic pulses. However, removing the blink fast assigned to the *IM* informational category left only blink slow. In this case, blink slow could be assigned only to one of the categories of *e-mail* and *Unable*. Therefore, although not statistically significant, we assigned blink slow to the *e-mail* informational category, which had a higher score of 3.80. Finally, haptic pulses dominant in the *Unable* information category were all assigned to different categories of information. Thus, as a second-best option, pulse slow was assigned to the *Unable* informational category. Pulse slow was significantly higher in the *Unable* informational category than in the *e-mail* informational category. Table 6 shows the final haptic pulse set, which represents each smartwatch informational category without overlap.

5. Verification Experiment of a Haptic Pulse Set by Informational Categories of Smartwatch

For the haptic pulse set proposed in Section 4 to have meaning, the user should be able to distinguish the smartwatch's informational category with only haptic pulses in constraint situations. Therefore, to verify the haptic pulse set, the experimental environment was made a constraint condition, and the experiment was performed to distinguish the informational category by vibration only. Among the haptic pulse sets in Table 6, there are three haptic pulses in the *Call* application. Since there is no significant difference between these haptic pulses, blink decreasing was arbitrarily selected to construct the experimental haptic pulse set.

A total of 10 participants (5 males and 5 females) were recruited for this experiment. The average age of the participants was 24.1 years, and the standard deviation was 1.52. The experiment took an average of 50 minutes, and the reward was about $-10. The device was the same as that used for the previous experiments, and the experiment coordinator made up the constraint situation by doing twenty questions with the participants. After filling out the basic

Table 6: A set of "smartwatch informational category—haptic pulse."

Informational category		Waveform of the haptic pulse	Name
Notification	E-mail	 Blink slow	Blink slow
	IM	 Blink fast	Blink fast
	Call	 Blink decreasing  Transmission, fixed intensity  Transmission, random intensity	Blink decreasing, transmission fixed intensity, transmission random intensity
Unable		 Pulse slow	Pulse slow
Low-Energy State		 Heartbeat	Heartbeat
Turning On		 Blink thrice	Blink thrice

personal information, the participants were informed of the meaning of six informational categories of smartwatches. Next, the participant was given 25 minutes to familiarize themselves with the "informational category—haptic pulse set." After having learned the haptic pulse set, the experiment coordinator performed twenty questions and, at the same time, provided a total of 12 haptic pulses (two for each informational category) to the participants. Under these constraints, participants determined the informational category for a haptic pulse and checked it on the evaluation sheet. The 12 haptic pulses were given in random order to remove the order effect, and the participants' comments were collected after the experiment. This experiment measured the accuracy of correctly distinguishing informational categories with only haptic pulses.

Experimental results show that only 6 out of 120 times the participants wrongly checked the smartwatch's informational category, and overall accuracy was as high as 95%. In addition, 5 out of 10 participants classified informational categories with 100% accuracy. Therefore, using the haptic pulse set proposed in this study, it was confirmed that the user could distinguish the informational category only by the haptic pulse in the constraint situation.

6. Discussion

To investigate the relationship between the smartwatch's informational category and haptic pulse, we experimented as presented in Section 3. In the analysis based on the smartwatch's informational category, there were statistically significant differences in the haptic pulses in the *Notification* category. Since multiple applications in this category resulted in mixed assessments, we decided to analyze it separately for each application. Among other informational categories, *Active* was excluded from the final analysis because there were no significant differences in the haptic pulses, and the user did not want to receive haptic feedback about it. Also, the *Healthcare* application of the *Notification* informational category did not show a statistically significant difference because users did not yet have a mental model, and, as a result, the *Healthcare* application was excluded from the analysis. The reason why the mental model was not built might be that users are not familiar with the *Healthcare* application in comparison with other applications such as e-mail. Therefore, only the six informational categories were used for analysis.

Next, a dominant haptic pulse set was derived for each informational category. This haptic pulse set was composed of haptic pulses with high scores in each information category. Interestingly, haptic pulses in four informational categories, *e-mail*, *IM*, *Low-Energy State*, and *Turning On*, consist of only a maximum intensity vibration and a minimum intensity vibration in five levels of vibration intensity. Participants noted that their mobile phones and smartphones delivered this information in a two-step vibration. Therefore, it can be seen from these prior experiences that users prefer familiar vibrations consisting of only two steps. Also, blink decreasing, transmission fixed intensity, and transmission random intensity have been adopted as haptic pulses representing the *Call* application, and these haptic pulses have been adopted to provide rhythmical and continuous vibration due to the experience of past mobile phones and smartphones.

Finally, based on the haptic pulse set derived in this study, we experimented to confirm whether a smartwatch's informational categories can be distinguished only by haptic feedback without visual attention in constraint situations. Experimental results showed that participants could identify informational categories with high accuracy of 95%. It was proven that the proposed haptic pulse set is valid.

7. Conclusions

This study proposes a method to encode and provide smartwatch information with various haptic pulses to solve the problems that cause high cognitive load when the user checks their smartwatch information in constraint situations. To do this, we investigated the informational category of smartwatches and generated various haptic pulses and analyzed the relationship between informational categories and haptic pulses. Haptic pulse sets, which represent the smartwatch's informational categories, were derived through several experiments.

Finally, we conducted a verification experiment of the haptic pulse set and showed that smartwatch users could distinguish information from their watch with only haptic pulses. The haptic pulse set proposed in this study has versatility that can be applied to all smartwatches equipped with vibration motors and is expected to provide insight to developers.

In addition, haptic pulses representing *Healthcare* applications could not be proposed because most participants do not have a mental model for *Healthcare* applications at this time. Therefore, further study will be needed to derive a haptic pulse when *Healthcare* applications in smartwatches are more common.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Yonghwan Yim and Jaemoon Sim should be considered the co-first author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Gartner Inc. (2016), https://www.gartner.com/newsroom/id/3198018.

[2] M. Ahmad, A. Khan, M. Mazzara, and S. Distefano, "Seeking optimum system settings for physical activity recognition on smartwatches," in *Proceedings of the Science and Information Conference*, pp. 220–233, Springer, Las Vegas, NV, USA, April 2019.

[3] M. Ahmad, M. A. Alqarni, A. Khan et al., "Smartwatch-based legitimate user identification for cloud-based secure services," *Mobile Information Systems*, vol. 2018, Article ID 5107024, 14 pages, 2018.

[4] M. E. Cecchinato, A. L. Cox, and J. Bird, "Always on (line)?: user experience of smartwatches and their role within multi-device ecologies," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 3557–3568, ACM, Denver, CO, USA, May 2017.

[5] V. G. Motti and K. Caine, "Smart wearables or dumb wearables?: understanding how context impacts the UX in wrist worn interaction," in *Proceedings of the 34th ACM International Conference on the Design of Communication*, p. 10, ACM, Silver Spring, MD, USA, September 2016.

[6] S. Pizza, B. Brown, D. McMillan, and A. Lampinen, "Smartwatch in vivo," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 5456–5469, ACM, San Jose, CA, USA, May 2016.

[7] D. McMillan, "The smartwatch in multi-device interaction," in *Proceedings of the International Conference of Design, User Experience, and Usability*, pp. 275–287, Springer, Vancouver, Canada, July, 2017.

[8] J. Sim, Y. Yim, and K. Kim, "Development and evaluation of the HaptiWatch with a smart notification system," *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 29, no. 6, pp. 504–516, 2019.

[9] K. S. Hale and K. M. Stanney, "Haptic rendering - beyond visual computing—deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations," *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 33–39, 2004.

[10] S. C. Lee and T. Starner, "BuzzWear: alert perception in wearable tactile displays on the wrist," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 433–442, ACM, Atlanta, Georgia, April 2010.

[11] L. M. Brown, S. A. Brewster, and H. C. Purchase, "Multidimensional tactons for non-visual information presentation in mobile devices," in *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services*, pp. 231–238, ACM, Helsinki, Finland, September 2006.

[12] S. Kinsey, J. Hu, J. Huang, and P. Khotpanya, "Systems and methods for configuring vibration patterns for notifications received at a wearable communication device,"

U.S. PatentApplication No. 14/684050, U.S. Patent and Trademark Office, Washington, DC, USA, 2015.

[13] D. Dobbelstein, P. Henzler, and E. Rukzio, "Unconstrained pedestrian navigation based on vibro-tactile feedback around the wristband of a smartwatch," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 2439–2445, ACM, San Jose, CA, USA, May 2016.

[14] S. Azenkot, R. E. Ladner, and J. O. Wobbrock, "Smartphone haptic feedback for nonvisual wayfinding," in *Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*, pp. 281-282, ACM, Dundee, Scotland, October 2011.

[15] K. Tsukada and M. Yasumura, "Activebelt: belt-type wearable tactile display for directional navigation," in *Proceedings of the International Conference on Ubiquitous Computing*, pp. 384–399, Springer, Nottingham, UK, September 2004.

[16] S. Akhter, J. Mirsalahuddin, F. B. Marquina, S. Islam, and S. Sareen, "A smartphone-based haptic vision substitution system for the blind," in *Proceedings of the 2011 IEEE 37th Annual Northeast Bioengineering Conference (NEBEC)*, pp. 1-2, IEEE, Troy, NY, USA, April 2011.

[17] D. Dakopoulos, S. K. Boddhu, and N. Bourbakis, "A 2D vibration array as an assistive device for visually impaired," in *Proceedings of the 2007 IEEE 7th International Symposium on BioInformatics and BioEngineering*, pp. 930–937, IEEE, Boston, MA, USA, October 2007.

[18] C. Harrison, J. Horstman, G. Hsieh, and S. Hudson, "Unlocking the expressivity of point lights," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 1683–1692, ACM, Austin, TX, USA, May 2012.

[19] J. R. Blum, I. Frissen, and J. R. Cooperstock, "Improving haptic feedback on wearable devices through accelerometer measurements," in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pp. 31–36, ACM, Charlotte, NC, USA, November 2015.

[20] M. J. Enriquez and K. E. MacLean, "The hapticon editor: a tool in support of haptic communication research," in *Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003*, pp. 356–362, IEEE, Los Angeles, CA, USA, March 2003.

[21] X. Liu, T. Chen, F. Qian et al., "Characterizing smartwatch usage in the wild," in *Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services*, pp. 385–398, ACM, Niagara Falls, NY, USA, June 2017.

[22] K. Baraka, "Effective non-verbal communication for mobile robots using expressive lights," Dissertion, Carnegie Mellon University, Pittsburgh, PA, USA, 2016.

[23] K. Kobayashi, K. Funakoshi, S. Yamada, M. Nakano, T. Komatsu, and Y. Saito, "Blinking light patterns as artificial subtle expressions in human-robot speech interaction," in *Proceedings of the RO-MAN, 2011*, pp. 181–186, IEEE, Atlanta, GA, USA, July 2011.

[24] Y. Liu, R. H. Liang, Y. H. Lee, Y. Chuang, and L. L. Chen, "Designing the expressiveness of point lights for bridging human-IoT system communications," in *Proceedings of the Conference on Design and Semantics of Form and Movement-Sense and Sensitivity, DeSForM 2017*, InTech, Eindhoven, Netherlands, October 2017.

[25] C. Min, S. Kang, C. Yoo et al., "Exploring current practices for battery use and management of smartwatches," in *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, pp. 11–18, ACM, Osaka, Japan, September 2015.

[26] M. Chan, D. Estève, J.-Y. Fourniols, C. Escriba, and E. Campo, "Smart wearable systems: current status and future challenges," *Artificial Intelligence in Medicine*, vol. 56, no. 3, pp. 137–156, 2012.

[27] C.-H. Wang, "A market-oriented approach to accomplish product positioning and product recommendation for smart phones and wearable devices," *International Journal of Production Research*, vol. 53, no. 8, pp. 2542–2553, 2015.

[28] D. A. Norman, "Some observations on mental models," in *Mental Models*, pp. 15–22, Psychology Press, Hove, UK, 2014.